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WELDING AND RELATED PROCESSES



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Welding and related processes

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The manual outlines the basics of welding and related processes in the discipline «Welding and Related Processes» for PhD-level higher education students studying in the specialty G08 «Materials Science».

The purpose of the manual is to provide applicants with the opportunity to study in more detail the basics of the theory and practice of welding technologies and obtain factual data for application in production and in scientific work.

The list and content of topics correspond to the program of the above-mentioned discipline.

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INTRODUCTION

Welding is one of the main technological processes in mechanical engineering and construction. It is difficult to name a branch of the national economy where welding is not used.

Welding has made it possible to make fundamental changes in production technology, to create fundamentally new machine designs. For example, the use of welded structures instead of riveted ones in construction has allowed to save about 20% of metal, to reduce the labor intensity of manufacturing structures by 5...30%.

Development of welding. The main type of welding is arc welding.

In 1802, for the first time in the world, professor of physics Vasily Vladimirovich Petrov discovered and observed an arc discharge from a super-powerful "volt pillar" he made, which consisted of 2100 pairs of dissimilar circles-elements (copper + zinc), laid with paper circles moistened with an aqueous solution of ammonia. This pillar, or battery, as V. V. Petrov called it, was the most powerful source of electric current at that time. Having conducted a large number of experiments with this battery, he showed the possibility of using an electric arc for lighting and melting metals. By the time of the discovery of the arc discharge, electrical engineering was just beginning to be created, V. V. Petrov's discovery was significantly ahead of its time, and about 80 years passed before the practical application of the arc for welding purposes.

This was done by the Ukrainian inventor Mykola Mykolayovich Benardos - the author of many inventions in the field of electrical engineering. In 1881, he first used an electric arc between a carbon electrode and metal for welding. After detailed development of his invention, M. M. Benardos received patents for it in England, Belgium, Germany, Italy, France, the USA and other countries. M. M. Benardos used the method he created not only for welding, but also for surfacing and cutting metals. Almost simultaneously with M. M. Benardos, another inventor worked - Mykola Gavrylovich Slavyanov, who did a lot for the development of arc welding. He developed a method of arc welding with a metal electrode with protection of the welded zone with a layer of powdered substance (flux) and the world's first mechanism - "electrofusion" - for semi-automatic feeding of the electrode rod into the welding zone. The method of welding with a consumable metal electrode was called "arc welding according to the Slavyanov method". The first public demonstration of the new method took place in 1888 in Perm.

The inventions of M. M. Benardos and M. G. Slavyanov found notable application at that time, primarily on railways, and then at several large machine-building and metallurgical plants.

A significant contribution to the development of the theoretical foundations of welding was made by scientists: V. P. Vologdin, V. P. Nikitin, K. Kh.

Khrenov, E. O. Paton, G. O. Nikolaev, N. O. Okerblom, N. N. Rykalin, K. V. Lyubavsky, B. E. Paton and others.

At the present stage of the development of welding production, due to the development of the scientific and technological revolution, the range of welded thicknesses, materials, and types of welding has greatly increased. Nowadays, materials with a thickness of several micrometers (in microelectronics) to several meters (in heavy engineering) are welded. Along with traditional structural steels, special steels and alloys based on titanium, zirconium, molybdenum, niobium and other materials are welded, as well as dissimilar materials.

The conditions for welding have expanded significantly. Along with the usual conditions, welding is performed under high temperatures, radiation, underwater, in deep vacuum, in weightlessness. New types of welding are being rapidly introduced - laser, electron beam, ion, light, diffusion, ultrasonic, electromagnetic, explosive, and the capabilities of arc and contact welding are significantly expanding.

The main means of accelerating scientific and technological progress and the development of production is to increase labor productivity and quality of work. In the field of welding production, this task is solved by mechanization and automation of the welding processes themselves, that is, by the transition from manual labor of the welder to mechanized, and by complex mechanization, which includes the mechanization of preparation, assembly, welding, finishing, auxiliary and control operations.

The main operations of welding production. Welding is the process of manufacturing inseparable joints by establishing interatomic bonds between the welded parts during their local (general) heating or plastic deformation, or their combined action. The essence of welding is to bring the elementary particles of the welded parts together so that interatomic bonds begin to act between them, which ensure the strength of the connection.

Welding production is a complex of production processes with the widespread use of welding equipment, which forms an independent, complete technology for manufacturing welded products.

The entire complex of welding production can be divided into six groups of operations: 1 - preparatory, 2 - assembly, 3 - welding, 4 - finishing, 5 - auxiliary, 6 - control.

Preliminary operations - operations for the manufacture of parts of welded structures. When performing preparatory operations, the following types of metal processing are used: cutting - mechanical and thermal, planing on machine tools;

stamping on presses; cleaning the edges and surfaces of parts from scale, rust, burrs; straightening and bending parts on rollers, presses, plates; mechanical processing of large parts - turning, planing, milling, drilling holes in them.

Assembly operations ensure the correct mutual placement and fastening of parts of the product being assembled and welded on a plate, rack, stand or special device.

In addition to the actual welding operations, welding operations include some auxiliary operations inextricably linked with welding, such as installing the product for welding or the welding head at the beginning of the seam, directing the electrode along the joint, turning the product during welding, moving the welder, etc.

Finishing operations include cleaning the seams, removing metal spatter and burrs, painting, packaging, as well as thermal and mechanical treatment of finished products, if they are performed in the welding shop.

Auxiliary operations include crane, transport, lifting and reloading operations: adjustment work with welding, gas-cutting and other equipment; assembly of parts and distribution of work; work on receiving and issuing material and tools, manufacturing electrodes, winding cassettes with welding wire; other auxiliary work related to the main production.

Control work includes a set of control operations at each stage of manufacturing a welded structure, including control of the initial welded and welded materials, quality control of preparatory, assembly, welding and finishing operations, control of welded joints and finished products.

1 GENERAL INFORMATION

1.1 Classification of welding and surfacing

Depending on the type of energy used in welding, three classes of welding are distinguished: thermal, thermomechanical and mechanical.

The thermal class includes types of welding carried out by melting, i.e. local melting of the parts to be joined using thermal energy.

The main sources of heat in fusion welding are the welding arc, gas flame, radiant energy sources and heat released during the electroslag process.

Heat sources are characterized by temperature and concentration, which is determined by the smallest heating area (heating spot) and the largest density of thermal energy in the heating spot.

These indicators (Table 1) determine the technological properties of metal heating sources during welding, surfacing and cutting. From Table 1 shows, for example, that the degree of heat concentration in the arc is tens of times. in plasma - thousands of times, in photon beams (during laser processing) - tens of thousands of times higher than in a gas flame.

The main types of thermal class welding - arc, gas, electroslag, electron beam, plasma, laser, thermal, etc.

Arc welding - fusion welding, in which heating is carried out by an electric arc. A special type of arc welding is plasma welding, in which heating is carried out by a compressed arc.

Gas welding - fusion welding, in which the edges of the parts to be joined are heated by a flame of gases compressed at the outlet of the gas welding torch.

Electroslag welding is a fusion welding in which the heat released when an electric current passes through molten conductive slag is used to heat the metal.

In electron beam welding, the energy of an electron beam is used to heat the parts to be joined. The heat is released by bombarding the welding zone with a directed electron beam.

Local melting of the parts to be joined in laser welding is carried out by the energy of a light beam obtained from a laser.

In thermal welding, the heat generated as a result of the combustion of thermite powder, which consists of a mixture of aluminum and iron oxide, is used.

The thermomechanical class includes types of welding that use thermal energy and pressure - contact, diffusion, gas-press, arc-press, etc.

The main type of thermomechanical class is contact welding - welding using pressure, in which heating is carried out by the heat released when an electric current passes through the parts to be joined that are in contact.

The thermomechanical class includes types of welding that use thermal energy and pressure - contact, diffusion, gas-press, arc-press, etc.

Table 1 – Characteristics of the main energy sources for welding and cutting

Energy source	Temperature, °C	The smallest heating area, cm ²	The highest energy density in the spot, W/cm ²
Electroslag process	2 000...2 200	-	-
Gas flame	3000...3500	1·10 ⁻²	5·10 ⁴
Arc in metal vapor	4 500...6 000	1·10 ⁻³	1·10 ⁵
Arc in gases	5 000...20 000	1·10 ⁻⁴	1·10 ⁵
Microplasma	-	1·10 ⁻⁶	1·10 ⁷
Electron beam	-	1·10 ⁻⁷	1·10 ⁸
Photon beam	-	1·10 ⁻⁸	1·10 ⁹

The main type of thermomechanical class is contact welding - welding using pressure, in which heating is carried out by the heat released when an electric current passes through the parts to be joined that are in contact.

The mechanical class includes types of welding performed using mechanical energy and pressure: cold, explosion, ultrasonic, friction, etc.

Cold welding - pressure welding with significant plastic deformation without external heating of the parts to be joined.

Explosion welding - welding in which the connection is made as a result of the explosion-induced collision of rapidly moving parts.

Ultrasonic welding - pressure welding performed under the action of ultrasonic vibrations.

Friction welding - pressure welding when heating is carried out due to friction arising from the mutual rotation of the parts to be welded.

Welding processes are used for surfacing. Surfacing is the process of applying a layer of metal to the surface of the product by welding. Surfacing is used to restore worn parts and obtain products with specified surface properties: wear resistance at normal and elevated temperatures, heat resistance, acid resistance, etc.

For surfacing, arc welding is mainly used: manual with consumable and non-consumable electrodes, mechanized and automatic under flux and in protective gases, vibrating arc, plasma. Along with arc welding, gas, electroslag, induction, and furnace surfacing are used.

There are several ways to obtain surfacing alloyed metal of a given chemical composition:

using an alloyed electrode rod, electrode wire or strip of solid cross-section and unalloyed coatings, flux or protective gas;

using wire and strips with alloyed fillers in combination with unalloyed coatings, flux or protective gas;

using an unalloyed electrode rod, wire or strip and an alloyed coating or flux;

applying alloying additives in the form of powders, pastes, briquettes, etc. to the surface to be surmounted.

Combinations of these methods are possible.

Manual arc surfacing is used to restore worn surfaces, restore casting defects and to surfacing surfaces with special properties.

Manual arc surfacing is performed with coated fusible and non-fusible electrodes, by melting a layer of loose surfacing alloy.

Automatic submerged arc surfacing is performed with solid and flux-cored wires, with one electrode, separate rollers, simultaneously with several electrodes and electrode tape. Solid and powder tapes are used.

Surfacing with fusible and non-fusible electrodes in a protective gas environment. Surfacing with a tungsten electrode is performed in an argon environment. The required properties of the surfacing metal are provided by using special filler wires or by blowing alloying powders into the arc zone.

It is possible to weld in inert gases and with a consumable electrode, however, the use of the same technology as for welding leads to an increased content of the base metal in the weld, therefore an additional filler wire is used. This method is widely used in the welding of high-alloyed chromium-nickel steels and alloys.

Plasma welding is carried out in several ways:

direct-action plasma with the supply of a filler wire;

with the supply of filler powder into the plasma jet;

over a layer of alloying material applied to the surface of the product;

with a current-carrying filler wire;

with two consumable electrodes.

Electroslag welding is carried out on flat and cylindrical surfaces to create surface layers with special properties and to create intermediate layers on the edges of workpieces for subsequent welding. The technique of electroslag welding is fundamentally no different from the welding technique.

Vibro-arc surfacing is used mainly as a means of restoring parts that wear out quickly, machine tool, metallurgical, agricultural equipment. Parts with a diameter of 8...10 mm and above can be subjected to this type of surfacing. The essence of vibro-arc surfacing is that surfacing is carried out using a special head that provides feed and vibration of the electrode wire, which facilitates arc excitation and increases process stability. During surfacing, electric discharges alternate with short circuits. An alkaline emulsion is supplied to the surfacing and arc zone, which protects the metal from the action of air and cools the parts,

as a result of which the heat-affected zone and welding deformations are reduced and the hardness of the surfacing layer is increased. Gas-oxygen flame is used mainly for surfacing with cast hard alloys.

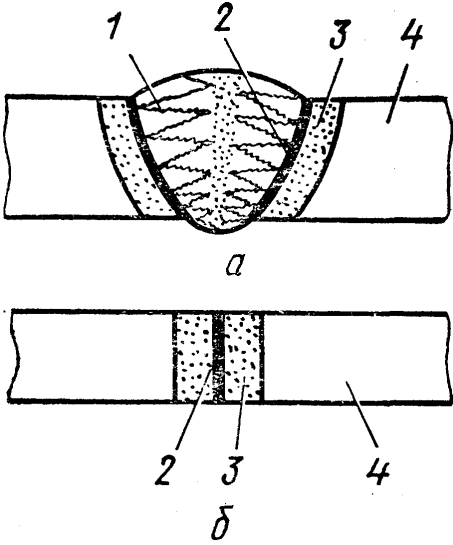


Figure 1 – Scheme of a welded joint:

a – during fusion welding; *b* – during pressure welding; 1 – weld; 2 – fusion zone (adhesion); 3 – heat-affected zone; 4 – base metal

A joint made by pressure welding (Fig. 1, *b*) in the solid state consists of a joint zone 2, where interatomic bonds of the joined parts are formed, a zone of thermomechanical influence 3, and base metal 4.

In the formation of the structure and properties of a welded joint during fusion welding, the decisive role belongs to thermal processes, while in pressure welding, plastic deformation plays a decisive role.

Welded joints can be butt, corner, T-shaped, and fillet (Fig. 2).

A butt weld is a welded joint of two elements located in the same plane or on the same surface.

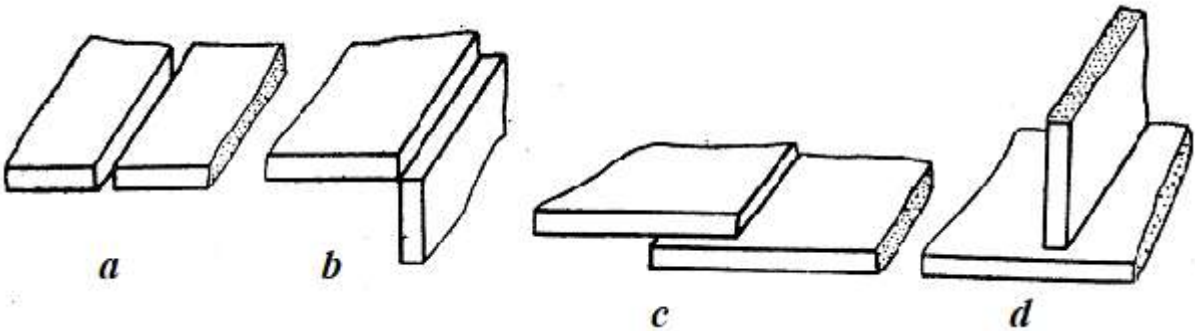


Figure 2 – Welded joints:

a – butt; *b* – corner; *c* – lap joint; *d* – T-joint

Connection	Welding					
	Manual arc	Automatic submerged arc	Electron beam	Contact		
				Butt	Spot	Seam
Butt						
Taper						
Flush						
Corner						

Figure 3 – Welded joints performed in the main types of welding

A corner joint is a joint of two elements placed at right angles and welded at the point where their edges meet.

A fillet joint is a welded joint in which the elements to be welded are placed parallel and overlap each other.

A fillet joint is a welded joint in which another element welded at an angle adjoins the side surface of one element.

A part of a structure in which the welded elements adjoin each other is called a welded joint.

Examples of welded joints performed in the main types of fusion and pressure welding are shown in Fig. 3.

A weld seam is a section of a welded joint formed as a result of the crystallization of the weld pool metal. The part of the weld seam that is in a liquid state during welding is called the weld pool.

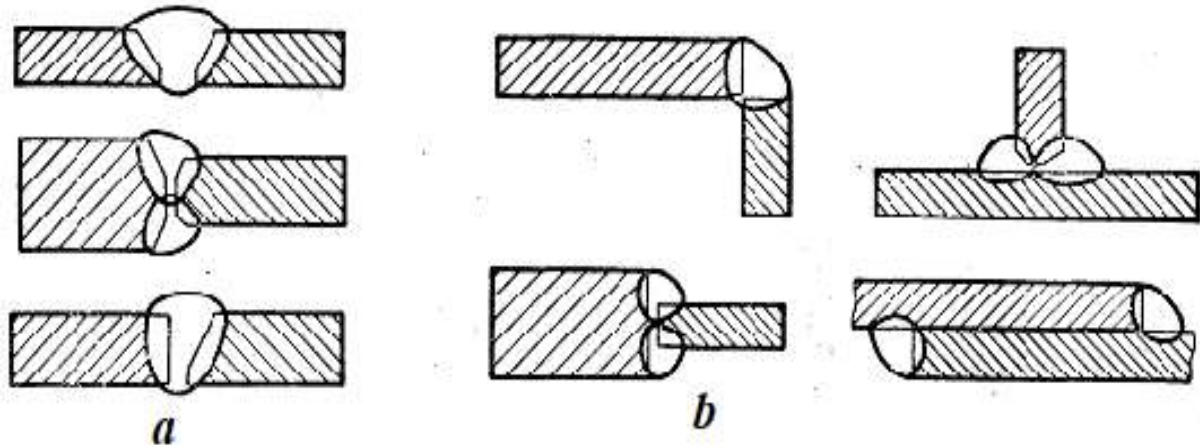


Figure 4 – Welds:
a – butt; *b* – corner

When welding without additional metal, only the base metal is melted. The metal intended for introduction into the weld pool is called the filler metal.

The molten base and filler metals, merging, form a common weld pool. The boundaries of the weld pool are the melted areas of the base metal and the previously formed seam.

Welds can be butt and corner (Fig. 4). Butt seam - a weld of a butt joint. Corner seam - a weld of a corner, T-shaped and fillet joints.

Welds can be continuous, intermittent, single- and multi-layer, single- and double-sided. Welds used to fix the mutual arrangement, dimensions and shape of elements assembled for welding are called tacks.

Fig. 5 shows the main positions of the seams in space.

To ensure high-quality penetration and formation of the weld, the edges are prepared for welding. Elements of the geometric shape of the preparation of the edges for welding (Fig. 6, a) are the edge clearance angle α , the bevel angle β of one edge δ , the gap b between the mating edges, the blunting of the edge, i.e. the unbeveled part c of the edge end.

Elements of the geometric shape of the weld (Fig. 6, b) are the width e and the depth h of the weld. depth h of the penetration, the convexity q (concaveness) of the weld.

Depending on the design features of the product and the type of welding, different requirements are imposed on the preparation and assembly of parts.

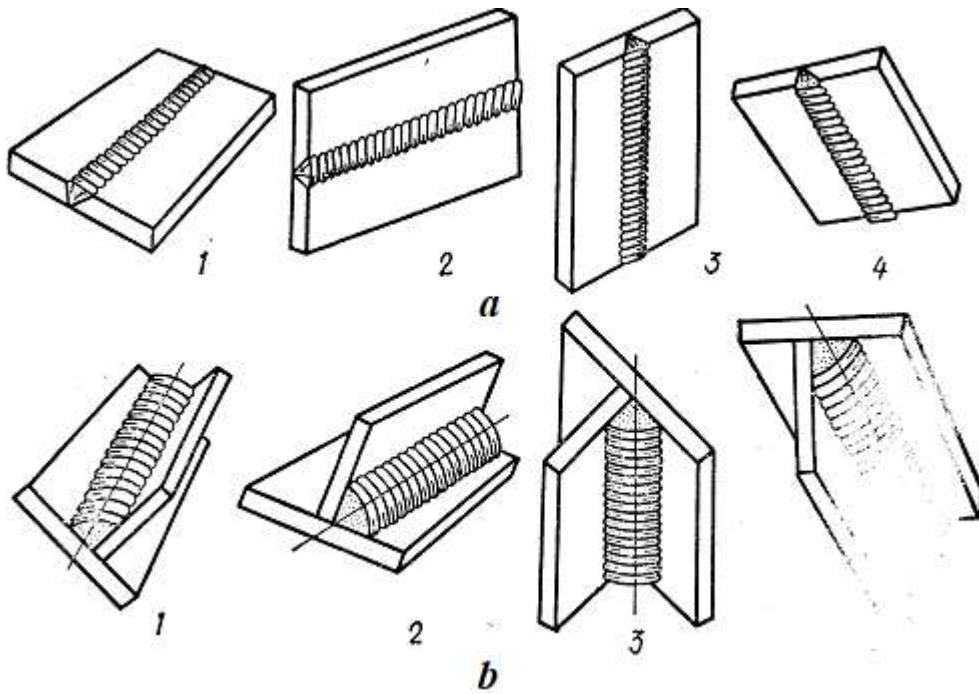


Figure 5 – Spatial position of welds:
a – butt; *b* – corner; 1 – bottom; 2 – horizontal; 3 – vertical; 4 – ceiling

State standards regulate the main types and structural elements of welded joints.

To manufacture welded structures, a large number of welding materials are used that ensure a high-quality welding process, formation, protection, and a specified chemical composition of the weld.

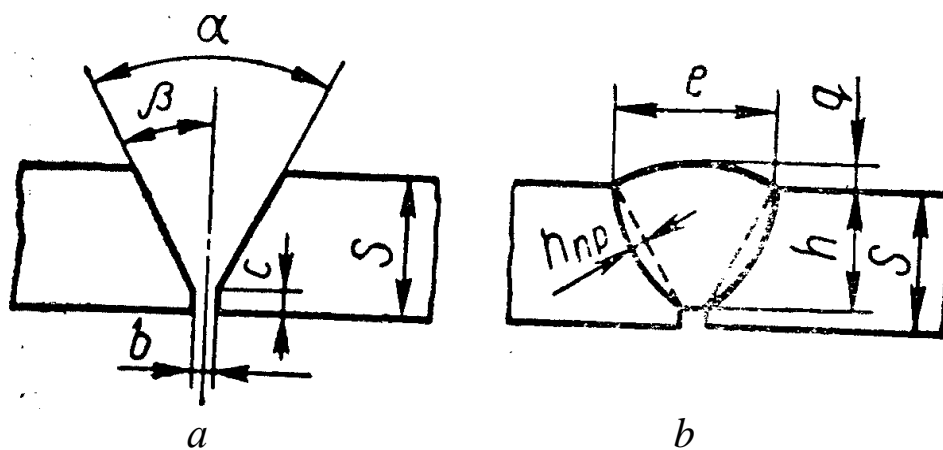


Figure 6 – Elements of the geometric shape of prepared edges for welding (*a*) and the performed seam (*b*)

Welding materials can be classified as follows.

1. Those that directly participate in the creation of a weld. These include artificial consumable electrodes for manual arc welding, electrode wires

for welding in protective gases, under flux and for electroslag welding, filler materials for various methods of fusion welding; to a lesser extent, fluxes or active gases participate in the formation of the composition of the welds.

2. Those that do not directly participate in the creation of the weld metal. These include non-consumable electrodes - tungsten, carbon, graphite; inert gases - argon, helium.

Welding materials are also classified into metallic and non-metallic. Metallic welding materials include welding and surfacing wires, solid cross-section and powder ribbons; electrodes - coated fusible and tungsten non-fusible; additional filler metal in the form of filler wire, granulated metal powders.

Non-metallic welding materials include fluxes - fusible and ceramic, shielding gases - inert and active; this group includes vacuum as a protective environment when welding active metals.

1.2 Weldability of metals and alloys

Weldability is the property of a metal or combination of metals to form a joint with the established welding technology that meets the requirements determined by the design and operation of the product.

There are physical and technological weldability. Physical weldability is the property of materials to create a monolithic joint with a chemical bond; such weldability is possessed by almost all technical alloys and pure metals, as well as a number of combinations of metals with non-metals.

Technological weldability is a technological characteristic of a metal that determines its reaction to the action of welding and the ability to form a welded joint with specified operational properties.

The weldability of a metal depends on its chemical and physical properties, crystal lattice, degree of alloying, impurities and other factors. The main indicators (criteria) of weldability of metals and their alloys:

- oxidizability of the metal during welding heating, which depends on its chemical activity;

- sensitivity of the metal to the thermal action of welding, which is characterized by the tendency of the metal to grain growth,

- structural and phase changes in the seam and heat-affected zone, changes in strength and plastic properties;

 - resistance to the formation of hot cracks;

 - resistance to the formation of cold cracks during welding;

 - sensitivity to the formation of pores;

- compliance of the properties of the welded joint with the specified operational requirements; these include: strength, plasticity, endurance, creep, toughness, heat resistance and heat resistance, corrosion resistance, etc.

In addition to the listed main indicators of weldability, there are other indicators on which the quality of welded joints depends. These include the quality of the weld formation, inherent stresses, deformations and gouging of the welded materials and products.

The oxidation of the metal during welding is determined by the chemical properties of the welded material. The more chemically active the metal, the greater its tendency to oxidation and the higher the quality of protection during welding should be. The most active metals that are easily oxidized during welding include Ti, Zr, Nb, Ta, Mo, W. When welding them, it is necessary to protect not only the molten metal from interaction with air, but also the base metal adjacent to the weld pool and the seam that cools from the outside. The best quality of protection is provided by high vacuum and high-purity inert gas.

Other non-ferrous metals are also distinguished by high chemical activity during welding: Al, Mg, Cu, Ni and alloys based on them; the quality of their protection is provided by inert gases, as well as special electrode coatings and fluxes.

When welding steels and iron-based alloys, the molten metal is protected from interaction with air by coatings, fluxes, and shielding gases.

The sensitivity of the metal to the thermal action of welding is one of the main indicators of weldability. The metal in any zone of the welded joint undergoes heating and subsequent cooling. The change in the temperature of the metal during welding is called the thermal cycle of welding. The maximum heating temperature in different zones of the joints is different: in the weld it exceeds it, in the melting zone it is close, in the heat-affected zone it is lower than the melting temperature, gradually decreasing with distance from the weld.

When heated, the following structural and phase transformations occur in the metal:

- dissolution of phases in the metal in the solid state, for example, carbides (compounds of metals with carbon) in the heated metal;

- polymorphic transformation, i.e. transformation of a low-temperature modification of the material into a high-temperature one;

- melting of the metal in areas heated above the melting point.

During cooling, structural and phase transformations occur in the reverse order:

- crystallization;

- polymorphic transformation, i.e., transition from a high-temperature phase to a low-temperature phase;

- precipitation of various secondary phases from the metal - carbides, intermetallics, etc.

In addition to the above transformations, structural changes occur in the metal in the low-temperature zone during welding, which cause weakening of the base metal - recrystallization, aging, etc.

Let us consider the thermal cycle and structure of a welded joint during arc welding of low-carbon steel (Fig. 7).

Fig. 7, a shows how the maximum temperature in the welded joint is distributed, Fig. 7, b - a schematic structure of various joint zones, Fig. 7, c, d - temperature changes (thermal cycles) in these zones and the properties of the metal.

Each metal consists of very small grains. These grains can be seen on a fracture. The totality of all grains of a metal is called its structure. In a metal, macro- and microstructure are distinguished. The macrostructure is visible to the naked eye and at small (up to 10...15 times) magnifications. The structure of a metal, which is studied at magnifications of more than 60...100 times, is called microstructure.

In section 1, the metal, which was in a molten state, solidifies, forming a weld, which has a cast structure of columnar crystals. The coarse columnar structure of the weld metal is unfavorable because it reduces the strength and plasticity of the metal.

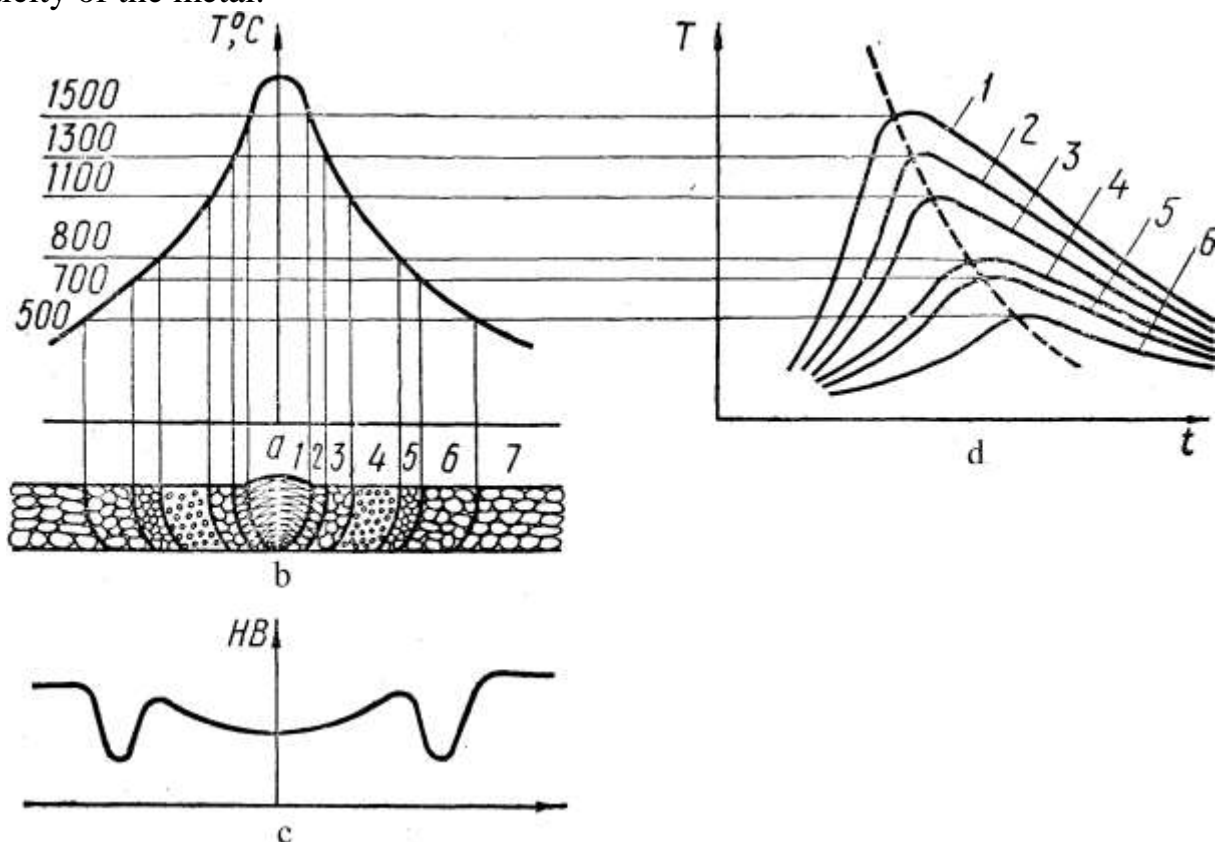


Figure 7 – Thermal cycle and scheme of changes in the structure and properties of a welded joint of low-carbon steel during single-pass welding:

a — distribution of maximum temperatures; b — scheme of changes in structure; c — change in hardness; d — thermal cycles at characteristic points of the joint

The heat-affected zone has several structural areas that differ in the shape and structure of the grain, caused by different heating temperatures within 450...1500 °C.

Incomplete melting zone 2 is the transition from the deposited metal to the base metal. In this area, a joint is formed and the fusion boundary passes, this is a very limited zone (0.1...0.4 mm) of the base metal heated to partial melting of the grains. Here, significant grain growth and accumulation of impurities are observed, so this area is usually the weakest point of the welded joint with reduced strength and ductility.

Overheating zone 3 is the zone of the base metal that is heated to temperatures of 1100...1450 °C, due to which the metal is characterized by a coarse-grained structure and reduced mechanical properties (ductility and impact toughness). These properties are lower, the larger the grain and the wider the overheating zone.

Normalization zone 4 is a zone of metal heated to 900... 1100 °C. The metal of this zone has high mechanical properties, because during heating and cooling, a fine-grained structure is formed in this zone as a result of recrystallization without overheating.

Incomplete recrystallization zone 5 is a zone of metal heated during welding to 725...900 °C. Due to incomplete recrystallization caused by insufficient time and heating temperature, the structure of this zone is characterized by a mixture of small grains that have recrystallized and large grains that have not yet had time to recrystallize. The metal of this zone has lower mechanical properties than the metal of the previous zone.

Recrystallization zone 6 is a zone of metal heated to 450...725 °C. If the steel was subjected to cold deformation (rolling, forging, stamping) before welding, then recrystallization processes develop in this area, which lead to grain growth, coarsening of the structure and, as a result, to a decrease in strength.

Area 7, heated to 200...450 °C, is a transition zone from the heat-affected zone to the base metal. In this area, aging processes can occur due to the precipitation of iron carbides and nitrides, as a result of which the mechanical properties of the metal in this area decrease. If the metal was annealed before welding, then no significant changes occur in areas 6 and 7.

The width of the heat-affected zone depends on the thickness of the metal, the type and welding modes. In manual arc welding, it is usually 5...6 mm, in submerged arc welding of medium thicknesses - about 10 mm, in gas welding - up to 25 mm.

Along with the structure, under the influence of the thermal cycle, the strength and ductility in different zones of the welded joint change (Fig. 7, B).

As a rule, the higher the strength of the welded material and the greater the degree of its alloying, the more sensitive the material is to the thermal cycle of welding and the more complex the technology of its welding.

The sensitivity of the metal to the thermal effects of welding is assessed by the properties of different zones of the joints and welded joints as a whole during static, dynamic and vibration tests (tensile, bending, determination of hardness, determination of the transition of the metal to a brittle state, etc.), as well as by the results of metallographic studies depending on the types and modes of welding used.

Resistance of the metal to the formation of cracks during welding. During welding, hot and cold cracks can occur in the weld metal and in the near-weld zone.

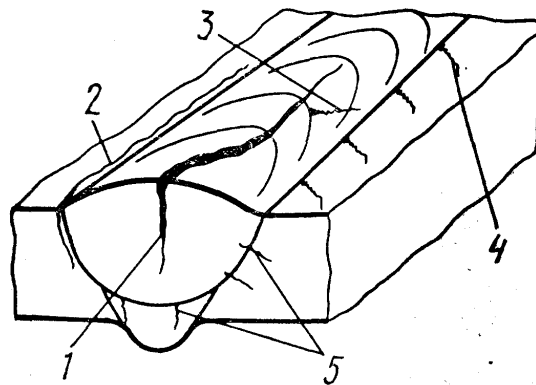


Figure 8 – Hot cracks in welded joints:

- 1, 2 – longitudinal; 3, 4 – transverse in the seam and surrounding area;
5 – transverse through the thickness of the welded metal

Hot cracks are brittle intercrystalline fractures of the weld metal and the surrounding zone that occur in the solid-liquid state during crystallization, as well as at high temperatures in the solid state.

During crystallization, the liquid weld metal first passes into the liquid-solid state, then into the solid-liquid state, and finally into the solid state. In the solid-liquid state, a framework of crystallites of the solidified metal (solid phase) is formed, in the gaps of which there is liquid metal, which in that state has very low plasticity and strength.

Shrinkage of the weld and linear reduction of the heated metal in the welded joint during cooling can lead to the formation of hot cracks. Hot cracks can form both along and across the weld (Fig. 8).

Two main types of tests are used to assess the weldability of metals by resistance to hot cracks - technological tests and machine tests.

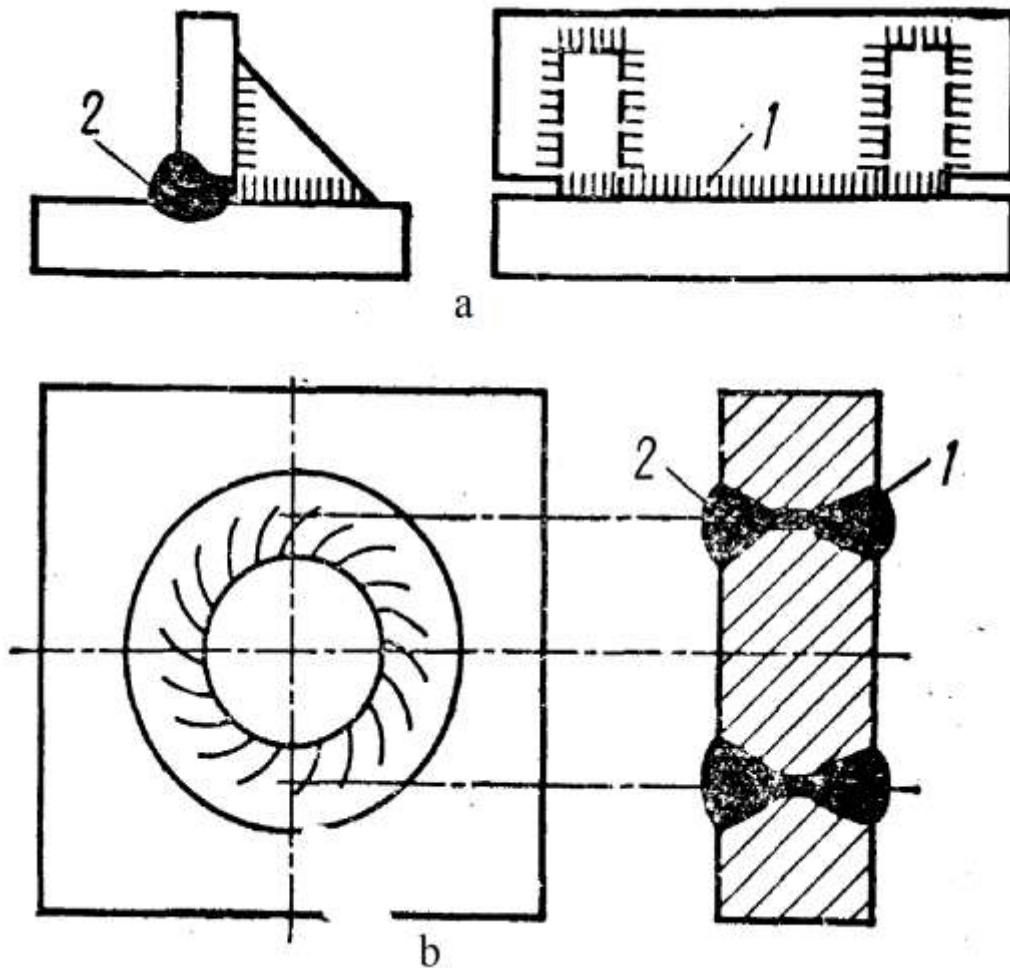


Figure 9 – Technological tests for determining the resistance of welded joints to the formation of hot cracks:
 a – T-shaped with stiffening ribs; b – annular

In technological tests, a node or sample of a given stiffness is welded. The suitability of the material, electrodes, and welding modes is assessed by the formation of a crack and its length. Examples of technological tests include ring and T-shaped tests with stiffening ribs (Fig. 9). First, weld seam 1, then 2, and then visually determine whether a crack appears in the second seam.

During machine tests, the sample is stretched or bent during welding. The resistance of materials is assessed by the critical value or the deformation rate at which a crack appears. To prevent the occurrence of hot cracks, it is necessary to correctly select the filler material and welding technology.

Cold cracks are local intercrystalline fractures that form in welded joints mainly at normal temperature, as well as at temperatures below 200 °C.

Causes of cold cracks during welding:

- increased fragility of the metal due to hardening processes during its rapid cooling;
- residual stresses arising in welded joints;

increased hydrogen content in welds, which enhances the adverse effect of the first two reasons.

To assess the weldability of a metal by its resistance to cold cracks, two types of tests are used, as in assessing the resistance to hot cracks, - technological tests and quantitative assessment methods with the application of an external constant mechanical load to the samples.

The advantage of technological tests is the ability to simulate welding technology and, therefore, to draw a conclusion about the resistance to crack formation in conditions close to real ones. The sample is a rigid welded joint. The stability of the material is assessed qualitatively by the presence or absence of cracks. Examples of tests can be a cross test and a Kirov plant test (Fig. 10).

In the cross test, the sequence of seam application is shown in numbers. The last fourth seam is in the most severe conditions, where crack formation is possible. In the Kirov Plant test, by changing the thickness of the metal in the recess zone, as well as applying additional heating or cooling, the cooling rate of the metal during welding or the degree of its hardening is changed. This indicator is used to judge the resistance of the metal to the formation of cold cracks.

There are other technological tests in which rigid nodes of welded structures are simulated. The tests give only a qualitative correspondence: a crack is formed or not.

The quantitative criterion for assessing the resistance of a welded joint to the formation of cold cracks is the minimum external stresses at which cold cracks begin to appear when the samples are held under a load applied immediately after welding. External loads reproduce the effect on the metal of its own welding and shrinkage stresses that arise immediately after welding and are constantly acting during storage and operation of the structure.

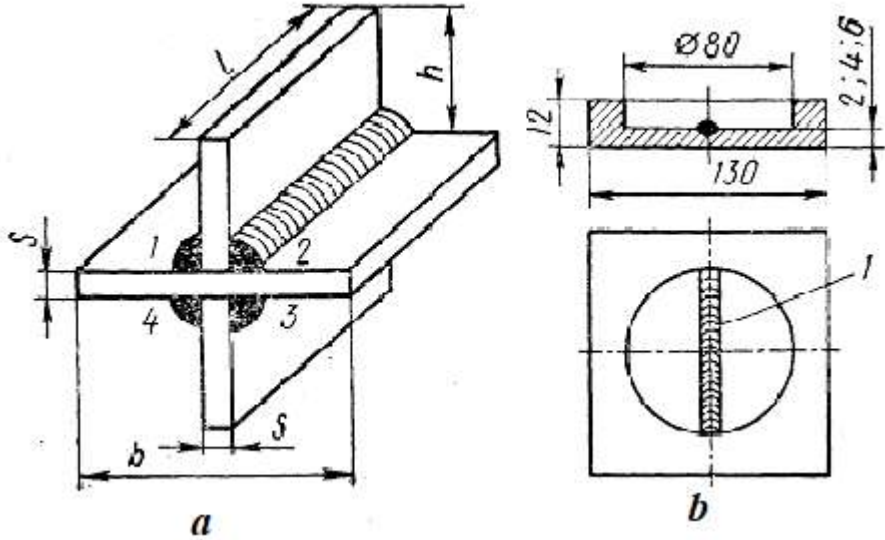


Figure 10 – Technological tests for determining the resistance of welded joints to the formation of cold cracks:
a – cross; *b* – factory; 1, 2, 3, 4 – sequence of welding seams

Methods of combating cold cracks are based on reducing the degree of metal hardening, removing residual stresses, limiting the hydrogen content. The most effective means for this is heating the metal before welding.

Pores in welds occur during the primary crystallization of the weld pool metal as a result of gas evolution. Pores are gas-filled cavities in the welds that have a rounded, elongated or more complex shape. Pores can be located along the axis of the weld, its cross-section or near the fusion boundary. They can extend or not to the surface, be located in a chain, in separate groups or singly, can be microscopic or large (up to 4...6 mm in diameter).

Causes of pores: release of hydrogen, nitrogen or carbon monoxide as a result of chemical reactions; different solubility of gases in molten and solid metal; entrapment of gas bubbles during crystallization of the weld pool.

To reduce porosity, careful preparation of the base and filler materials for welding is required (cleaning from rust, oil, moisture, hardening, etc.), reliable protection of the welding zone from air, introduction of deoxidizing elements (from the base metal, welding wire, coating, flux) into the welding bath, compliance with welding modes.

Along with pores, the integrity of the weld metal is violated by slag inclusions. Slag inclusions are associated with refractory, increased viscosity and high density of slags, poor surface cleaning of edges and individual layers during multilayer welding, slag flowing into the gaps between the welded edges and into the places of undercuts. In addition to slag inclusions, the weld may contain microscopic oxide, sulfide, nitride, phosphorus-containing inclusions, which worsen the properties of the weld.

Welding technology (type of welding, welding materials, welding technique) is selected depending on the main weldability indicator (or combinations of several indicators) for each specific material.

The weldability of different metals and alloys depends on the degree of alloying, structure and content of impurities. Carbon has the greatest influence on the weldability of steels. With an increase in the carbon content, as well as a number of other alloying elements, the weldability of steels deteriorates. The main difficulties in welding structural low-carbon, low-alloy, and medium-alloy steels are:

- sensitivity to hardenability and the formation of cold cracks;
- tendency to the formation of hot cracks;
- ensuring uniform strength of the welded joint.

The higher the content of carbon in the steel, the higher the risk of cold and hot cracks and the more difficult it is to ensure uniform strength of the welded joint. An approximate quantitative indicator of the weldability of steel of known chemical composition is the equivalent carbon content, which is determined by the formula

$$C_e = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15},$$

where the carbon and alloying element content is given in percentages.

Depending on the equivalent carbon content and the associated tendency to hardening and cold cracking, steels are divided into four groups according to weldability: good, satisfactory, limited and poorly weldable steels (Table 2).

Steels of the first group have $C_e \leq 0.25\%$, weld well without the formation of hardening structures and cracks in a wide range of modes, thicknesses and structural shapes. Steels that weld satisfactorily ($C_e = 0.25...0.35\%$) are not very prone to cold cracking with the correct selection of welding modes, in some cases preheating is required. Limitedly weldable steels ($C_e = 0.36...0.45\%$) are prone to cracking, the possibility of adjusting the resistance to cracking by changing welding modes is limited, preheating is required. Poorly weldable steels ($C_e > 0.45\%$) are very susceptible to hardening and cracking, and require preheating, special welding techniques, and heat treatment during welding.

Table 2 – Classification of steels by weldability

Weldability group	Steel	
	carbon	structural alloy
1. Good	СТ1, СТ2, СТ3, СТ4, steel 08, 10, 15, 20, 25, 12кп, 15кп, 16кп, 18кп, 20кп	15Г, 20Г, 15Х, 15ХА, 20Х, 15ХМ, 14ХГС, 10ХСНД, 10ХГСНД, 15ХСНД
2. Satisfactory	СТ5, steel 30, 35	12ХН2, 12ХН3А, 14Х2МР, 10Г2МР, 20ХН3А, 20ХН, 20ХГСА, 25ХГСА, 30Х, 30ХМ
3. Limited	СТ6, steel 40, 45, 50	35Г, 40Г, 45Г, 40Г2, 35Х, 40Х, 45Х, 40ХН, 40ХМФА, 30ХГС, 30ХГСА, 30ХГСМ, 35ХМ, 20Х2Н4А, 4ХС, 12Х2Н4МА
4. Bad	steel 65, 70, 75, 80, 85, У7, У8, У9, У10, У11, У12	50Г, 50Г2, 50Х, 50ХН, 45ХН3МФА, 6ХС, 7Х3, 9ХС, 8Х3, 5ХНТ, 5ХНВ

1.3 Preparation of metal for welding

Cast, forged and stamped blanks are usually supplied for welding in a given size. But it is a different matter with rolled parts. After selecting the metal

by size and steel grade, the following operations must be performed: straightening, marking, cutting, edge processing, bending and cleaning for welding.

Straightening is carried out by local plastic deformation in the cold state. The most common types of deformation of sheet steel are waviness, local protrusions and concavities, broken edges, sickle shape in the plane of the sheet.

Multi-roll machines are used to straighten sheets and strips with a thickness of 0.5 to 50 mm (the number of rolls is more than five). Straightening is carried out by multiple bending when passing the sheets between the upper and lower rows of rolls arranged in a staggered manner (Fig. 11, a). Sheets less than 0.5 mm thick are straightened by stretching using devices on presses or on special stretching machines. Small, medium-sized, and profiled rolled products are straightened on roller machines (Fig. 11, b), which operate according to the scheme of a sheet straightening machine. I-beams and channels are usually straightened by bending on cam-type straightening and bending presses (Fig. 11, c).

If it is necessary to create significant deformations, straightening and bending should be carried out in a hot state.

Marking can be individual (such marking is laborious) and according to a planned template. Marking is more productive, but the manufacture of special marking templates is not always economically feasible.

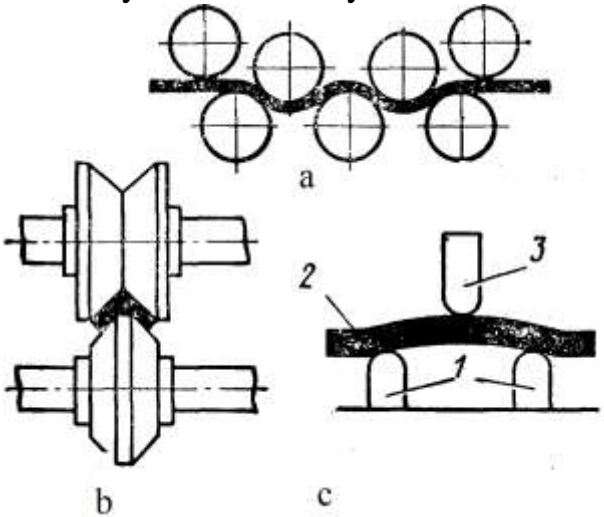


Figure 11 – Scheme of straightening sheet and profile elements:
 a – on sheet straightening rollers; b – in angle straightening rollers;
 c – on a press; 1 – support; 2 – profile; 3 – pusher

The optical method according to the pattern projected onto the marked plane allows marking without a template. Marking and marking machines with a pneumatic core perform marking at a speed of up to 8...10 m/min with an error of ± 1 mm. These machines use software control. The use of a device for dimensional cutting of rolled metal, as well as thermal cutting machines with a

large-scale photocopying or software control system, allows you to do without marking.

Metal cutting and edge processing. Mechanical cutting is carried out on scissors, on cutting machines and in dies on presses. For cutting, sheet shears with an inclined blade, cutting, disc shears, combined shears, press shears, standard shears for cutting angles, channels and I-beams, manual pneumatic and electric shears are used.

Sheet metal parts with straight edges made of metal up to 40 mm thick are usually cut on guillotine shears and press shears. Disc shears, which are cut using round rotating knives, allow you to cut sheet metal parts with non-straight edges up to 20...25 mm thick. To obtain a sheet metal part of a given width with parallel edges, disc knives are placed in pairs at a given distance from each other. Press shears and combined shears with shaped knives are used for cross-cutting of shaped rolled products. Cutting machines are used for cutting pipes, shaped and standard material.

On cutting machines, you can cut metal with larger cross-sections than on scissors, while ensuring a higher quality of cut. However, the laboriousness of cutting on cutting machines is much greater than when cutting on scissors. Therefore, cutting machines are used for profiles that cannot be cut on scissors, for example, for cutting pipes, large-section profiles, profiles at an angle or in cases where it is necessary to ensure high accuracy of the cut. Details of welded structures are cut on cutting machines with circular and band saws, pipe cutting machines, on machines with abrasive wheels, in some cases with a smooth disk due to friction forces. The process of cutting out blanks for welding in dies in mass production is productive.

Thermal cutting is less productive than cutting on scissors, but more versatile and is used to obtain welded blanks of various thicknesses of both straight and curved profiles.

Thermal cutting is based on the property of metal to burn in a jet of technically pure oxygen and the removal of combustion products from the cut cavity. Depending on the heat source used for cutting, there are gas cutting, which is based on the use of heat from a gas flame; arc cutting by melting using the heat of an electric arc, which usually burns between the metal being cut and the electrode; plasma arc cutting (compressed arc cutting) is a special type of arc cutting, which is based on the melting of metal from the cut cavity, directed by a plasma flow.

Metal from the cut cavity in the process of thermal cutting is removed in one of the following ways:

- thermal - due to melting and flowing out of the metal from the cut cavity;
- chemical - due to the oxidation of the metal, its transformation into oxides and slags, which are also removed from the cut cavity;
- mechanical - due to the mechanical action of a gas jet, which helps to push liquid and softened products out of the cut cavity.

In gas cutting, all three methods operate simultaneously, in arc and plasma arc cutting - mainly thermal and mechanical.

Now, along with gas cutting, plasma arc welding is increasingly used, which allows processing almost any metals and alloys. The use of compressed air as a plasma-forming gas provides not only economic, but also technical advantages, because along with high cutting quality, a significant increase in cutting speed is ensured, especially for metal of small and medium thickness (up to 60 mm).

Thermal cutting is divided into manual, mechanized and automatic. Manual and mechanized cutting is performed according to marking, automatic - using copying devices, according to a scale drawing and on machines with program control. Scale drawings are drawings of the contour of the cut parts, reduced to a certain scale, containing information only about the trajectory, so the start of each individual cut has to be done manually. The use of machines with numerical program control allows you to automate the process within the entire sheet without the participation of the operator while simultaneously increasing the accuracy of the cut. For mass production, in some cases, cutting sheets with a package of a total thickness of about 100 mm is effectively used. Laser cutting is beginning to be used, its advantages are an extremely small cut width (fractions of a millimeter), cut accuracy, and the ability to cut metal of small thickness (from 0.05 mm).

Edges are prepared by thermal and mechanical methods. Edges with one or two-sided bevels can be obtained by simultaneously using two or three cutters, which are placed at certain angles. Mechanical processing of edges on machines is performed to ensure the required assembly accuracy; to form chamfers that have a certain outline; if technical conditions require removal of metal from the surface of the edges after cutting. The essence of thermal types of separate cutting is considered in section 3. Bending. Sheet elements with a thickness of 0.5...50 mm are bent on sheet bending rolls with rolls up to 13 m long to obtain cylindrical and conical surfaces. At $R/S \geq 25$, where R is the bending radius, S is the sheet thickness, they are bent in a cold state, at $R/S < 25$ - in a hot state. Sheet elements with a surface having a spatial curvature are obtained on special rollers of variable diameter. In serial and mass production, cold stamping from sheet material up to 10 mm thick is widely used to obtain elements with a surface of complex outline. High productivity, accuracy of dimensions and shape of the resulting blanks, and their low cost ensure the creation of fairly technological die-welded products. Explosion stamping is used to shape large-sized winding elements.

When bending profiled rolled products and pipes, roller and pipe bending machines are used. If there are grounds for violating the shape of the cross-section, it is advisable to use special bending machines with induction local heating of the deformed area of the blank, which is continuously moved and bent.

To produce parts from thick sheet metal, hot bending is used on bending rollers and presses.

Cleaning of the metal surface for welding is used to remove traces of preservation, contamination, lubricating and cooling fluids, rust, scale, scale, burrs and slag from the metal surface.

When welding metal with an untreated surface, various defects in the seam appear - pores and cracks, and the seam formation deteriorates. Mechanical and chemical methods are used to clean rolled products, parts and welded joints. Mechanical methods include shot blasting and metal shot blasting, cleaning with metal brushes, needle cutters, grinding wheels and belts.

Shot blasting and metal shot blasting are used for sheet and profile rolled products and welded joints to clean scale, rust and contamination with a metal thickness of 3 mm or more. In shot blasting machines, the shot is thrown onto the surface to be cleaned through a nozzle using compressed air, in shot blasting machines—by the blades of a rotating rotor due to centrifugal force. For cleaning, cast and chopped cast iron shot, cast steel shot, chopped, chopped, 0.7...0.9 mm in size with a metal thickness of up to 4 mm; 0.9...1.6 mm — with a thickness of up to 30 mm; 1.6—2.5 mm — above 30 mm are used.

Shot blasting and shot blasting cleaning are carried out in chambers equipped for placing and transporting the products to be cleaned, with devices for collecting, cleaning, and returning the shot to the shot blasting machine and for extracting contaminated air. Before welding, blanks and rolled products are usually cleaned by the shot blasting method, welded joints (in hard-to-reach places) — by shot blasting.

Chemical cleaning methods degrease and pickle the surfaces of welded parts. There are two types of cleaning: bath and jet methods. In the first case, the parts are sequentially immersed in baths with different solutions and kept in each of them for a certain time, in the second case, the surface of the parts is sequentially treated with jets of solutions of different compositions, which allows for a continuous cleaning process. The chemical cleaning method is effective, but in the production of welded structures it is used mainly for cleaning non-ferrous metals. To prevent metal corrosion, in addition to cleaning, the surfaces are usually passivated or primed, which allows the metal to be welded without removing the protective coating.

1.4 Welded joint control

Classification of types of weld joint control. Welded joints are considered to be of good quality if they do not have unacceptable defects and their properties meet the requirements for them in accordance with the operating conditions of the welded unit or structure.

There are the following types of quality control of welded joints - preliminary, during which the quality of the starting materials (welded metal or

welding materials), preparation of parts for welding and assembly of units, as well as the condition of welding equipment and devices, qualifications of assemblers and welders are checked. At the stage of preliminary control, weldability tests are performed, which also include mechanical tests, metallographic studies of welded joints and tests for resistance to the formation of hot and cold cracks; current (during the welding process) which involves checking compliance with welding technology, cleaning intermediate seams, welding craters final, during which finished welded structures are checked in accordance with the requirements for the product.

The complexity of control operations can reach 30% of the total complexity of manufacturing a welded structure.

Classification of defects. In the process of forming a welded joint, defects may occur in the weld metal and the heat-affected zone, i.e. deviations from established standards and requirements, which lead to a decrease in strength, operational reliability, accuracy, as well as a deterioration in the appearance of the product. Defects of welded joints are distinguished by the causes of their occurrence and by their location.

Depending on the causes of their occurrence, they can be divided into two groups. The first group includes defects associated with metallurgical and thermal phenomena that occur during the formation, shaping, and crystallization of the weld pool and cooling of the welded joint: hot and cold cracks in the weld metal and the surrounding area, pores, slag inclusions, adverse changes in the properties of the weld metal and the heat-affected zone.

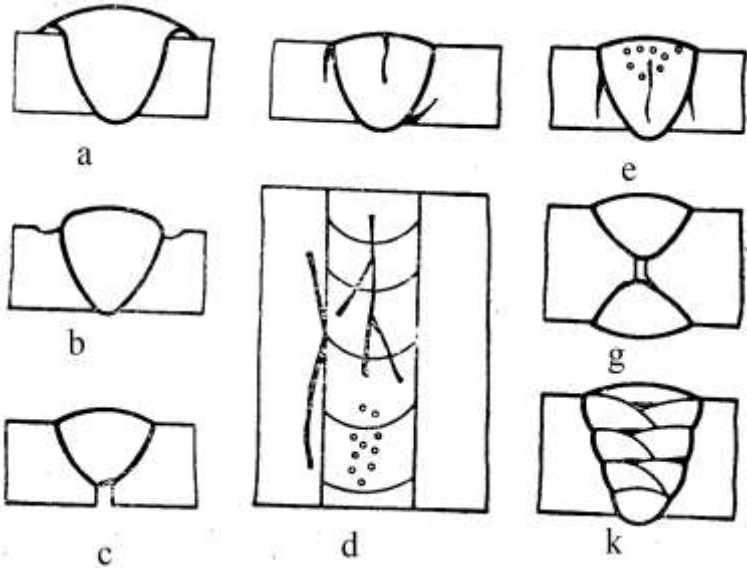


Figure 12 – Types of defects in welded joints:

- a – inflow; b – undercut; c – non-penetration; d – external cracks and pores; e – internal cracks and pores; g – internal non-penetration; k– slag inclusions

The second group of defects, called weld formation defects, includes defects whose occurrence is mainly associated with violation of the welding regime, improper preparation and assembly of structural elements for welding, equipment malfunction and low welder qualification and other violations of the technological process. Defects in this group include non-compliance of welds with the calculated dimensions, non-penetration, undercuts, losses, inflows, unwelded craters, etc.

Defects are distinguished by location into external and internal. External defects include defects that can be detected by external inspection (weld formation defects, non-penetration, undercuts, inflows, losses, craters, cracks and pores that reach the surface, etc.).

To detect internal defects (cracks, pores), special methods of non-destructive and destructive testing are required.

Defects greatly affect the strength of welded joints and are often the causes of premature failure of welded structures. Particularly dangerous are cracks and non-penetrations, which sharply reduce the strength under cyclic loads. Some types of defects are shown in Fig. 12.

Methods of quality control of welded joints. Depending on whether the integrity of the welded joint is violated or not during control, non-destructive and destructive control methods are distinguished.

Non-destructive methods include: external inspection; control for impermeability by hydraulic testing, kerosene, compressed air, vacuuming, leak detectors; methods used mainly to detect defects that appear on the surface of welded joints (magnetic, electromagnetic, luminescent, color); methods used mainly to detect hidden and internal defects (radiation, ultrasonic, magnetographic).

External inspection serves to determine external . defects in welds and inconsistency of the geometric dimensions of the welds with the design ones (the dimensions of the welds and defects are determined by a measuring tool and special templates), undercuts, non-penetrations, surface cracks and external pores, significant scaliness and unevenness of the weld, unfused craters, gouging of the product or its individual elements. External inspection is carried out with the naked eye or a magnifying glass with a magnification of no more than 10 times. External inspection is carried out on all welded structures.

Liquid storage tanks, vessels and pipelines operating at excess pressure are subjected to a leak test. During hydraulic testing, the tanks are filled with water, and excess liquid pressure is created in the vessels and pipelines, exceeding 1.5...2 times the working pressure. In this state, the product is kept for 5...10 minutes. The welds are inspected to detect leaks, drops and sweating. This test method also serves to assess the strength of the structure.

During pneumatic testing, compressed air is pumped into the vessel at a pressure exceeding atmospheric pressure by 10...20 kPa, the seams are

moistened with soap solution or the entire product is immersed in water. Leaks in the seams are determined by a soap bubble or air bubbles in water.

The vacuum method is based on creating a vacuum and registering the penetration of air through defects on one side of the seam accessible for testing. Soap solution is used as a foam indicator.

When testing with a helium leak detector, a vacuum is created inside the vessel, and the seams are blown with a mixture of air and helium from the outside. In the event of leaks, helium, which has an exclusively penetrating ability, penetrates the vessel, from where it is sucked into a leak detector with special equipment for its detection. The leakiness of the seams is judged by the amount of helium captured.

When testing with kerosene, welds are lubricated with kerosene on one side and chalk on the other. In case of leakage, dark spots of kerosene appear on the surface of the weld painted with chalk. The high permeability of kerosene allows you to detect defects of 0.1 mm or less in size.

Magnetic control methods are based on detecting the magnetic scattering field that is formed in the places of defects when the controlled products are magnetized. The product is magnetized by closing the magnetic circuit of an electromagnet with it or placing it inside a solenoid. The required magnetic flux can be created by passing current through the turns (3...6 turns) of welding wire, which is wound onto the controlled part. Depending on the method of detecting scattering fluxes, the following magnetic control methods are distinguished: magnetic powder, induction and magnetographic.

In the magnetic powder method, magnetic powder (scale, iron filings, etc.) is applied to the surface of the magnetized connection in dry form (dry method) or a suspension of magnetic powder in a liquid - kerosene, soap solution, water (wet method). An accumulation of powder in the form of a correctly oriented magnetic spectrum is created above the defect location. To facilitate the mobility of the powder, the product is slightly tapped. Using magnetic powder, cracks invisible to the naked eye, internal cracks at a depth of no more than 15 mm, metal delamination, as well as large shells and slag inclusions at a depth of no more than 3...5 mm are detected.

In the induction method, the magnetic flux in the product is induced by an alternating current electromagnet. Defects are detected using a finder, in the coil of which an EMF is induced under the action of the scattering field, which causes an optical or sound signal on the indicator.

In the magnetographic method, the scattering field is recorded on an elastic magnetic tape, which is tightly pressed to the surface of the joint. The recording is played back on a magnetographic flaw detector. As a result of comparing the controlled joint with the standard, a conclusion is made about the quality of the joint.

Radiation control methods are reliable and widespread methods based on the ability of X-ray and gamma radiation to penetrate through the metal.

Detection of defects by radiation scanning is based on the different absorption of X-ray or gamma radiation by areas of metal with or without defects; welded joints are scanned using special devices. Radiation sources are placed on one side of the seam at a certain distance from it, and a cassette with a sensitive film is tightly pressed on the opposite side (Fig. 13). During scanning, the radiation passes through the welded joint and irradiates the film. In places where there are pores, slag inclusions, under-penetrations, large cracks, darker spots are formed on the film. The appearance and size of the defects are determined by comparing the film with reference images. Transillumination does not allow to detect cracks if they are not located in the direction of the central beam (angle more than 5°), as well as under-penetrations in the form of adhesion of welded metals without a gas or slag layer.

The sources of X-ray radiation are special X-ray apparatuses (RUP-150-10, RUP-120-5-1), pulse apparatuses (IRA-1D, IRA-2D, RINA-1D, etc.). X-ray examination is advisable to detect defects in metal up to 60 mm thick. In this case, defects are recorded, the size of which is 1...3% of the metal thickness.

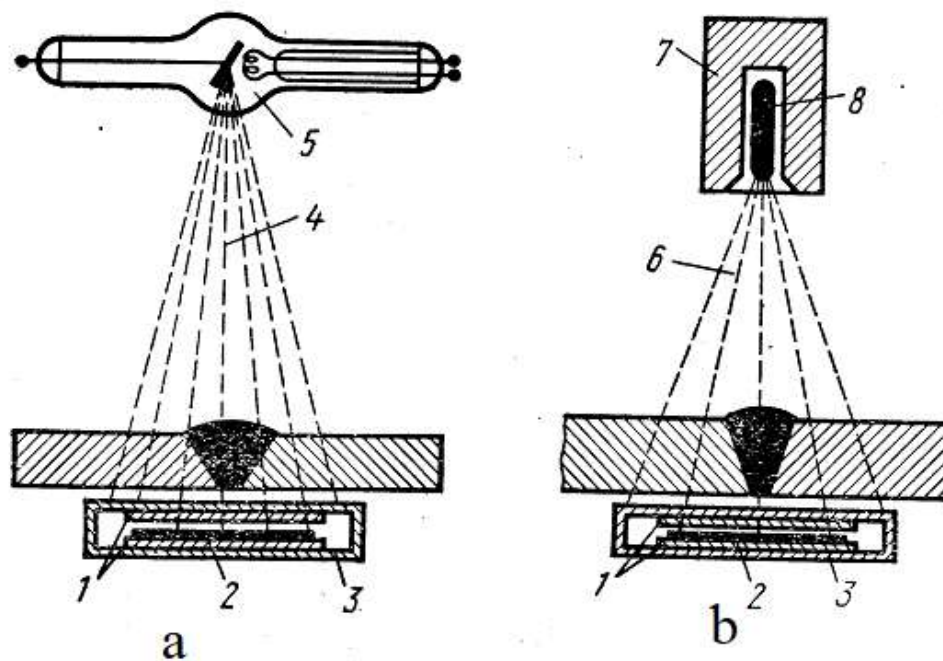


Figure 13 – Scheme of weld examination:

a – X-ray radiation; b – gamma radiation;

1 – intensifying screen; 2 – X-ray film; 3 – cassette; 4 – X-ray radiation;

5 – X-ray tube; 6 – gamma radiation; 7 – lead casing; 8 – ampoule of radioactive substance

Along with radiography, i.e. exposure to film, fluoroscopy is used, i.e. obtaining a signal about defects when the metal shines through the screen. The screen is covered with fluorescent substances (platinocyanide barium, zinc sulfide, etc.), which glow under the influence of X-ray radiation. Due to the different degree of absorption of rays in different parts of the metal, the glow is

different. X-ray radiation control using screens is used in combination with television devices that convert the X-ray image into a visible one (a PI type installation - an X-ray television introscope). The sensitivity of fluoroscopy control is not inferior to radiographic control (1% or more), and the productivity is higher. The advantage of radiography is a document on the quality of the connection in the form of a film.

When irradiating welded joints with gamma radiation, the radiation source is radioactive isotopes: cobalt-60, thulium-170, iridium-122, etc. The ampoule with the radioactive isotope is placed in a lead container. The technique of irradiating welded joints with gamma radiation is similar to the technique of X-ray irradiating. This method reveals similar internal defects - darkening of areas of the film placed in the cassette. Gamma radiation differs from X-rays in greater rigidity and shorter wavelength, so it can penetrate the metal deeper than X-rays and allows irradiating metal up to 300 mm thick. Due to the portability of the equipment, gamma radiation can be used in any conditions (in workshops, in field conditions, during assembly, etc.). In addition, gamma irradiation is a less expensive method.

The disadvantages of gamma radiation examination compared to X-ray examination are lower sensitivity (when examining thicknesses up to 50 mm, relatively large defects with sizes exceeding 2...4% of the metal thickness are detected); the inability to regulate the radiation intensity, which in X-ray machines is regulated by the voltage that is applied; the great danger of gamma radiation in case of careless handling of gamma machines.

Ultrasonic control is based on the ability of ultrasonic waves to be reflected from the surface of the interface between two media. In flaw detection, a piezoelectric method of generating ultrasonic waves is used, which is based on the excitation of mechanical oscillations (vibrations) in piezoelectric materials (quartz, lithium sulfate, barium titanate, etc.) when an alternating electric field is applied. Elastic vibrations reach their maximum value when the frequency of the electrical vibrations coincides with the vibrations of the sensor's piezo plate; ultrasonic vibration frequencies usually exceed 20,000 Hz.

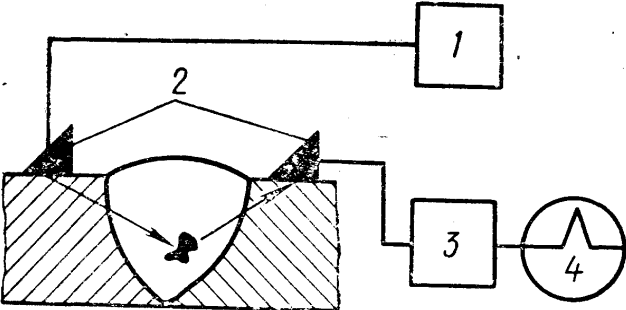


Figure 14 – Ultrasonic inspection scheme:
 1 – ultrasonic generator; 2 – piezoelectric probe;
 3 – amplifier; 4 – flaw detector screen

Using a piezometric probe of an ultrasonic flaw detector placed on the surface of a welded joint, directional ultrasonic vibrations are sent into the metal (Fig. 14). Ultrasound is introduced into the product in separate pulses at an angle to the metal surface. When encountering a defect, a reflected ultrasonic wave occurs, which is perceived either by another probe (receptive in the case of a two-probe scheme) or by the same (sending in the case of a single-probe scheme) during the pause between pulses. The reflected ultrasonic signal is converted into electrical, amplified and fed to the oscilloscope tube, where the defect in the joint is recorded as a peak on the oscilloscope screen.

Ultrasonic control has the following main advantages: high sensitivity (1...2%), which allows you to detect, measure and determine the location of defects with an area of 1...2 mm²; high penetration of ultrasonic waves, which allows you to control materials of considerable thickness (steel up to 2.5 m); the ability to control the entire welded joint from only one side; high productivity; lack of bulky equipment (devices UZD-7, UDM-1M, DUK-13YM, etc.).

A significant disadvantage of the ultrasonic method is the difficulty of establishing the type of defect.

Ultrasonic control is also used as the main type of control and as a preliminary one with subsequent irradiation of welded joints with X-ray or gamma radiation.

Destructive methods of control of welded joints include: mechanical tests, metallographic studies, special tests to obtain the characteristics of welded joints.

These tests are carried out on welded samples that are cut from the product itself or from specially welded control joints made in accordance with the requirements and technology for welding products in conditions corresponding to welding. The purpose of these tests is: assessment of the strength and reliability of welded joints and structures; assessment of the quality of the main and welding materials; assessment of the correctness of the selected technology; assessment of the qualifications of welders.

The properties of the welded joint are compared with the properties of the base metal. The results are considered unsatisfactory if they do not meet the specified regulated level.

One of the main types of tests is mechanical testing, which provides for the following types of tests of welded joints and weld metal:

testing of the welded joint (welded metal, heat-affected zone, base metal) for static (short-term) tension, static bending, impact bending (on notched samples), for resistance to mechanical aging;

measuring the hardness of the metal of different sections of the welded joint and the welded metal.

Static tensile tests determine the strength of welded joints. Static bending tests determine the ductility of the joint by the magnitude of the bending angle

before the formation of the first crack in the stretched zone. Static bending tests are carried out on samples with longitudinal and transverse welds with the weld force removed flush with the base metal. Impact bending and impact rupture tests determine the impact toughness of the welded joint. The results of hardness determination are used to judge structural changes and the degree of metal hardening during cooling after welding.

Metallographic studies of welded joints. The main task of metallographic analysis is to establish the structure of the metal and the quality of the welded joint, to detect the defect and its nature. Metallographic studies include micro- and macrostructural methods for studying metals.

With macrostructure, this method studies macrosections and metal fractures with the naked eye or a magnifying glass (magnification up to 20 times). Macroscopic studies allow you to determine the nature and location of visible defects in different areas of welded joints.

In microstructural analysis (microanalysis), the structure of the metal is examined at a magnification of 50...2000 times using optical microscopes. Microanalysis allows you to establish the quality of the metal, including detecting burn-through, oxides along grain boundaries, contamination of the metal with non-metallic inclusions (oxides, sulfides), the size of the metal grains, changes in the composition of the metal during welding, microscopic cracks, pores and other structural defects.

The method of making micrographs for metallographic studies consists in cutting samples from welded joints, grinding, polishing and etching the metal surface with special substances.

Metallographic study of welded joints is supplemented by measuring hardness and, if necessary, chemical analysis.

Special tests are carried out to obtain the characteristics of welded joints that take into account the operating conditions of the welded structure: determination of corrosion resistance for structures operating in corrosive environments; fatigue strength under cyclic loads; creep during operation under conditions of elevated temperatures, etc.

Control questions

1. What is the essence of welding and how are types of welding classified?
2. What is a welded joint and a welded seam?
3. What is meant by the weldability of materials? Name the main weldability indicators.
4. What processes make up the preparation of metal for welding?
5. How are the main types of control of welded joints classified? their essence.

2 BASICS OF MANUAL ARC WELDING TECHNOLOGY AND EQUIPMENT FOR IT

2.1 The essence of the method, equipment, accessories, tools

The most extensive among other types of welding is manual arc welding - welding by melting with artificial electrodes, in which the electrode feed and movement of the arc along the welded edges are performed manually. The process diagram is shown in Fig. 15. The arc burns between the electrode rod 1 and the base metal 7. Under the influence of the heat of the arc, the electrode and the base metal melt, forming a metal welding bath 4. Drops 8 of liquid metal from the melting electrode rod are transferred to the bath through the arc gap.

Simultaneously with the rod, the electrode coating 2 melts, forming a gas shield 3 around the arc and a liquid slag bath on the surface of the molten metal.

The metal and slag baths together form a welding bath. As the arc moves, the metal of the weld pool solidifies and a weld seam 6 is formed. As the liquid slag cools, it forms a hard slag crust 5 on the surface of the seam, which is removed after the seam has cooled. To ensure the specified composition and properties of the seam, welding is performed with coated electrodes, which are subject to special requirements (see section 2.2).

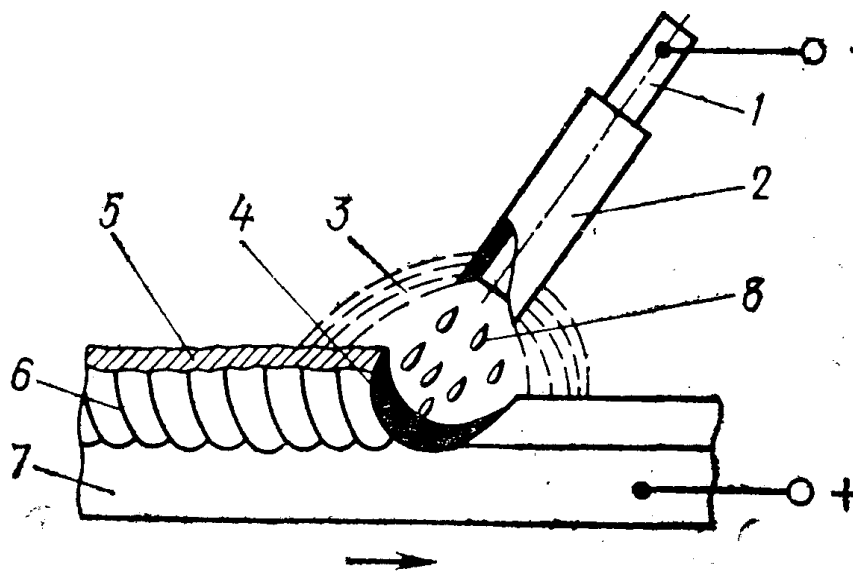


Figure 15 – Manual arc welding with a coated metal electrode (arrow shows welding direction)

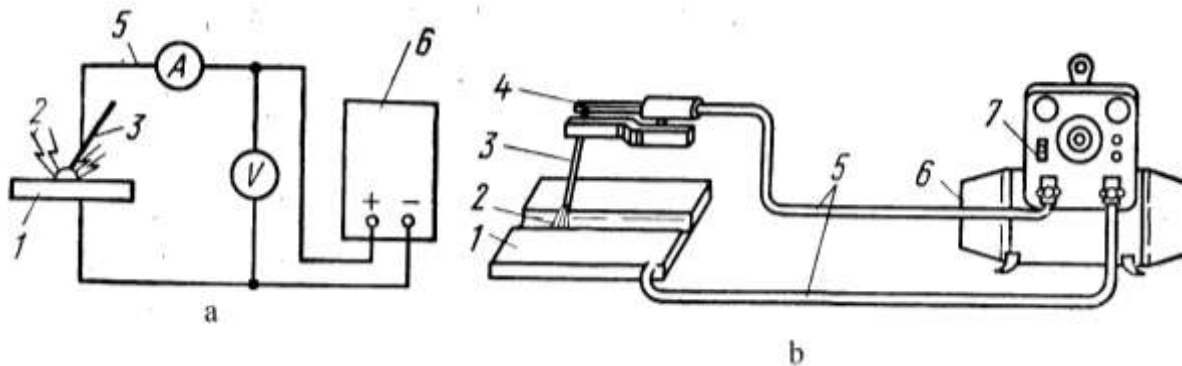


Figure 16 – Arc power supply diagram for manual arc welding (direct current):
 a – electrical diagram; b – general layout of the welding station; 1 – product; 2 – welding arc; 3 – electrode; 4 – electrode holder; 5 – welding wires; 6 – power source; 7 – panel with devices for monitoring and adjusting welding mode parameters

The welding station for manual arc welding is equipped with a power source, a power supply, and the necessary tools. The arc power supply diagram is shown in Fig. 16. Welding stations can be stationary and mobile.

Stationary stations include stations located in the workshop, mainly in separate welding cabins, in which small-sized products are welded.

Mobile welding stations are usually used for the installation of large-sized products (pipelines, metal structures, vessels) and repair work. In this case, portable power sources are often used.

Depending on the materials being welded and the electrodes used, alternating or direct current sources with a steeply falling characteristic are used for manual arc welding.

The welder's main working tool for manual welding is an electrode holder, which serves to clamp the electrode and supply welding current. Spring, plate, and screw-type electrode holders are used (Fig. 17).

Electrode holders are available in three types depending on the strength of the welding current:

Type I — for current up to 125 A; II — 125...315 A; III — 315...500 A.

Welding wires are used to supply current from the power source to the electrode holder and the product. The cross-section of the wires is selected according to the established standards for electrical installations (5...7 A/mm²).

Auxiliary tools for manual welding include steel wire brushes for cleaning edges before welding and for removing slag residues from the surface of the seams, a slag hammer for removing slag crust, especially from corner and root seams during deep cleaning, a chisel, a set of templates for checking the dimensions of the seams, a steel stamp for stamping the seams, a meter, a steel ruler, a plumb line, a square, a drawing board, chalk, as well as a box for storing and carrying the tool.

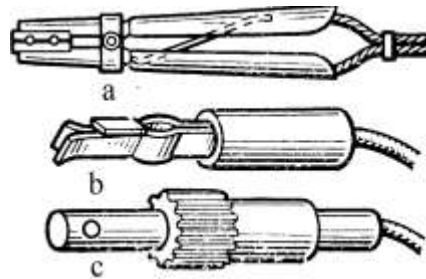


Figure 17 – Electrode holders for manual arc welding:
a – spring; b – plate; c – screw

2.2 Steel welding and surfacing wire and electrodes

A special welding and surfacing wire is used for arc welding and surfacing.

Steel welding wire of various chemical compositions is produced; 6 grades of low-carbon steel (Sv-08, Sv-08A, Sv-08AA, Sv-08GA, Sv-10GA, Sv-10G2); 30 grades of alloyed steel (Sv-08GS, Sv-08G2S, Sv-18KhGS, etc.); 41 grades of high-alloyed steel (Sv-12Kh11NMF, Sv-10Kh17T, Sv-06Kh19N9T).

Alloyed steel contains from 2.5 to 10% of alloying elements, and high-alloyed steel contains more than 10%.

Letters and numbers in the writing of wire grades indicate: Sv — welding, the number after Sv — carbon content in hundredths of a percent (for example, 08 means 0.08% carbon); A — reduced, AA — even more reduced sulfur and phosphorus content; letters — conventional designations of alloying elements; numbers after letter designations — average content of alloying elements in percent.

Chemical elements in steels are conventionally designated as follows: aluminum (Al) - Y, nitrogen (N) - A (only in high-alloy steels), boron (B) - P, vanadium (V) - F, tungsten (W) - B, silicon (Si) - C, cobalt (Co) - K, manganese (Mn) - G, copper (Cu) - D, molybdenum (Mo) - M, nickel (Ni) - H, niobium (Nb) - B, titanium (Ti) - T, chromium (Cr) - X, zirconium (Zr) - C. Steel welding wire, intended for all types of fusion welding and the manufacture of electrodes, is produced according to GOST 2246-70 in the following diameters: 0.3; 0.5; 0.8; 1.0; 1.2; 1.4; 1.6; 2.0; 2.5; 3.0; 4.0; 5.0; 6.0; 8.0; 10.0 and 12.0 mm.

The wire is supplied twisted into coils with an internal diameter of 150 to 750 mm, weighing from 1.5 to 40 kg, as well as wound on spools and cassettes (for automatic and semi-automatic welding).

Steel surfacing wire according to GOST 10543-82 is manufactured with a diameter of 0.3 to 8.0 mm: from carbon steel—9 grades (Np-25, Np-40, etc.), from alloy steel—11 grades (Np-40G, Np-50G, Np-30KhGSA, etc.), from high-alloy steel—11 grades (Np-20Kh14, Np-30Kh13, Np-30Kh10G10T, etc.). The wire is used for submerged arc welding, in protective gases, electroslag welding and the manufacture of coated electrodes for manual welding. The wire grade is

selected depending on the purpose and the required hardness of the deposited metal.

Electrodes for manual arc welding. Consumable electrodes for manual arc welding are rods up to 450 mm long made of welding wire, on which a coating layer is applied - a mixture of substances to enhance ionization, protect against the harmful effects of air and metallurgical treatment of the weld pool. The coating includes the following components:

- gas-forming - inorganic substances (marble CaCO_3 , magnesite MgCO_3 , etc.) and organic substances (starch, food flour, etc.);

- slag-forming, which form the basis of the coating - usually these are ores (manganese, titanium), minerals (ilmenite and rutile concentrates, feldspar, silica, granite, chalk, fluorspar, etc.);

- alloying elements and deoxidizing elements - Si, Mn, Ti, etc., which are used in the form of alloys of these elements with iron, the so-called ferroalloys; Al is introduced into the coating in the form of a powder - powder;

- binding components - aqueous solutions of sodium and potassium silicates, which are called sodium and potassium liquid glass, as well as sodium-potassium liquid glass;

- molding additives - substances that give the coating better plastic properties (bentonite, kaolin, dextrin, mica, etc.).

To increase welding productivity, iron powder is added to the coating up to 60% of the coating mass.

Classification of steel coated electrodes. Metal electrodes for arc welding of steels and surfacing are manufactured in accordance with GOST 9466-75 "Metal coated electrodes for manual arc welding of steels and surfacing. Classification, dimensions and general technical requirements". Steel coated electrodes for manual arc welding and surfacing are divided by purpose (GOST 9467-75):

- for welding carbon and low-alloy structural steels with a temporary tensile strength of up to 600 MPa, the standard provides for nine types of electrodes (338, 342, 342A, 346, 346A, 350, 350A, 355, 360), which are designated by the common index U;

- for welding alloyed heat-resistant steels - with a temporary tensile strength above 600 MPa - five types (370, 385, 3100, 3125, 3150), index L;

- for welding alloyed heat-resistant steels - nine types, index T;

- for welding high-alloyed steels with special properties - 49 types (GOST 10052-75), index B;

- for surfacing surface layers with special properties - 44 types (GOST 10051-75), index N.

The numbers in the designations of the types of electrodes for welding structural steels mean the guaranteed strength limit of the weld metal.

By type of coating, electrodes are classified: with an acidic coating A; basic B; cellulose C; rutile P; mixed type - the corresponding double

designation, with other types of coatings P. If the coating contains iron powder in an amount of more than 20%, the letter Zh is added to the designation of the type of coating.

Acid coatings A (electrodes ANO-2, SM-5, etc.) consist mainly of iron and manganese oxides (usually in the form of ore), silica, ferromanganese. Electrodes with an acid coating are technological, but manganese oxides make them toxic.

Rutile coatings P (electrodes ANO-3, ANO-4, OZS-3, OZS-4, OZS-6, MP-3, MP-4, etc.) have a predominant amount of rutile TiO_2 in their composition. Rutile coatings are technological, less harmful to the welder's respiratory organs than others.

Cellulose coatings C (electrodes VSC-1, VSC-2, OZS-1, etc.) consist of cellulose, organic resin, ferroalloys, talc, etc. These coatings are convenient for welding in any spatial position, but give a deposited metal of reduced plasticity.

The main coatings B (electrodes UONI-13/45, UP-1/45, OZS-2, DSK-50, etc.) do not contain iron and manganese oxides. For example, the coating of the UONI-13/45 brand consists of marble, fluorspar, quartz sand, ferrosilicon, ferromanganese, ferrotitanium, liquid glass. The weld metal made by an electrode with a main coating has greater plasticity. These electrodes are used to weld critical structures.

According to the coating thickness, depending on the ratio of the electrode diameter (D) and the diameter of the steel rod (d), electrodes are distinguished:

with a thin coating ($D/d \leq 1.20$) - M;

with a medium coating ($1.20 < D/d \leq 1.45$) - C;

with a thick coating ($1.45 < D/d \leq 1.80$) - D;

with a particularly thick coating ($D/d > 1.88$) — G. According to the quality, i.e. the accuracy of manufacture, the condition of the coating surface, the continuity of the weld metal made by these electrodes, the content of sulfur and phosphorus in the deposited metal, the electrodes are divided into groups 1, 2 and 3. The higher the number, the better the quality.

According to the permissible spatial positions of welding and deposition, the electrodes are divided into the following groups: 1 — for all positions; 2 — for all positions, except vertical from top to bottom; 3 — for the lower, horizontal on a vertical plane and vertical from bottom to top; 4— for the lower and lower "in a boat".

2.3 Welding arc

Types of welding arcs (Fig. 18). The source of heat in arc welding is the welding arc - a stable electrical discharge in a highly ionized mixture of gases and vapors of the materials used in welding, characterized by current density and high temperature.

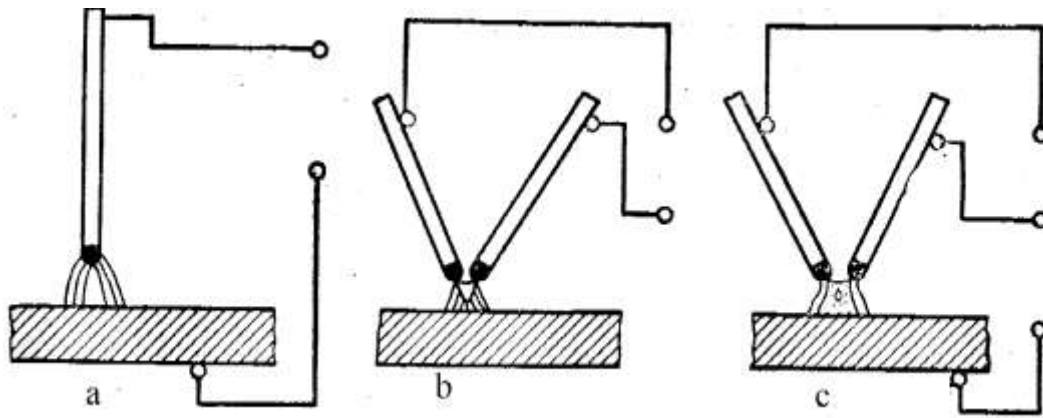


Figure 18 – Types of welding arcs:
a – direct; b – indirect; c – combined action (three-phase)

Depending on the number of electrodes and the methods of connecting the electrodes and the welded part to the electric circuit, the following types of welding arcs are distinguished (Fig. 18):

direct action, when the arc burns between the electrode and the product;

indirect action, when the arc burns between two electrodes, and the welded product is not included in the electric circuit;

three-phase arc/excited between two electrodes, as well as between each electrode and the base metal.

By type of current, arcs powered by alternating and direct current are distinguished. When using direct current, welding is distinguished between direct and reverse polarity. In the first case, the electrode is connected to the negative pole and it serves as a cathode, and the product is connected to the positive pole and it serves as an anode; in the second case, the electrode is connected to the positive pole and serves as the anode, and the product is connected to the negative pole and serves as the cathode.

Depending on the material of the electrode, arcs are distinguished between non-consumable electrodes (carbon or tungsten) and fusible metal electrodes.

The welding arc has a number of physical and technological properties, on which the efficiency of using the arc for welding depends. Physical properties include electrical, electromagnetic, kinetic, temperature, and light.

The main technological properties include: arc power, spatial stability, self-regulation.

Electrical properties of the arc. To form and maintain the arc burning, it is necessary that electrically charged particles - electrons, positive and negative ions - are present in the space between the electrodes. The process of forming ions and electrons is called ionization, and the gas containing electrons and ions is called ionized. Ionization of the arc gap occurs during arc ignition and is continuously maintained during its burning.

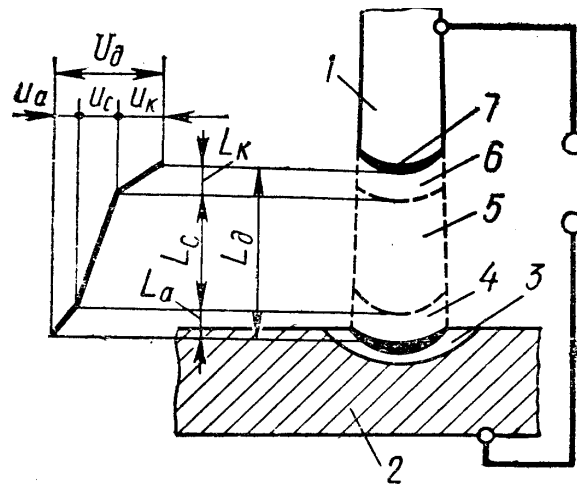


Figure 19 – Scheme of the welding arc and the voltage drop in it:

- 1 – electrode; 2 – product; 3 – anode spot; 4 – anode section of the arc;
5 – arc column; 6 – cathode section of the arc; 7 – cathode spot

The following zones are distinguished in the arc gap (Fig. 19): cathode L_K and anode L_A , where a significant voltage drop is observed, caused by the formation of space charges near the electrodes (accumulation of charged particles), and the arc discharge zone located between them, which is called the arc column L_C . Electrode spots are formed on the surface of the anode and cathode, which represent the base of the arc column, through which the entire welding current passes. Electrode spots are distinguished by the brightness of the glow. The total length of the welding arc L_d is equal to the sum of the lengths of all three zones: $L_d = L_k + L_c + L_a$, where L_d is the total length of the welding arc; L_K — length of the cathode zone, which is approximately 10^{-5} cm;

L_c — length of the arc column; L_a — length of the anode zone, which is approximately $10^{-3} \dots 10^{-4}$ cm.

The total voltage of the welding arc, respectively, consists of the sum of the voltage drop in the individual arc zones:

$U_d = U_k + U_c + U_a$, where U_d , U_k , U_c , U_a — respectively, the total voltage drop in the arc, in the cathode zone, arc column and anode zone, V.

The dependence of the voltage in the welding arc on its length is described by the equation $U_d = a + b \cdot L_d$, where a — sum of the voltage drop in the cathode and anode zones, V;

L_d — length of the arc column, mm; b — specific voltage drop in the arc, referred to 1 mm of the arc column, V/mm.

Thermal power of the arc. The main characteristic of the welding arc as a source of energy for welding is the effective thermal power qJ . The effective thermal power of the welding heat source is the amount of heat introduced into the metal per unit of time and spent on its heating. The effective thermal power is part of the total thermal power of the arc q , because some amount of arc heat

is unproductively spent on heat dissipation in the metal, radiation, and heating of droplets during spraying.

The ratio of the effective thermal power to the total thermal power of the heat source is called the effective coefficient of efficiency (EFC) of the heating process $\eta_{\text{дж}} = q_{\text{дж}} / q$.

The total thermal power of the welding arc, i.e. the amount of heat released by the arc per unit of time, is approximately considered equal to the thermal equivalent of its electric power $q = IU_d$, where I is the welding current, A; U_d is the voltage drop across the arc, V.

Accordingly, the effective thermal power is determined by the expression

$$qJ = I \cdot U_d \cdot \eta_{\text{дж}}$$

The value of qj can vary from 0.3 to 0.95 and for different types of welding is approximately: open carbon arc - 0.5...0.65; argon arc - 0.5...0.6; welding with artificial covered electrodes - 0.7...0.75; submerged arc welding - 0.85...0.93.

The amount of heat introduced into the metal by the heating source and referred to a unit of weld length is called the welding energy. The energy, J/m, is equal to the ratio of the effective power of the heat source (arc) qj to the arc speed v : $qj/v = IU_j/v$.

When forming a weld, the effective thermal power of the arc is spent on melting the base and filler metals.

2.4 Power sources for arc welding

Stability of welding arc burning. The welding system in arc welding includes a power source, an arc and a molten metal bath (product). High quality of the welded joint is ensured when the entire system operates stably during welding, stably in all three of its links and, above all, when stable arc burning is ensured.

However, in the welding process, factors that disrupt its stable burning affect the arc moving through the metal, such as a change in the arc length (which depends on the welder's qualifications), assembly quality, transfer of liquid metal drops to the weld pool, a change in the welding current value during voltage fluctuations in the network, a change in welding speed, magnetic arc blow (deflection of the arc under the influence of electromagnetic fields and ferromagnetic masses) and other factors.

The stability of an alternating current arc is lower than that of a direct current arc. This is due to the fact that when the arc is powered with a frequency of 50 Hz, the arc goes out and is re-excited 100 times per second. To increase the stability of the arc, substances (potassium, calcium, cesium compounds, etc.) are introduced into the coatings and fluxes, which contribute to better conductivity of the arc gap. Special devices are also used, the so-called oscillators and pulse generators, which contribute to the excitation of the arc synchronously with the frequency of the power supply network.

Requirements for power sources for arc welding. To ensure the stability of the arc, power sources for arc welding must meet the following requirements:

- have an open-circuit voltage, i.e. the voltage at the terminals of the current source when the welding circuit is open, sufficient for easy excitation of the arc and its stable burning, but not exceeding occupational safety standards, i.e. no more than 80...90 V;

- have sufficient power to perform welding work;

- provide a short-circuit current that does not exceed the set values, so that the power source can withstand long-term short circuits of the welding circuit without overheating and damaging the winding, with sufficient process stability;

- have good dynamic properties, i.e. ensure rapid restoration of the arc voltage after short circuits;

- have devices for smooth adjustment of the arc of the welding current;

- have a given external characteristic.

External characteristic of the power source and volt-ampere characteristic of the arc. Current sources for powering the welding arc must have a special welding external characteristic.

The external characteristic of the power source is the relationship between the voltage at its output terminals and the current in the welding circuit. External characteristics (Fig. 20) can be of the following main types:

- steep-falling 1, gently falling 2, hard 3, rising 4.

A current source with the appropriate external characteristic is selected depending on the current-voltage characteristic of the arc.

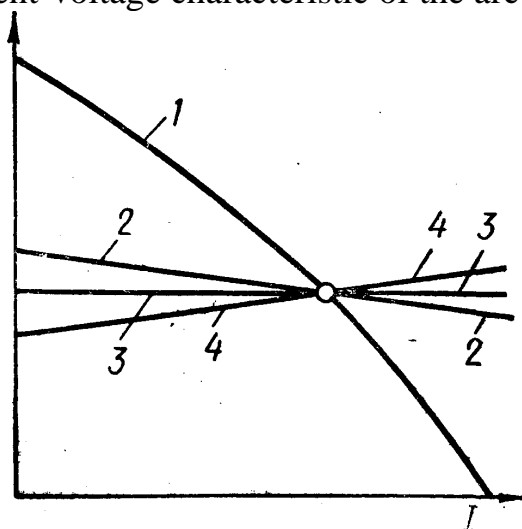


Figure 20 – Main types of external characteristics of power sources for arc welding

The current-voltage characteristic (VAC) of the arc is the dependence of the arc voltage on the welding current (Fig. 21). The VAC has three zones - falling I, hard II, rising III. This is due to the fact that for an arc discharge, resistance is not a constant value, because the number of charged particles in it depends on the intensity of ionization, mainly on the current. Therefore, an

electric arc in gases does not obey Ohm's law and the VAC is usually nonlinear. At low currents up to 100 A (zone I), with increasing current, the number of charged particles increases intensively (mainly as a result of heating and increasing cathode emission), the resistance of the arc column decreases, therefore the voltage required to maintain the discharge decreases and the arc characteristic will be falling. With a further increase in current (zone II), the arc column begins to contract, the volume of gas participating in charge transfer decreases, which leads to a slower rate of increase in the number of charged particles. Therefore, the arc voltage becomes less dependent on the current, and the characteristic becomes flat and rigid. An even further increase in current is characterized by a strong contraction of the arc column (zone III), and the volt-ampere curve becomes increasing, which indicates an increase in the energy consumed inside the arc.

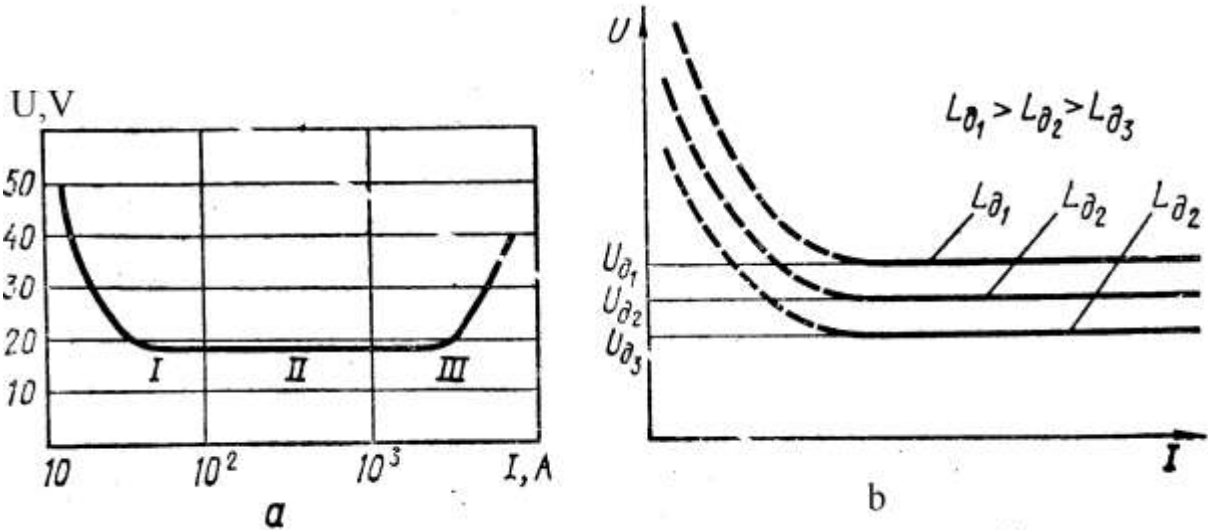


Figure 21 – Volt-ampere characteristic of the arc:
 a – general view, b – dependence of the arc voltage U_d on its length L_d (b)

Zones I and II of the VAC characteristic correspond to the welding modes used in manual welding with a consumable covered electrode, as well as with a non-consumable electrode in a protective gas environment. Mechanized submerged arc welding corresponds to zone II and partially captures zone III when using thin electrode wires and increased current density, welding with a consumable electrode in protective gases corresponds to zone III of the VAC characteristic. To power an arc with a falling or rigid VAC characteristic, power sources with a falling or gently falling external characteristic are used. To power an arc with a rising I-V characteristic, current sources with a rigid or increasing external characteristic are used.

To power the welding arc, alternating current sources (welding transformers) and direct current sources are used - welding generators driven by

an electric motor (welding converters), welding generators driven by an internal combustion engine (welding units) and semiconductor welding rectifiers.

Welding transformers, due to their technical and economic indicators, have advantages over direct current sources. They are easier to operate, more durable, and have higher efficiency.

Direct current sources are more advantageous in technological terms: when they are used, the arc burning stability increases, welding conditions in different spatial positions improve.

The main technical indicators of welding arc power sources are external characteristics, no-load voltage, relative operating time (TR) and relative on-time duration (TV) in intermittent mode.

The value of TR is defined as the ratio of the duration of the operating period of the power source to the duration of the full cycle of operation and is expressed in percent: $TR = (t_p/t_{\Sigma}) \cdot 100$, where t_p — continuous operation under load (welding); t_{Σ} — duration of the full cycle (welding + pause). The optimal value of TR is taken equal to 60%. The difference between TR and TV is that in the first case, the power sources are not disconnected from the network during a pause and operate at idle when the welding circuit is open, and in the second, the sources are completely disconnected from the network, which occurs during mechanized welding.

Welding transformers. These are special step-down transformers, the external characteristic of which provides power to the welding arc and regulation of the welding current. Transformers, as a rule, have a falling characteristic, they are used for manual arc welding and automatic submerged arc welding. Transformers with a rigid characteristic are used for electroslag welding.

The transformer consists of a core - a magnetic core made of transformer steel, on which two windings are placed - primary and secondary. Alternating current from the network, passing through the primary winding of the transformer, magnetizes the core, creating an alternating magnetic flux in it, which, crossing the turns of the secondary winding, induces an alternating current in it.

The voltage of the induced current depends on the number of turns of the secondary winding: the fewer the turns, the lower the voltage of the induced current and, conversely, the more turns, the higher the voltage. The regulation of the welding current and the creation of an external characteristic is ensured by changing the magnetic leakage flux or by switching on an additional inductive resistance in the welding circuit. Accordingly, welding transformers are divided into two main groups.

The first group includes transformers with increased magnetic leakage. Transformers of this group can be divided into three main types: transformers with magnetic shunts, moving coils and turn (step) regulation (TS, TD, STSH, TSK, TSP).

The second group includes transformers with normal magnetic leakage and an additional coil - a choke (SNT, TSD).

Let us consider the structure of the TSK-500 transformer (Fig. 22) with increased magnetic leakage, with a moving coil, when moving which the welding current is regulated. In the lower part of the core 1 there is a primary winding 3, consisting of two coils" placed on two rods of the magnetic core. The coils of the primary winding are fixed immovably.

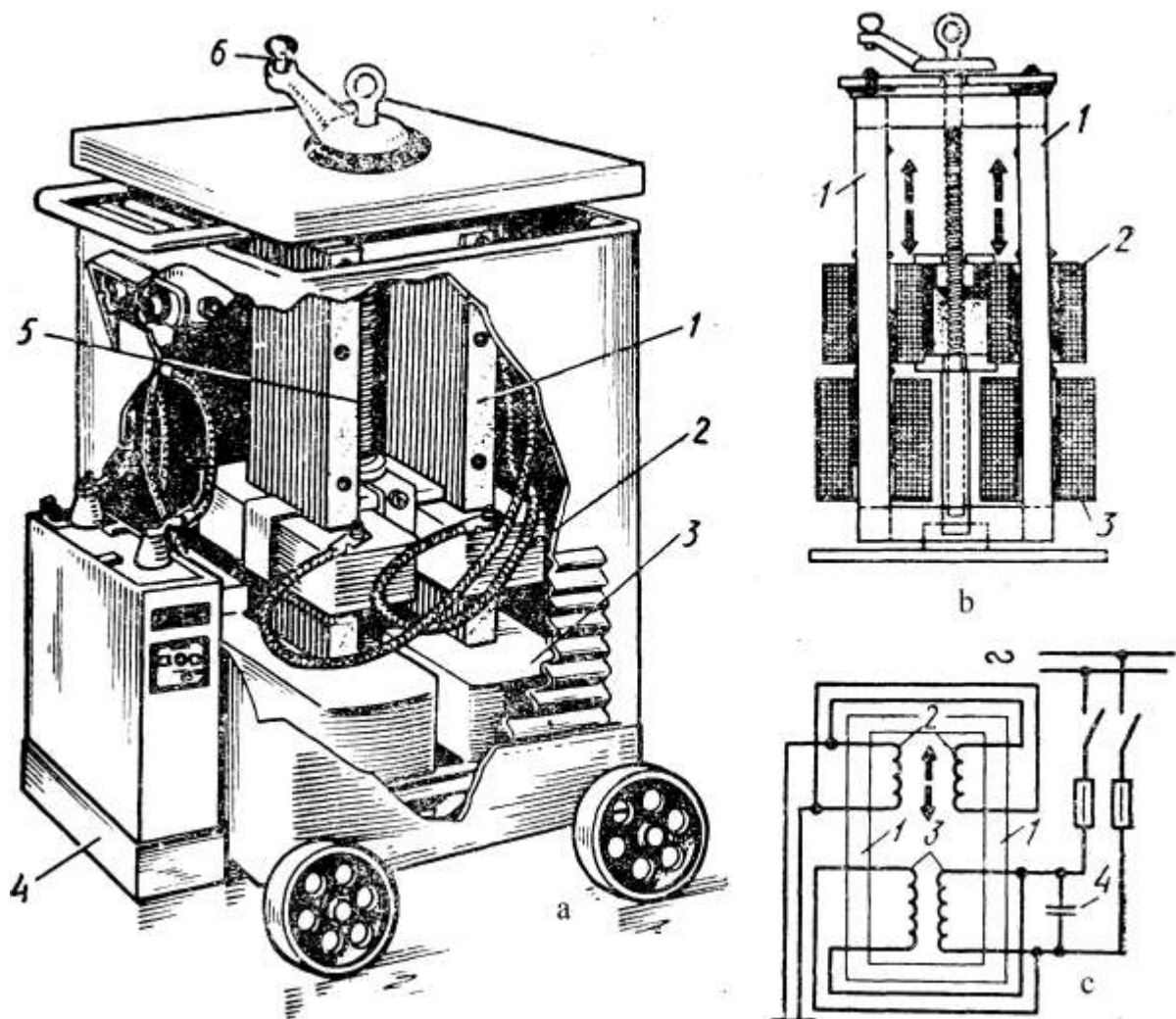


Figure 22 – Scheme of the welding transformer TSK-500:
a – appearance; b – scheme of welding current regulation;
c – electrical scheme

The secondary winding 2, which also consists of two coils, is located at a considerable distance from the primary. The coils of both the primary and secondary windings are connected in parallel. The secondary winding is movable and can move along the core using the screw 5, with which it is

connected, and the handle 6, which is located on the cover of the transformer casing.

The welding current is regulated by changing the distance between the primary and secondary windings. When the handle 6 is rotated clockwise, the secondary winding approaches the primary, the magnetic flux leakage and inductive resistance decrease, the welding current increases. When the handle is rotated counterclockwise, the secondary winding moves away from the primary, the inductive resistance and magnetic flux leakage increase and the welding current decreases. The welding current adjustment limits are 165...650 A.

The serial connection of the primary and secondary windings allows you to get small welding currents with adjustment limits of 40...165 A. For an approximate setting of the welding current strength, a scale with divisions is placed on the cover of the casing. More precisely, the current is set using an ammeter. To increase the power factor, the TSK-500 welding transformer has a 4-high capacity capacitor in the primary circuit.

Welding rectifiers. These are sources of direct welding current, consisting of a welding transformer with a regulating device and a block of semiconductor rectifiers (Fig. 23). Sometimes the welding rectifier kit also includes a choke, which is included in the DC circuit. The choke serves to create a falling external characteristic. The operation of welding rectifiers is based on the fact that semiconductor elements conduct current in only one direction. The most commonly used in welding rectifiers are selenium and silicon semiconductors. Welding rectifiers are mainly performed according to a three-phase circuit, the advantages of which are a large number of voltage ripples and a more uniform loading of the three-phase network.

Welding rectifiers have a number of advantages over converters with rotating parts. They have better energy, dynamic and mass indicators, higher efficiency, are easy to maintain, are more reliable, because there are no rotating parts, and there is no noise during their operation.

Welding rectifiers, depending on the external characteristics, can be divided into three types: with steep, hard (or soft) characteristics and universal. Universal rectifiers provide the possibility of obtaining both hard and falling external characteristics, so they can be used for various types of arc welding. The number in the rectifier brand means the rated current strength at $TP = 60...65 \%$.

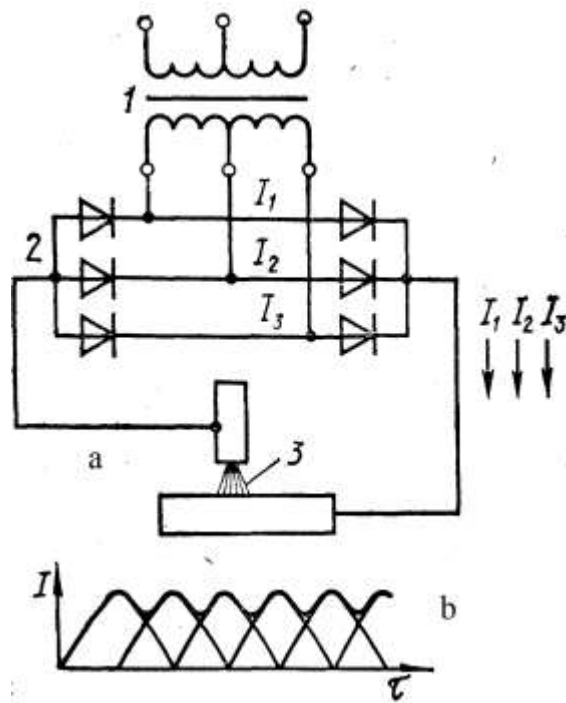


Figure 23 – Three-phase rectifier circuit:
 a – switching circuit; b – rectified current of the external circuit;
 1 – step-down transformer; 2 – selenium or silicon rectifier block; 3 – welding arc

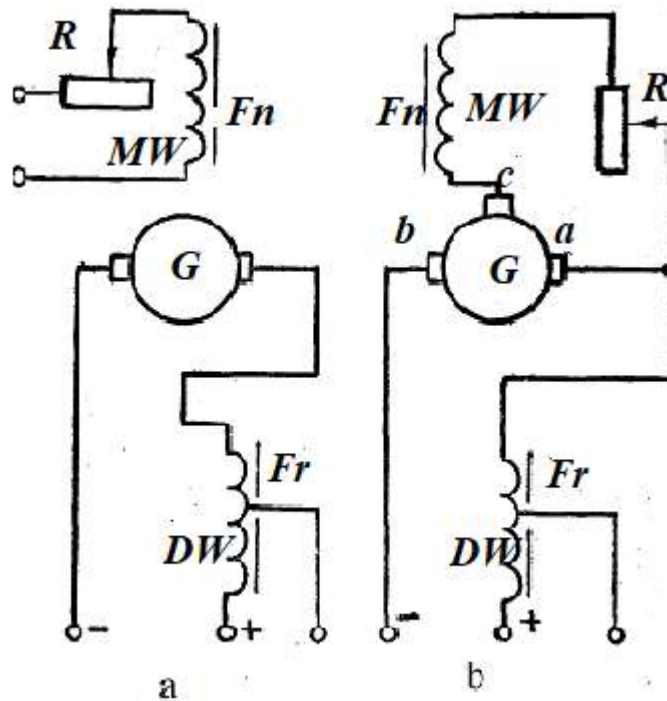


Figure 24 – Schematic diagram of a welding generator:
 a – with independent excitation and demagnetizing series winding; b – with self-excitation and demagnetizing series winding;
 G – generator; R – rheostat; MW – magnetizing winding;
 DW – demagnetizing winding; a, b, c – brushes

Welding generators. These are special MW generators, the external characteristics of which allow for stable arc burning, which is achieved by changing the magnetic flux of the generator depending on the welding current. A DW welding generator consists of a stator with magnetic poles and an armature with a winding and collectors. During generator operation, the armature rotates in a magnetic field created by the stator poles. The armature winding crosses the magnetic lines of the generator poles, and therefore an alternating current arises in the winding turns, which is converted into direct current by means of a collector. The rotation of the armature of the welding generator is provided in welding converters by an electric motor, and in welding units by an internal combustion engine. Carbon brushes are pressed against the collector, through which direct current is supplied to the clamps. Welding wires going to the electrode holders and the product are connected to these clamps.

Welding generators are made according to different electrical schemes. They can be with a falling characteristic, with a hard and gently falling characteristic and universal/ The most common welding generators with falling external characteristics operate according to the following schemes:

- with independent excitation and a demagnetizing series winding;
- with self-excitation and a demagnetizing series winding.

The scheme of a generator with independent excitation and a demagnetizing series winding is shown in Fig. 24, a. The generator has an independent excitation winding MW, powered by a separate DC source, and a series demagnetizing winding DW, which is connected to the welding circuit in series with the armature winding. The current strength in the independent excitation circuit is regulated by a rheostat R. The magnetic flux F_n , created by the independent excitation winding MW, is opposite in direction to the magnetic flux F_r , created by the demagnetizing winding DW. The resulting flux is the difference of the fluxes $F_{rez} = F_n - F_r$.

With an increase in the current in the welding circuit, F_r will increase, and F_n remains unchanged, the resulting flux F_{rez} , EMF and voltage at the generator terminals will fall, creating a decreasing external characteristic of the generator. The welding current in generators of this system is regulated by a rheostat R and sectioning the series winding, that is, by changing the number of ampere-turns.

In generators with self-excitation and a demagnetizing series excitation winding (Fig. 24, b), the principle of self-excitation is used. The voltage on the magnetizing excitation winding MW is removed from the brushes a and from the generator itself; this voltage has almost become constant in magnitude, so the magnetic flux F_n practically does not change.

Now, the considered types of sources, which are still widely used in industry, are being replaced by a new generation of power sources using thyristors, modulators and microprocessors, which have better performance characteristics.

2.5 Metallurgical processes in fusion welding

Melting of metal. Electrode metal during arc welding melts due to the heat released at the end of the electrode in the near-electrode zone of the arc; heat coming from the arc column; heating of the electrode tip when the welding current passes from the current conductor and from the arc. The greater the electrode tip, the greater its resistance and the more heat is released.

The end of the electrode is heated to 2300...2500 °C, which ensures its melting. Drops of molten metal are formed at the end of the electrode, which are transferred through the arc space into the weld pool.

Drops are formed at the end of the electrode and are transferred under the influence of surface tension forces, mass, pressure of gases formed inside the molten metal, pressure of the gas flow, electrostatic and electrodynamic forces, reactive pressure of metal vapor.

Depending on the ratio of forces acting on the drop, the nature of the transfer of electrode metal can be different:

large-drop (typical for manual arc welding with a covered electrode) or small-drop (observed during welding under flux and in protective gases—argon, carbon dioxide, etc., Fig. 25, a);

jet (when welding in argon at currents greater than some critical values, Fig. 25, c); due to short circuits (typical for welding in carbon dioxide, Fig. 25, b).

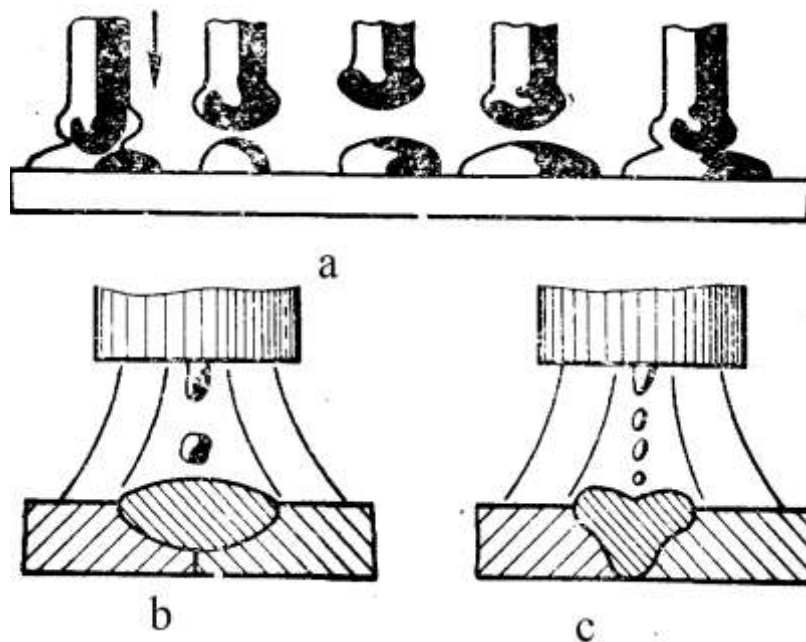


Figure 25 – Scheme of melting and transfer of electrode metal

The main forces that form and hold the drop at the end of the electrode are surface tension forces that arise on the surface of the drop and are directed inside it.

The separation of the drop and its transfer are provided by electrodynamic forces and the pressure of gas flows. These forces increase with increasing welding current, an increase in current leads to the crushing of drops. The weight of the drop is of significant importance at low current density and contributes to the separation and transfer of metal drops only when welding in the lower position.

The transfer of electrode metal in the arc is accompanied by the ejection of part of the metal beyond the weld pool by spattering. Spattering is mainly associated with the electrical explosion of the bridge between the separated drop and the end of the electrode under the action of electrode forces.

The base metal melts as a result of heat release in the active spot (in the electrode zone) on the surface of the product and the heat of the arc column. The shape of the penetration (depth and width) is determined by the concentration of the thermal and force effects of the arc.

The main components of the force effect of the arc:

surface forces - pressure caused by the braking of the arc plasma jet on the metal surface, the reactive pressure of the vapor jet from the surface of the weld pool;

volumetric electrodynamic force in the liquid metal.

The pressure of the axial plasma flow is caused by electromagnetic forces, its magnitude is proportional to the square of the current. An arc with a consumable electrode exerts a greater force effect on the weld pool than an arc with a non-consumable electrode. The pressure force from the gas flow is insignificant and is about 1% of the force of the flow pressure caused by electromagnetic forces.

The process of metal penetration is determined by the thermal and force effects of the arc.

Formation and crystallization of the weld pool. The formation of the weld pool occurs under the influence of the gravity of the molten metal P_m the pressure of the heat source (for example, the pressure of the arc) P_l and the surface tension forces P_n acting on the metal surface (Fig. 26). The nature of the action of these forces depends on the welding position.

When welding in the lower position with through penetration, the liquid pool is held in a hanging position by the surface tension forces P_n , which balance the pressure acting on the pool by the heat source $P_{so}=P_{dj}$, and the gravity force P_m (the mass of the liquid metal): $P_n = P_m + P_{so}$.

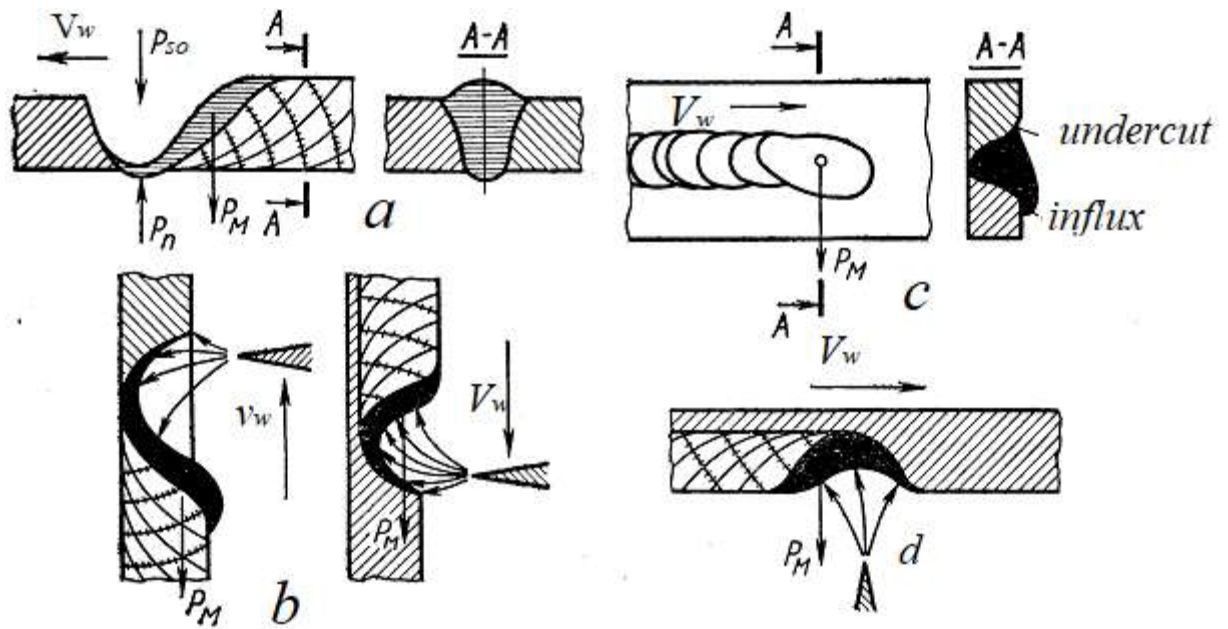


Figure 26 – Scheme of forces acting in the weld pool and seam formation in different spatial positions:
 a – bottom position; b – vertical; c – horizontal; d – ceiling;
 V_w – welding direction

When the weight of the molten metal and the pressure of the heat source exceed the surface tension forces, i.e. $P_{dj} + P_m > P_p$, the surface layer will break in the weld pool, and the liquid metal will flow out of the pool, creating a weld pool.

In the conditions of a moving weld pool (during welding), additional hydrodynamic forces arise due to the movement of the molten metal to the tail of the pool. When the surface tension forces cannot balance the destructive forces, special measures must be taken - to limit the volume of the weld pool, to use welding on supports, to use holding devices. Keeping the pool from flowing is especially important when welding in vertical and ceiling positions. When welding in a vertical position, the process can be carried out from top to bottom (downhill) and from bottom to top (uphill). In both cases, the weight of the pool is directed downward along the longitudinal axis of the seam. When welding in a downward direction, the pressure of the arc and the surface tension force help to keep the pool from flowing. When welding in an upward direction, the pool is held only by surface tension forces. When welding in a vertical position, the thermal power and the size of the pool must be limited to hold the pool.

Performing seams in a ceiling position is complicated not only by the danger of the pool flowing. There is a need to transfer the filler metal into the pool in the direction opposite to the action of gravity. When welding in a ceiling position, the pool is held by the forces of surface tension and the pressure of the arc. To hold the pool in a ceiling position, it is also necessary to limit its volume.

Very unfavorable conditions for forming a seam when performing horizontal seams on a vertical plane. The molten metal of the pool flows onto the lower welded edge, which leads to the formation of asymmetric reinforcement of the seam, as well as undercuts. When welding horizontal seams, strict requirements are placed on reducing the size of the weld pool.

Crystallization of the weld pool metal. When welding by fusion, the weld pool can be conditionally divided into two sections: the main one, where the base and additional metals melt, and the tail one, where the molten metal solidifies. The transition of the weld pool metal from a liquid state to a solid state is called crystallization. Distinctive features of weld pool crystallization:

1. The heat source during welding moves along the joined edges, and the melting space and the weld pool move with it. During arc welding, the arc column, located in the main part of the pool, exerts a mechanical effect (pressure) on the surface of the molten metal due to the impact of charged particles, gas pressure and arc blow. The pressure leads to the extrusion of liquid metal from under the base of the arc and the immersion of the arc column into the thickness of the base metal. Liquid metal, squeezed out from under the base of the arc, as the arc moves, is thrown back into the tail part of the weld pool. When the arc is removed, the heat removal begins to exceed the inflow and solidification begins - crystallization of the weld pool. During the solidification process, common crystallites are formed along the melting boundary, which ensures the monolithicity of the joint.

2. The small volume of the weld pool, which depends on the type and mode of welding, and varies from 0.1 to 10 cm³. Therefore, the heat removal into the adjacent cold metal is very large, and the crystallization rate is also high.

3. Significant overheating of the molten metal and its intensive mixing.

4. Crystallization of the weld pool metal during fusion welding begins mainly from ready-made crystallization centers - partially melted grains of the base metal. The metal of a weld made by fusion welding has a columnar structure, because it consists of elongated (columnar) crystallites that grow during crystallization in the direction opposite to heat removal.

Metallurgical reactions during welding. When welding without protection, the molten metal intensively absorbs atmospheric gases, so the welds have low mechanical properties. To isolate the metal from the air during the welding process, various protective agents are used: electrode coatings, fluxes, protective gases, vacuum. However, it is usually not possible to completely isolate the metal from the air, the protective agents themselves also interact with the metal, even inert gas and vacuum, which contain a certain amount of impurities. Chemical reactions of the interaction of molten metal with gases and protective agents are called welding metallurgical reactions.

There are two main zones or stages of the interaction of molten metal with gases and slag - the end of the electrode with the drops formed on it, and the weld pool. The completeness of the course of metallurgical reactions depends on

the temperature, interaction time, surface and concentration of reacting substances.

The characteristic conditions of metallurgical reactions during welding, as well as during crystallization, are high heating temperature, relatively small volume of molten metal, short duration of the process.

The average temperature of the drops of electrode metal entering the bath increases with increasing current density and is from 2200 to 2700 °C when welding steels, i.e. it is characterized by significant overheating. The temperature of the weld pool during arc welding is also characterized by a significant excess over the melting point, overheating is 100...500 °C. High temperature contributes to a high rate of reaction, but due to high cooling rates, reactions during welding usually do not have time to complete completely.

Metallurgical reactions during welding occur simultaneously in the gas, slag and metal phases.

Interaction of metal with gases. In arc welding, the gas phase of the arc zone in contact with the molten metal consists of a mixture of N₂, O₂, H₂, CO₂, CO, H₂O vapor, as well as their dissociation products and metal and slag vapors. N₂ enters the welding zone mainly from the air, the sources of O₂ and H₂ are air, welding materials (electrode coatings, fluxes, shielding gases, as well as oxides, surface moisture) and other contaminants on the surface of the base and filler metals. Finally, O₂, H₂ and N₂ can be contained in excess in the remelted metal. In the high-temperature zone, gas molecules dissociate into atoms (dissociation). Molecular oxygen, nitrogen and hydrogen dissociate and pass into the atomic state $O_2 \rightarrow 2O$, $N_2 \rightarrow 2N$, $H_2 \leftrightarrow 2H$. The activity of gases in the atomic state increases sharply.

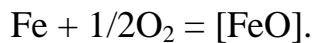
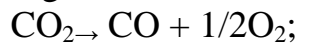
When molten metal in the gas or slag phase comes into contact, O₂ dissolves in the metal, and when the solubility limit is reached, chemical interaction occurs with the formation of oxides. At the same time, oxidation of impurities and alloying elements contained in the metal occurs. First of all, elements that have a greater affinity for O₂ are oxidized. For example, Ti is oxidized by the reaction $Ti + O_2 = TiO_2$, Mn - by the reaction $Mn + O_2 = MnO_2$.

Iron forms three compounds (oxides) with O₂: FeO contains 22.27% O₂, Fe₃O₄ — 27.64% O₂, FeO₂ — 30.06% O₂. These compounds in the metal reduce its strength and plastic properties.

Nitrogen dissolves in most structural materials and forms compounds called nitrides with many elements. With iron, it forms nitrides Fe₂N (11.15% N₂) and Fe₄N (5.9% N₂), which causes brittleness, pores and aging of steels.

Hydrogen also dissolves in most metals. Metals capable of dissolving H₂ can be divided into two groups. The first group includes metals that do not have chemical compounds with H₂ (Fe, Ni, Co, Cu, etc.). The second group includes metals (Ti, Zr, V, Ta, Ra, rare earth elements, etc.) that form chemical compounds with hydrogen, which are called hydrides. Hydrogen is a very harmful impurity, because it causes pores, micro- and macrocracks in the weld

and in the heat-affected zone. Carbon dioxide, which is present in the arc zone during welding in CO₂, actively oxidizes the metal by a reaction that occurs in two stages:



In summary, the reaction will be as follows:



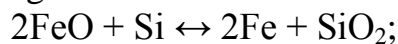
The carbon monoxide CO that is formed does not dissolve in the weld metal; it is removed during the crystallization of the weld pool and can form pores. Carbon dioxide is used to protect the welding zone when using elements (Mn, Si) for deoxidation, which neutralize the oxidizing effect of CO₂.

Water vapor, which is in the gas phase, interacts with liquid metal according to the equation $\text{H}_2\text{O} + \text{Fe} = [\text{FeO}] + \text{H}_2$.

The main ways to combat the harmful effects of gases are high-quality protection and the use of deoxidizer elements in welding materials.

Interaction of metal with slag. When the electrode coating, welding flux, and core of the flux-cored wire melt, slag is formed. The main purpose of welding slag is to isolate the molten metal from air. Fluxes and coatings stabilize the arc, contribute to the high-quality formation of the weld, and carry out metallurgical processing of the molten metal - its deoxidation and alloying.

Typical deoxidation reactions are the deoxidation reactions of iron (II) oxide by silicon and manganese, which are present in welding fluxes and coatings:



Silicon and manganese oxides turn into slag.

Welding materials, along with oxidants, may contain harmful components - SiP, which cause hot cracks and brittleness of the weld metal.

Sulfur, combining with Fe, forms iron sulfide FeS. The metal is purified from S by introducing a more active element than the welded metal, according to the reaction $\text{FeS} + \text{Mn} \leftrightarrow \text{Fe} + \text{MnS}$.

Manganese sulfide is less soluble in steel than iron sulfide, which causes the redistribution of sulfur from the molten metal into the slag.

Chemical composition of the weld metal. The chemical composition of the weld metal and its properties depend on the composition and proportion of participation in the formation of the weld of the base and electrode (filler) metal, the reactions of the interaction of the molten metal with atmospheric gases and protective agents. The weld metal during welding with either a consumable electrode or the use of metal additives (wire, powder, etc.) is formed as a result of mixing in the bath of the base and electrode (filler) metal. The proportion of base metal (ψ_0) in the weld depends on the type of connection (with edge cleaning, without cleaning), the type and mode of welding and can be determined by the ratio of the area occupied by the base metal in the cross-

section of the weld to its entire area (Fig. 27): $\psi_0 = F_0/(F_{np} + F_H)$, where F_0 , F_{np} are the areas occupied by the base, electrode (filler) and deposited metal, respectively.

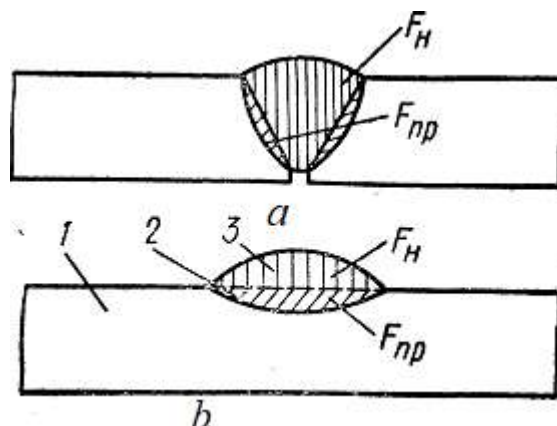


Figure 27 – Cross section of the weld:

a – butt joint; b – surfacing;

1 – base metal; 2 – molten metal; 3 – surfacing metal

In manual arc welding with a covered electrode, the proportion of base metal in the weld is: 0.15...0.40 — when surfacing beads, 0.25...0.50 — when welding root welds, 0.25...0.60 — when welding under flux.

When there are no chemical reactions in the welding zone, the content of any element in the weld metal (C_w) can be found by the formula

$$C_w = C_0\psi_0 + C_e(1 - \psi_0),$$

where C_0 , C_e — the initial content of the element in the base and electrode metal, ψ_0 — the proportion of base metal. For example, let us determine the nickel content in the weld metal during arc welding of steel containing 1.2% Ni using an electrode wire containing 1.5% Ni (butt welding without cleaning). Taking the average value $\psi_0 = 0.3$, we obtain $C_{sh}(\text{Ni}\%) = (1.2 \times 0.3) + [1.5 \times (1 - 0.3)] = 1.41\%$.

When chemical reactions of the molten metal with gases, coatings, and slag bath occur, the composition of the weld metal is determined taking into account the transition coefficients, which show what proportion of the metal contained in the electrode wire passes into the weld metal.

$C_{sh} = C_0\psi_0 + C_e(1 - \psi_0)$, where C_0 , C_e is the transition coefficient, which varies within 0.3...0.95 depending on the chemical activity of the element, type and welding technology, etc.

2.6 Manual arc welding technology

Selecting the manual arc welding mode. The welding mode is understood as a set of controlled parameters that determine the welding conditions. The

parameters of the welding mode are divided into basic and additional. The basic parameters of the manual welding mode include the diameter of the electrode, the magnitude, type and polarity of the current, the voltage on the arc, and the welding speed. The additional parameters include the magnitude of the electrode protrusion, the composition and thickness of the electrode coating, the position of the electrode, and the position of the product during welding.

The diameter of the electrode is selected depending on the thickness of the metal, the leg of the seam, and the position of the seam in space.

The approximate ratio between the metal thickness S and the electrode diameter d_e when welding in the lower position of the seam is:

S, mm	1...2	3...5	4...10	12...24	30...60
d_e, mm	2...3	3...4	4...5	5...6	6...8

The current strength mainly depends on the diameter of the electrode, but also on the length of its working part, the composition of the coating, and the position of the weld. The higher the current, the higher the productivity, i.e. the greater the amount of deposited metal: $G = k_H I_w t$, where G is the amount of deposited metal, g; k_H is the deposition coefficient, g/(A h); I_w is the welding current strength, A; t is time, h.

However, with excessive current for a given electrode diameter, the electrode quickly overheats above the permissible limit, which leads to a decrease in weld quality and increased spatter. With insufficient current strength, the arc is unstable, often breaks, and there may be gaps in the weld.

The current strength can be determined by the following formulas:

$I_d = (20 + 6d_e)d_e$ — when welding structural steels for electrodes with a diameter of 3...6 mm;

$I_d = 30d_e$ — for electrodes with a diameter of less than 3 mm, where d_e is the electrode diameter, mm.

Welding of seams in vertical and ceiling positions is performed, as a rule, with electrodes with a diameter of no more than 4 mm. In this case, the current strength should be 10...20% lower than for welding in the lower position. The arc voltage varies within relatively narrow limits - 16...30 V.

Welding technique. The arc can be excited by two methods: by touching it close and drawing it perpendicularly upwards or by "chirping" the electrode like a match. The second method is more convenient, but unsuitable in narrow and inconvenient places.

During welding, it is necessary to maintain a certain arc length, which depends on the brand and diameter of the electrode. Approximately, the normal arc length should be $L_d = (0.5...1.1)d_e$.

The arc length significantly affects the quality of the weld and its geometric shape. A long arc contributes to more intensive oxidation and nitriding of the

molten metal, increases spatter. When welding with electrodes of the main type, metal porosity occurs.

During welding, the electrode is given movement in three directions.

The first movement is translational, in the direction of the electrode axis. This movement maintains a constant (within certain limits) arc length depending on the electrode melting rate.

The second movement is the movement of the electrode along the axis of the roller to form a weld. The speed of this movement is set depending on the current strength, electrode diameter, its melting rate, type of weld, and other factors. When there are no transverse movements of the electrode, we get the so-called thread roller, 2...3 mm larger than the electrode diameter, or a narrow seam with a width of $e \leq 1.5de$.

The third movement is the movement of the electrode across the seam to get a seam wider than the thread roller, the so-called expanded roller.

The transverse oscillatory movements of the electrode end (Fig. 28) are determined by the shape of the clearance, the dimensions and position of the seam, the properties of the welded material, and the skills of the welder. For wide seams obtained with transverse oscillations, $e = (1.5...5)de$.

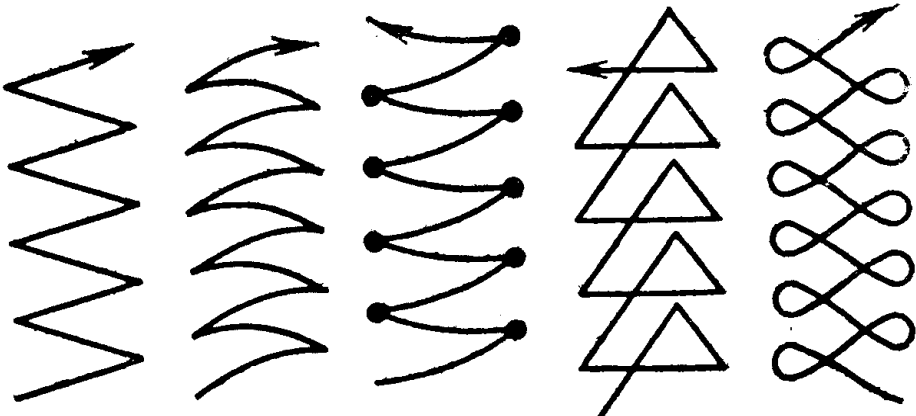


Figure 28 – Trajectory of the electrode end during manual arc welding

To increase the performance of welded structures, reduce internal stresses and deformations, the order of filling the seams is of great importance.

The order of filling the seam is understood as the order of filling the seam clearance in the cross section, as well as the sequence of welding along the length of the seam.

By length, all seams can be conditionally divided into three groups: short - up to 300 mm, medium - 300...1000, long - more than 1000 mm.

Depending on the length of the seam, material, requirements for accuracy and quality of welded joints, welding of such seams can be performed in different ways (Fig.29).

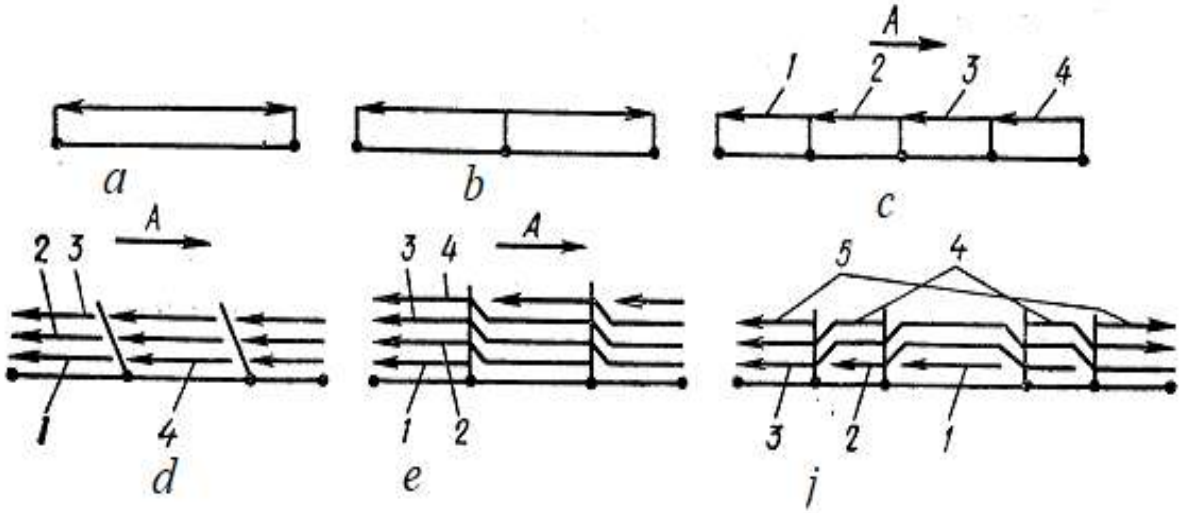


Figure 29 – Welding schemes:

a - in the passage; *b* - from the middle to the edges; *c* - in the reverse step method; *d* - in blocks; *e* - in a cascade; *j* - in a slide; *A* - the direction of filling the clearing (the arrows show the welding direction);
 1-5 - the welding sequence in each layer

Short seams are performed in the passage - from the beginning of the seam to its end. The seams of the middle line are welded from the middle to the ends or in the reverse step method. Long seams are performed in two ways: from the middle to the edges (the reverse step method) and in a scattered manner.

With the reverse step method, the entire seam is divided into small sections 150...200 mm long, in each section the welding is carried out in the direction opposite to the general welding direction. The length of the sections is usually from 100 to 350 mm. Depending on the number of passes (layers) required to perform the design cross-section of the weld, single-pass (single-layer) and multi-pass (multi-layer) welds are distinguished (Fig. 30). From the point of view of productivity, single-pass welds are the most appropriate, which are usually used when welding metal of small thicknesses (up to 8...10 mm) with preliminary edge cleaning.

Welding of joints of critical structures of large thickness (above 20...25 mm), when volumetric stresses arise and the risk of cracks increases, is performed using special methods of filling the seams with a "slide" or "cascade" method

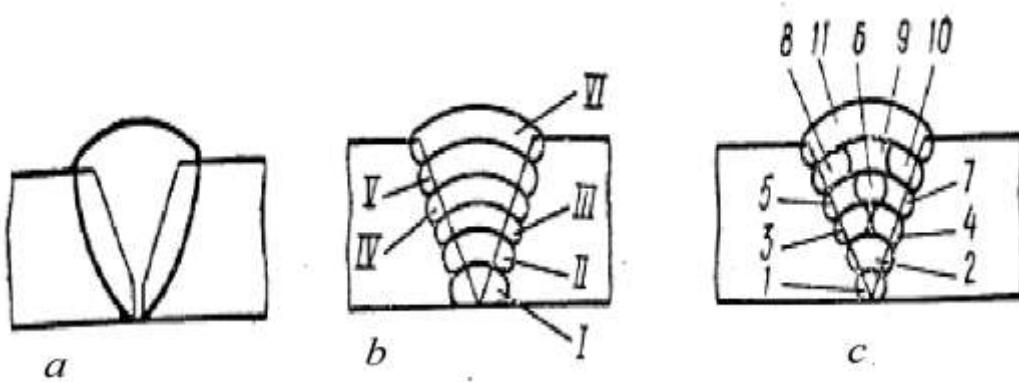


Figure 30 – Cross-sections of butt joints:
a – single-pass (single-layer); *b* – multilayer;
c – multi-pass; I–VI – layers; 1–11 – passes

When welding with a "slide", first a small layer of metal 200...300 mm long is welded to the place of edge clearing, and then a second layer, which overlaps the first and is twice as long as it. The third layer overlaps the second and is longer than it by 200...300 mm. Layers are welded in this way until the place of edge clearing is filled in a small area above the first layer. Then from this "slide" welding is carried out in different directions with short seams in the same way. Therefore, the welding zone is always in a hot state, which prevents the appearance of cracks. The "cascade" method is a type of "slide".

The joints for welding are assembled in devices, most often with tacks. The cross-section of the tack seam is approximately 1/3 of the cross-section of the main seam, its length is 30...50 mm. Corner seams are welded "in a corner" or "in a boat" (Fig. 31). When welding "in a corner", assembly is simpler, a large gap between the welded parts is allowed (up to 3 mm), but the welding technique is more complicated, defects such as undercuts and overflows are possible, and productivity is lower, because it is necessary to weld seams of a small cross-section (legs < 8 mm) in one pass and use multi-layer welding. Welding "in a boat" is more productive, allows for larger leg lengths of the seam in one pass, but requires more careful assembly.

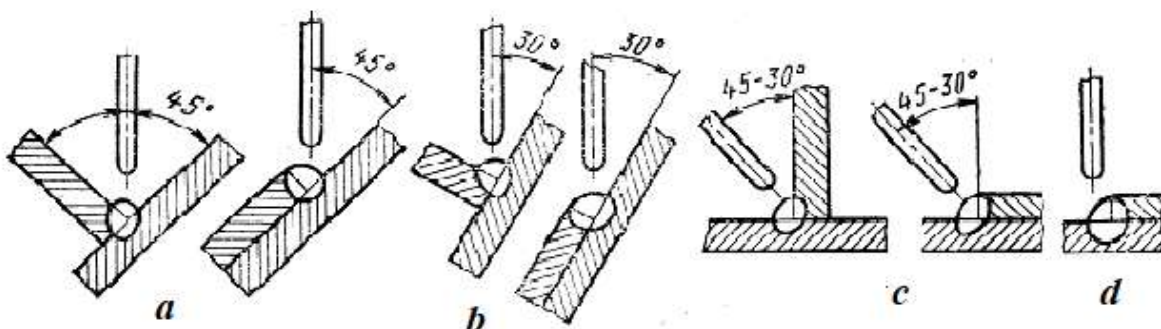


Figure 31 – Position of the electrode and the product when performing fillet welds:

a – welding in a symmetrical "shuttle"; *b* – in an asymmetrical "shuttle";
c – "into a corner" with an inclined electrode; *d* – with melting of the edges

Ensuring regulatory requirements for welding technology and techniques is the main condition for obtaining high-quality welds. Deviations in the size and shape of the weld from the design ones are most often observed in fillet welds and are associated with violation of welding modes, improper preparation of edges for welding, uneven welding speed, as well as untimely control measurement of the weld.

Non-fusion is called the local absence of fusion between the welded elements, between the weld metal and the base metal or individual layers of the weld in multilayer welding. Non-fusion reduces the cross-section of the weld and causes stress concentration, therefore it can significantly reduce the strength of the structure. The areas of the weld where non-penetration is detected, the value of which exceeds the permissible value, should be removed and this place should be welded again. Non-penetration at the root of the weld is mainly caused by insufficient current or increased welding speed, non-penetration of the edge (non-fusion with the edges) - by the displacement of the electrode from the axis of the electrode, as well as by arc wandering, non-penetration between layers - by poor cleaning of the previous layers, a larger volume of deposited metal, and the flow of molten metal before the arc.

Undercut is a local reduction in the thickness of the base metal near the weld edge. Undercut leads to a reduction in the metal cross-section and a sharp concentration of stress when it is located perpendicular to the operating stresses.

Inflow is the flow of the weld metal onto the surface of the base metal without fusing with it.

A cavity in the weld formed as a result of the leakage of the weld pool, which is an unacceptable defect in the welded joint.

A crater is an unwelded depression formed after the arc is broken at the end of a weld. As a rule, shrinkage embrittlements are formed in a crater, which often turn into cracks.

Burns are small areas of molten metal on the base metal outside the weld.

Undercuts, leaks, overflows, burns, unwelded craters, slag and spatter left after welding, melting of edges (in fillet welds) are mainly caused by excessive current and voltage on the arc, larger electrode diameter, incorrect manipulation of the electrode, poor preparation for welding, low qualification or negligence of the welder.

Manual arc welding is widely used in surfacing processes for restoring worn surfaces, restoring casting defects and for surfacing surfaces with special properties. Surfacing has a number of distinctive features compared to joining welding. When surfacing surface layers with specified properties, the chemical composition of the surfacing metal is significantly different from the chemical composition of the base metal. The surfacing metal is selected taking into account operational requirements and weldability.

Technological requirements and features of surfacing compared to joint welding are:

- minimum mixing of the surfacing layer with the base metal to ensure the specified chemical composition of the layer and prevent cracks;
- ensuring a minimum heat-affected zone;
- minimal deformations and stresses.

These requirements are ensured by reducing the penetration depth by adjusting the parameters of the mode, power energy, surfacing technique, electrode oscillations, increasing its flight, using a wide strip of small thickness, surfacing symmetrical layers in a scattered manner, forging them after surfacing and other technological techniques.

The surfacing technique should ensure maximum surfacing productivity, i.e. the maximum amount of melted electrode (filler) metal per unit of time.

Manual arc surfacing is performed with covered fusible and non-fusible electrodes. Before surfacing with a fusible electrode, the surface of the part must be thoroughly cleaned, after which the metal is deposited with separate rollers. In this case, each subsequent roller should melt the previous one by 1/3...1/2 of the width. The electrodes are selected based on the operating conditions of the surfacing surface. The productivity of arc surfacing with covered electrodes is 0,8...3 kg/h.

Powder mixtures are deposited with a carbon (graphite) electrode with direct current of direct polarity. A thin layer of flux (0,2...0,3 mm), most often calcined borax, is poured onto the surface cleaned of contamination, then a layer of charge 3...5 mm thick and 20...60 mm wide. The arc is excited on the base metal, then transferred to the charge, the charge is melted with minimal melting of the base metal.

2.7 Increasing the productivity of manual arc welding

The productivity of welding with a consumable electrode is determined by the melting and deposition coefficients. The melting of the filler metal is characterized by the melting coefficient:

$\alpha_p = G_p / (I_w t)$, where α_p is the melting coefficient, g/(A h);

G_p is the mass of the electrode metal melted during time t , g;

t is the arc burning time, h; I_w is the welding current, A.

The amount of deposited metal or the deposition rate is determined by the deposition coefficient: $\alpha_h = G_h / (I_w t)$, where α_h is the deposition coefficient, g/(A h); G_h is the mass of the metal deposited during time t , g (taking into account losses).

The difference in the coefficients α_p and α_h is determined by the losses of the electrode metal due to spatter, spattering, evaporation, etc. The coefficient of these losses ψ_{em} is determined by the formula

$$\psi_{em} = \frac{\alpha_p - \alpha_h}{\alpha_p} 100\% .$$

The coefficients α_p , α_n , ψ_{sm} depend on the type, method and parameters of the welding mode. At low current densities (manual arc welding), the values of the melting and surfacing coefficients do not exceed 7...10 g/(A h). With increasing current density, the values of the coefficients increase to 17 g/(A h) and more. The loss coefficient for different welding methods is 1...5%.

Welding productivity is determined by the amount of molten metal Q_n per unit of time, and the main welding time is determined by the formula

$$t_0 = G_H / (\alpha_n I_w) = F_H l / (\alpha_n I_w).$$

From the formula it follows that to reduce the main time it is necessary to try, on the one hand, to increase the welding current I_w and the deposition coefficient α_n , on the other hand, to reduce the cross-section of the deposited metal F_H .

The current and volume of molten metal are increased by using electrodes of large diameters (6...10 mm), welding with a handful of electrodes, welding with special paired electrodes when using a three-phase arc. In all these cases, the increase in current is achieved by increasing the total cross-sectional area of the electrode rods. It should be borne in mind that the increase in the mass of the electrode and electrode holder increases the fatigue of the welder. There are difficulties in ensuring penetration in narrow places of edge cleaning and corner welds. These methods are advisable to use when welding casting defects, filling the places of cleaning of thick sheet metal.

Productivity improvement by increasing the deposition coefficient α_n is achieved by using electrodes with a large Q_n and electrodes containing iron powder in the coating. Electrodes with iron powder contain up to 50...60% of powder in the coating (for example, OZS-6), so the weld is formed by melting the rod and the coating powder. In this case, the deposition coefficient increases to 12...18 g/(A h), and productivity is 1.5...2 times.

The cross-sectional area of the deposited metal F_d at a given thickness of the welded metal is reduced by appropriate edge cleaning, for example, by using a double-sided bevel of the edges instead of a single-sided one. Reducing F_d by increasing the depth and area of penetration is achieved by resistance welding (with deep penetration by a submerged arc). The essence of the method is that the electrode is supported with a light pressure of the coating against the welded metal at an angle of 15...20° to the vertical, moved at an angle back along the line of application of the roller without transverse oscillations. Electrodes with increased coating thickness are used. The welding current is increased by 20...40%, according to the formula $I_w = (60+70)d_e$. Increased power of the welding arc, concentrated heat input, rapid movement of the electrode at an angle and intensive extrusion of the molten metal of the weld pool from under the arc by arc pressure create conditions for deep penetration with minimal

spatter. This method is used when welding in the lower position of butt joints and corner "in a boat".

Increased productivity is also achieved by using welding with an inclined electrode and one that lies, due to the fact that one worker can simultaneously service 2-3 posts.

2.8 Occupational safety during arc welding

The main hazards and hazards that lead to occupational injuries during welding are:

- electric shock during electric welding;
- damage to vision and exposed skin surfaces by electric arc radiation;
- poisoning of the body with harmful gases, dust and fumes released during welding;
- injuries from explosions of compressed gas cylinders, acetylene generators and vessels from flammable substances;
- fire hazard and burns;
- mechanical injuries during preparation and assembly welding operations;
- risk of radiation damage when controlling welded joints by radiation methods.

Each worker undergoes briefing or special technical minimum on safety precautions upon employment.

Safety precautions are a set of technical and organizational measures aimed at creating safe and healthy working conditions. The administration of these enterprises is responsible for the organization and state of safety at the enterprise.

General control over the implementation of labor protection norms and rules, including safety rules, is carried out by the relevant inspections (State Supervision, State Sanitary Inspection, Fire Supervision Inspection, State Energy Supervision) and trade union organizations.

A set of measures on industrial sanitation, occupational hygiene, recreation, medical care and safety ensure the labor protection of employees at enterprises.

Electrical safety. Electric shock occurs when touching live parts of electrical wiring and welding equipment used for arc contact and beam welding. Currents passing through the human body, more than 0.05 A (at a frequency of 50 Hz), can cause serious consequences and even death (> 0.1 A). The resistance of the human body, depending on its condition (fatigue, skin moisture, health status), varies widely from 1000 to 20000 Ohm. The open-circuit voltage of normal arc power sources reaches 90 V, and of compressed arc - 200 V. According to Ohm's law, if the welder is in poor condition, a current close to the limit can pass through him:

$$I = U/R = 90/1000 = 0,09 \text{ A.}$$

Electrical safety is ensured by:

fulfilling the electrical safety requirements of electric welding equipment, reliable insulation, use of protective fences, automatic locking, grounding of electrical equipment and its elements, limiting the open-circuit voltage of power sources (DC generators up to 80 V, transformers up to 90 V);

personal protective equipment (working in dry and durable overalls and gloves, in shoes without metal pins and nails);

compliance with working conditions (stopping work during rain and heavy snowfall when there is no shelter; using a rubber mat, rubber helmet and galoshes when working inside the vessel, as well as a portable lamp with a voltage of no more than 12 V; repair of electric welding equipment and devices by electricians).

In case of electric shock, the victim must be given assistance: free from electrical wires (with observance of safety precautions), ensure access to fresh air, if the victim loses consciousness, immediately call an ambulance, and perform artificial respiration until the doctor arrives.

Protection of vision and exposed skin. The electric welding arc creates three types of radiation: light, ultraviolet, infrared.

Light rays are blinding because their brightness significantly exceeds permissible standards. Ultraviolet radiation, even with short-term exposure for several seconds, causes an eye disease called electrophthalmia. It is accompanied by acute pain, tearing, and eyelid spasms. Prolonged exposure to ultraviolet radiation leads to skin burns. Infrared radiation, with prolonged exposure, causes clouding of the lens of the eye (cataract), which can lead to weakening and loss of vision, the thermal effect of these rays causes skin burns.

Protection of vision and facial skin during arc welding is provided by the use of shields, masks, or helmets made of heat-resistant dielectrics (fiber impregnated with a special solution, plywood, etc.) with protective glasses - light filters (size 52x102 mm), which withstand and absorb arc radiation. Depending on the power of the arc, various light filters are used. Closed cabins are installed to protect against arc radiation in stationary conditions, and portable shields and screens are used during construction and installation work. Overalls made of thick tarpaulin or cloth, sometimes made of asbestos fabric, are used to protect the body.

Protection against poisoning by harmful gases, dust and fumes. The composition and amount of harmful gases, dust and fumes depend on the type of welding, the composition of protective equipment (coating, fluxes, gases), welded and electrode materials. The amount of welding dust (aerosol) and volatile compounds during welding is from 10 to 150 mg per 1 kg of molten electrode metal. The main components are oxides of iron (up to 70%), manganese, silicon, chromium, fluoride and other compounds.

The most harmful are chromium, manganese and fluoride compounds. In addition to aerosols, the air in working rooms during welding is polluted with various harmful gases: nitrogen oxides, carbon, hydrogen fluoride, etc.

Along with short-term poisoning, which manifests itself as dizziness, headache, nausea, vomiting, weakness, etc., toxic substances can be deposited in the tissues of the human body and cause chronic diseases. Particular attention should be paid to the concentration of manganese, because its presence in the air more than 0.3 mg/m^3 can cause serious diseases of the nervous system.

The most harmful is welding with coated electrodes, and with automatic welding methods the amount of harmful emissions is much lower.

The main measures aimed at protecting against poisoning by harmful emissions during welding and improving working conditions are:

- use of local and general ventilation;

- mechanization and automation of welding processes;

- replacement of harmful processes and materials with less harmful ones (for example, replacement of electrodes with an acidic coating with a high content of manganese oxide with rutile);

- use of insulating and protective devices;

- in especially dangerous cases, use of individual protective equipment (respirators with a chemical helmet, gas masks).

Fire safety. Causes of fire during welding work can be sparks and drops of molten metal and slag, careless handling of the torch flame in the presence of flammable materials near the welder's workplace. The risk of fire should be especially taken into account at construction and installation sites and during repair work in premises not adapted for welding.

The main fire safety requirements are set out in the "Fire Safety Rules for Welding and Other Fire Work at National Economic Facilities". Places where welding is performed must be equipped with fire extinguishers, boxes with sand, shovels and scoops, barrels or buckets with water. Wooden structures located closer than 5 m from welding posts are plastered or covered with sheet asbestos or sheet steel on felt soaked in clay mortar. There should be no flammable objects in the area of metal splashes and sparks. Flammable and explosive materials should be at a distance of at least 30 m from the welding site. Wooden floors, decking, platforms, if necessary, are protected from sparks and drops of molten metal and slag with sheets of asbestos or iron. Welders are provided with overalls, shoes, gloves and a hat.

To ensure explosion safety, welding work in containers containing flammable products is carried out only after they have been thoroughly cleaned of product residues and rinsed twice or thrice with a hot 10% alkali solution followed by steam or air blowing. Gas pipelines can be repaired only after thorough blowing.

Injuries (impacts, cuts) occur during preparation and assembly-welding operations. Such injuries are caused by failure to observe safety precautions when working on metal-cutting equipment during preparation operations, lack of devices for transporting and assembling heavy parts; malfunction of vehicles

- trolleys, chains, cables, grippers, failure of personnel to observe basic rules for rigging work;

malfunction of tools - anvils, hammers, chisels, keys, etc.

The main measures to reduce injuries are safety-conscious harvesting, assembly, and welding technologies, proper equipment of workplaces, and compliance by personnel with basic safety rules.

Review questions

1. What is the essence of manual arc welding with a consumable electrode? Name the main equipment, accessories and tools for manual arc welding.

2. How is welding wire classified and marked?

3. How are steel coated electrodes classified for welding and surfacing? What is the type of electrode, brand of electrode?

4. Name the main metallurgical processes in arc welding?

5. Name the main features of manual arc welding. How are the welding mode parameters selected?

6. Describe the schematic diagram of power sources for arc welding: transformers, rectifiers, generators.

7. Ways to increase the productivity of manual arc welding.

8. Tell us about the basic safety regulations in manual arc welding.

3 FUNDAMENTALS OF GAS WELDING AND CUTTING TECHNOLOGY AND EQUIPMENT FOR THEM

3.1 General information

Flammable gases. In gas flame processing (welding, cutting, surface treatment, soldering), a gas flame is used as a heat source - a flame of a combustible gas, which is burned for this purpose in oxygen in special burners.

Acetylene, hydrogen, natural gases, petroleum gas, gasoline vapor, kerosene, etc. are used as combustible gases. The acetylene-oxygen flame has the highest temperature compared to the flames of other gases, which is why it is most often used (Table 3).

The main raw material for acetylene production is calcium carbide. This is a chemical compound of calcium with carbon (CaC_2). It is obtained in electric arc furnaces at a temperature of 1900–2300°C by fusing coke (C) with quicklime (CaO) according to the reaction $\text{CaO} + 3\text{C} = \text{CaC}_2 + \text{CO}$. Molten calcium carbide is poured from the furnace into special molds, in which it solidifies and hardens, after which it is crushed and sorted by the size of pieces from 2 to 80 mm. Since calcium carbide actively interacts with water and intensively absorbs moisture from the air and decomposes, it is packed in special sealed drums made of roofing steel with a capacity of 100 and 130 kg. Acetylene (C_2H_2) is a chemical compound of carbon and hydrogen. It is obtained in special devices - acetylene generators when water interacts with calcium carbide (CaC_2). The decomposition reaction of calcium carbide with the formation of gaseous acetylene and slaked lime proceeds rapidly with significant heat release Q:



When 1 kg of calcium carbide decomposes, 0.25-0.3 m³ of acetylene is formed. Theoretically, 0.562 kg of water is required to decompose 1 kg of calcium carbide; in practice, from 5 to 20 kg of water is used for decomposition and cooling.

Acetylene (C_2H_2) under normal conditions (temperature 20 °C, pressure 760 mm Hg) is a colorless gas with a sharp specific garlic odor. Acetylene is lighter than air - 1 m³ of acetylene under normal conditions has a mass of 1,09 kg, it is explosive. With air it forms explosive mixtures in the range from 2,2 to 81% by volume (acetylene) at normal atmospheric pressure, with oxygen - from 2,3 to 93%. The most explosive mixtures contain 7 - 13% acetylene. The autoignition temperature of acetylene varies in the range from 500 to 600 °C at a pressure of 0,2 MPa, at a pressure of 2,2 MPa - 350 °C, the presence of copper oxides reduces the ignition temperature to 240 °C.

The explosion hazard of acetylene is reduced when it is dissolved in liquids. It dissolves very well in acetone. Under normal conditions, up to 20

volumes of acetylene dissolve in one volume of technical acetone. The solubility of acetylene in acetone increases with increasing pressure and decreasing temperature. Acetylene is delivered to the welding site in special steel cylinders filled with a porous mass impregnated with acetone, under a pressure of 1,9 MPa.

Along with obtaining it from calcium carbide, acetylene is also obtained from natural gas, oil, and coal, which is 30-40% cheaper. Acetylene obtained from natural gas is called pyrolysis.

In addition to acetylene, other cheaper and less scarce combustible gases and liquid vapors are used in cutting, as well as in welding, soldering, surfacing, flame hardening, and metallization (Table 3). In oxygen cutting, combustible gases are used, which, when burned in a mixture with oxygen, produce a flame with a temperature of at least 2000 °C. The use of substitute gases when cutting metals of small thicknesses gives a higher cut purity. In welding, the flame temperature of the substitute gas should be approximately twice the melting point of the welded metal.

Along with the flame temperature, the choice of combustible gas depends on its calorific value. The calorific value of a gas is the amount of heat in joules (kilocalories) obtained during the complete combustion of 1 m³ of gas. To calculate the replacement of acetylene with another substitute gas, the acetylene replacement coefficient is used. The acetylene replacement coefficient (ψ) is the ratio of the substitute gas flow rate (V_3) to the acetylene flow rate (V_a) at the same effective thermal power

$$Q_{dj} : \psi = V_3/V_a.$$

The effective thermal power of the flame q_j is the amount of heat introduced into the metal being heated per unit time. The higher the calorific value of the gas and the flame temperature, the higher its effective power, the lower the gas consumption during welding and cutting. The main properties of combustible gases and liquids in the field of their application are given in Table.

Hydrogen (H₂) is a combustible gas without color and odor, 14,5 times lighter than air, explosive, obtained by the decomposition of water with an electric current.

Coke oven gas is a colorless gas with the odor of hydrogen sulfide, obtained during the production of coke from coal, consists of a mixture of combustible products: hydrogen, methane and other unsaturated hydrocarbons.

Town gas is a mixture of combustible gases (in percentages by volume): methane - 70-95, hydrogen - up to 25, heavy hydrocarbons - 1, nitrogen - up to 3, carbon monoxide - up to 3, carbon monoxide (IV) - up to 1.

Propane-butane mixtures are mixtures consisting mainly of propane (C₃H₈) and butane (C₄H₁₀), colorless, odorless gases, with the highest calorific value.

Gasoline and kerosene are products of oil refining, colorless liquids that evaporate easily.

Oxygen (under normal conditions) is a colorless, odorless, non-flammable gas, slightly heavier than air, 1 m³ of its mass is 1,33 kg. Oxygen has high chemical activity, forming compounds with all elements (except inert gases), it actively supports combustion with the release of a large amount of heat.

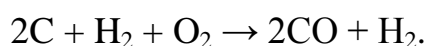
Oxygen is extracted from air under special conditions. Atmospheric air is a mixture containing by volume: nitrogen — 78,08%, oxygen — 20,95%, inert gases — 0,94%, 0,3% — carbon dioxide, hydrogen and other gases. The recycled air, passing through filters, is cleaned of harmful impurities, dust, carbon dioxide, dried, then compressed by a compressor to a pressure of 20 MPa, after which it is cooled in heat exchangers until liquefied. The division of air into nitrogen, oxygen and inert gases (argon, helium) is based on the difference in their boiling and evaporation temperatures: the boiling point of liquid nitrogen is 196 °C, and that of liquid oxygen is 182,9 °C at normal atmospheric pressure.

During evaporation, nitrogen will first pass into the gaseous phase, because it has a lower boiling point than oxygen, and the remaining liquid will be enriched with oxygen. Oxygen separated from nitrogen is pumped into gas holders, from which oxygen cylinders are filled to a pressure of 15 MPa. Oxygen is delivered to the welding site either in a gaseous state in oxygen cylinders or in a liquid state in special vessels with good thermal insulation. To convert liquid oxygen into gas, gasifiers and pumps with evaporators for liquid oxygen are used. In this case, the gas is supplied to the workstations through a gas pipeline system.

At normal atmospheric pressure and a temperature of 20 °C, 1 dm³ of liquid oxygen when evaporated gives 860 dm³ of gaseous oxygen. Therefore, delivering oxygen in a liquid state allows you to reduce the weight of the container by about 10 times, save metal for the manufacture of cylinders, and reduce the costs of their transportation and storage.

For welding and cutting, technical oxygen is produced in three grades: 1st—purity not less than 99,7%, 2nd—not less than 99,5%, 3rd—not less than 99,2% by volume. Oxygen purity is of great importance for oxygen cutting. The purer the oxygen, the higher the cutting speed, cleaner the edges and lower the oxygen consumption.

Gas flame. The acetylene-oxygen flame consists of three zones (Fig. 32): the flame core 1, the middle reduction zone 2, the flame torch—oxidation zone 3. The core is a gas mixture of highly heated oxygen and dissociated (decomposed) acetylene— $2C + H_2 + O_2$, the core stands out with a sharp outline and bright glow. Combustion begins in zone 2. The first stage of acetylene combustion occurs in it due to oxygen coming from the cylinder, according to the reaction



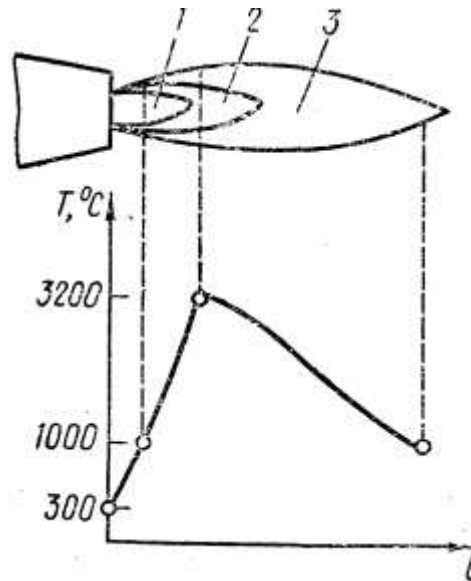


Figure 32 – Diagram of a normal oxy-acetylene flame and temperature distribution

Carbon does not burn completely, and hydrogen, as it has a lower affinity for oxygen than carbon, is not oxidized (does not burn) in this zone. Zone 2, which has the highest temperature and reducing properties, is called the welding or working zone. In zone 3 (torch), the second stage of acetylene combustion occurs due to atmospheric oxygen according to the reaction $2\text{CO} + \text{H}_2 + 3/2\text{O}_2 = 2\text{CO}_2 + \text{H}_2\text{O}$. Carbon dioxide and water vapor at high temperatures oxidize iron, so this zone is called the oxidizing zone.

For complete combustion of one volume of acetylene, two and a half volumes of oxygen are required: one volume comes from an oxygen cylinder and one and a half volumes from air. For complete combustion of the same volume of different gases, different amounts of oxygen are required.

The gas flame heats the metal due to heat exchange processes - forced convection and radiation. The thermal characteristics of the gas flame (temperature, effective heat power, distribution of the flame heat flux over the heating spot) depend on the calorific value of the combustible gas, the purity of oxygen and their ratio in the mixture.

The temperature of the gas flame ($^{\circ}\text{C}$) is not the same in different parts of it and reaches the highest value on the flame axis, which is obtained in welding torches, conditionally estimated by the hourly acetylene consumption V_a (l/h).

The effective flame power q_j , i.e. the amount of heat introduced into the metal being heated, increases per unit time with increasing gas consumption.

The effective efficiency of the metal heating process k_{dj} by a gas flame, defined as the ratio of the effective power $\langle q_j \rangle$ to the total flame power $\langle q \rangle$, is equal to $k_{dj} = q_j/q = q_j/(kV_a)$, where kV_a is the total thermal power of the oxyacetylene flame; k is a coefficient, $k \approx 0,84$; k_{dj} depends on the flame power and varies from 0,8 (low power) to 0,25 (high power).

A gas flame is a dispersed source of heat. The largest heat flux on the axis of the oxyacetylene flame of a conventional welding torch is 8...12 times smaller than that of an open welding arc of approximately the same effective power, therefore the gas flame heats the metal more slowly and smoothly than the welding arc (see Table 1).

3.2 Gas welding technology

Gas welding is a fusion welding in which the metal in the joint zone is heated to melting with a gas flame (Fig. 33). When heated with a gas flame 4, the edges of the welded workpieces 1 melt together with the filler metal 2, which can be additionally introduced into the flame of the burner 3. After the liquid metal solidifies, a weld seam 5 is formed.

The advantages of gas welding include: simplicity of the method, simplicity of equipment, lack of an electrical energy source. The equipment of a gas welding station is shown in Fig. 34. The disadvantages of gas welding include: lower productivity, complexity of mechanization, a larger heating zone and lower mechanical properties of welded joints than in arc welding.

Gas welding is used in the manufacture and repair of products made of thin-sheet steel with a thickness of 1...3 mm, welding of cast iron, aluminum, copper, brass, surfacing of hard alloys, correction of casting defects, etc.

Mode parameters. Depending on the material being welded, its thickness and type of product, the following main parameters of the welding mode are elected: welding flame power, type of flame, brand and diameter of the filler wire, flux, welding method and technique.

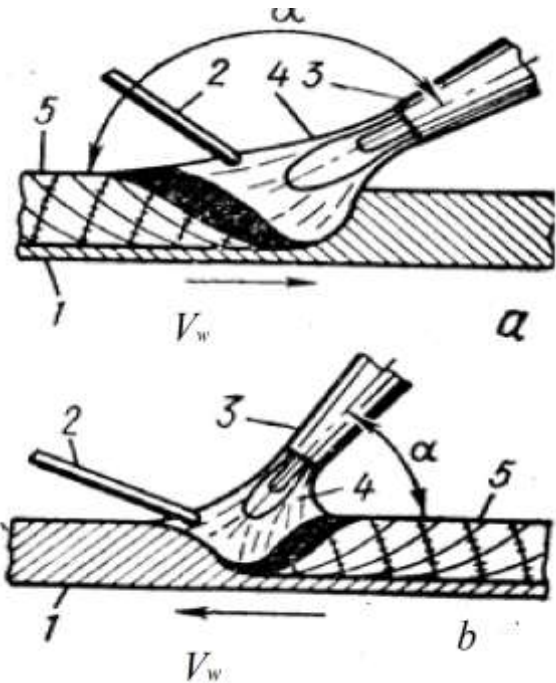


Figure 33 – Gas welding scheme:
a - right; b - left method

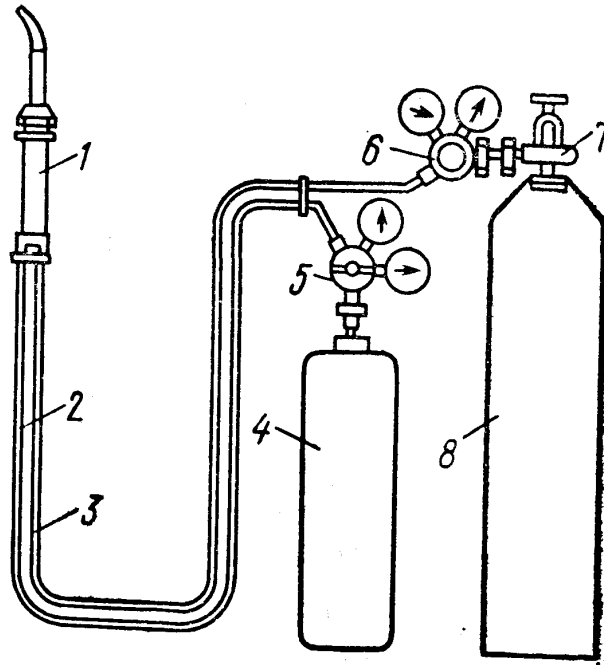


Figure 34 – Equipment of a gas welding station:

- 1 – torch; 2 – acetylene supply hose; 3 – oxygen supply hose; 4 – acetylene cylinder; 5 – acetylene reducer; 6 – oxygen reducer; 7 – oxygen valve;
8 – oxygen cylinder

The thermal power of the welding flame is determined by the flow rate of acetylene passing through the torch in one hour. It is regulated by the interchangeable torch tips (tip number). The power is determined by the empirical formula

$$Q_a = AS,$$

where Q_a is the flow rate of acetylene, dm^3 ; S is the thickness of the metal, mm; A is the coefficient determined by experiment, $\text{dm}^3/\text{h}\cdot\text{mm}$), for carbon steels $A = 100\dots130$, for copper - 150, for aluminum - 75.

A certain type of flame is required for welding different metals - normal ($a = \text{VO}_2/\text{VC}_2\text{H}_2 = 1\dots1,3$), oxidizing ($b > 1.3$) or carburizing ($c > 1$). The gas welder sets and regulates the type of welding flame by eye. Most steels are welded with a normal flame. Oxidizing flame, which has a bluish tint and a pointed core shape, is used when welding brass. Carburizing flame, which becomes sooty, lengthens and has a reddish tint, is used mainly when welding cast iron to compensate for the burning carbon.

Before welding, the edges of the connected elements and the surfaces adjacent to them in an area of 20...40 mm (on each side) should be cleaned to a metallic shine from rust, oil and other contamination with metal or round drive brushes, sometimes with files or sandpaper. When welding critical parts,

sandblasting or shot blasting, mechanical cutting tools, less often, chemical cleaning with special acid-based pastes are used.

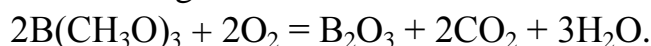
Filler material for gas welding is used in the form of wire, cast rods and granulated powdered metal (when surfacing with hard alloys).

Welding wire for gas welding and surfacing is supplied under the same technical conditions as for arc welding: steel welding wire made of low-carbon, alloyed and high-alloyed steels - according to GOST; welding wire made of aluminum and aluminum alloys - according to GOST, welding wire and rods made of copper and copper-based alloys - according to GOST 16130-85.

Depending on the purpose, cast iron rods for welding and surfacing are manufactured in the following grades: A - for hot gas welding (with general heating of the product); B - for gas welding with local heating and for electrode rods. To protect the molten metal from oxidation and remove oxides formed during gas welding, low-melting welding fluxes are used. Fluxes can be introduced into the welding bath in various ways: by pouring into the welding zone with a scoop; by preparing pastes and applying them to the edges of the welded parts and the filler material; by introducing them in powder and gas form directly into the welding flame through a torch.

Borax, boric acid, oxides and salts of barium, potassium, lithium, sodium, fluorine, etc. are used as fluxes. For example, when welding cast iron, powdered calcined borax ($\text{Na}_2\text{B}_4\text{O}_7$) or a mixture of it with other low-melting salts of alkali metals is most often used as a flux.

Borax, when decomposed in the welding zone, releases Na_2O and B_2O_3 , which interact with oxides, converting them into slag. When welding aluminum and its alloys, a flux of the AF-4a brand is used, containing 50% potassium chloride, 14% lithium chloride, 8% sodium fluoride and 28% sodium chloride. The flux is diluted with distilled water and applied to the edges to be welded and the filler rod in the form of a paste. When welding copper and its alloys, along with powdered fluxes based on borax, high quality is obtained when using flux BM-1, consisting of 25% methyl alcohol and 75% methyl borate, or flux BM-2, consisting only of methyl borate $\text{B}(\text{CH}_3\text{O})_3$. These fluxes are introduced into the welding bath in the form of a vapor together with acetylene using a special flux feeder, through which acetylene is passed before entering the burner. In the flame, the flux burns according to the reaction



Boric anhydride B_2O_3 is a fluxing agent.

Approximate gas consumption when welding with gas burners of different power is given in Table 4.

Table 4 – Gas consumption when welding steel with PC-53 and GSM-53 type torches

Tip number	Metal thickness, mm	Working oxygen pressure, kPa	Gas consumption, l/h	
			oxygen	acetylene
0	0.2...0.7	50...400	22...70	20...65
1	0.5...1.5	100...400	55...135	50...125
2	1...2.5	150...400	130...360	120...210
3	2.5...4	200...400	260...440	230...400
4	4...7	200...400	430...750	400...700
5	7...11	200...400	740...1200	670...1100
6	10...18	200...400	1150...1950	1050...1750
7	17...30	200...400	1900...3100	1700...2800

Welding technique. In practice, two welding methods are used - right and left (Fig. 33). With the right method, welding is carried out from left to right, the welding flame is directed to the welded section of the seam, and the filler wire is moved after the torch. Since with the right method the flame is directed to the weld, better protection of the weld pool from oxygen and nitrogen in the air, a large penetration depth, and slow cooling of the weld metal during the crystallization process are provided. The heat of the flame is dissipated less than with the left method, so the angle of development of the edges is not 90 °, but 60 ... 70 °, which reduces the amount of deposited metal and gouging. With the right method, productivity is 20 ... 25% higher, and gas consumption is 15 ... 20% lower than with the left method. The right method is advisable to use when welding metal with a thickness of more than 5 mm and metals with high thermal conductivity. With the left method, welding is carried out from right to left, the welding flame is directed to the still unwelded edges of the metal, and the filler wire is moved ahead of the flame. With the left method, the welder sees the welded metal well, so the appearance of the seam is better than with the right method; preheating the edges of the welded metal ensures good mixing of the weld pool. Due to these properties, the left method is the most common and is used for welding thin-sheet materials and low-melting metals.

The power of the welding torch for the right-hand method is selected at the rate of 120...150 dm³/h of acetylene, and for the left-hand method - 100...130 dm³/h per 1 mm of the thickness of the welded metal.

The diameter of the filler wire is selected depending on the thickness of the welded metal and the welding method. For the right-hand method of welding, the diameter of the filler wire is $d = S/2$ mm, but not more than 6 mm, for the left-hand method $d \leftrightarrow S/2 + 1$ mm, where S is the thickness of the welded metal, mm.

The heating rate is regulated by changing the angle of inclination α of the mouthpiece to the surface of the welded metal (Fig. 35, a). The thicker the metal and the greater its thermal conductivity, the greater the angle of inclination of the mouthpiece to the surface of the welded metal. During welding, the gas welder uses the end of the torch mouthpiece to simultaneously perform two movements: transverse (perpendicular to the seam axis) and longitudinal (along the seam axis, Fig. 35). The main one is the longitudinal movement. The transverse movement serves to evenly heat the edges of the base metal and obtain a seam of the required width.

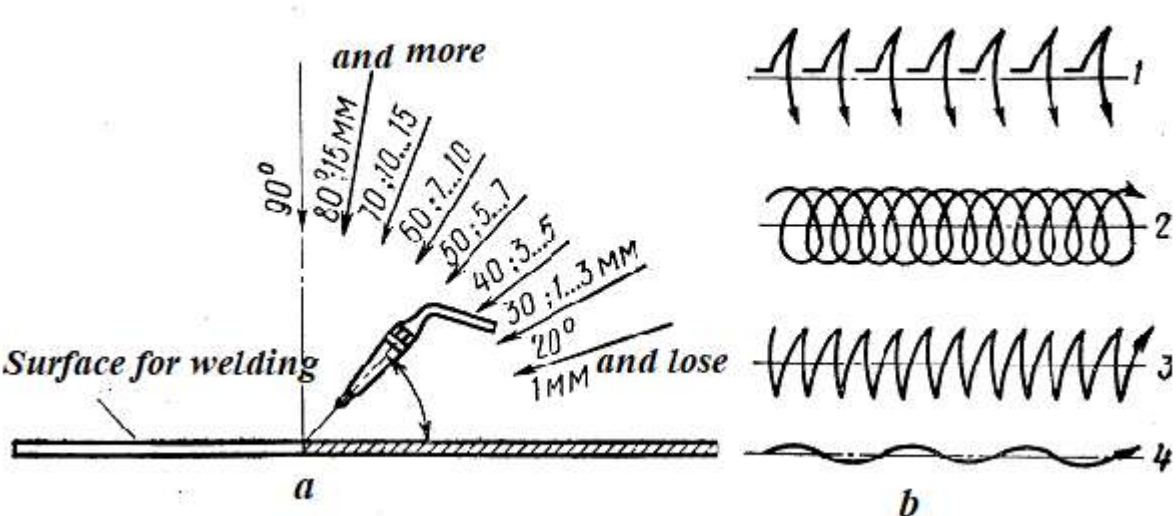


Figure 35 – Angles of inclination of the torch nozzle when welding different thicknesses (a) and methods of moving the torch nozzle (b):

- 1 – with torch separation; 2 – spiral; 3 – crescent; 4 – wave

Gas welding can be used to perform bottom, horizontal (on a vertical plane), vertical and ceiling seams. Horizontal and ceiling seams are usually performed using the right welding method, vertical seams from the bottom up using the left method.

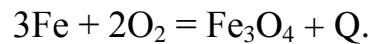
Oxygen-oxygen flame surfacing is rarely used due to the relatively large deformations of the surfacing parts. Oxygen-oxygen flame is used mainly for surfacing with cast hard alloys.

3.3 Oxygen cutting technology

Oxygen cutting is a method of metal separation based on the use of metal oxidation to heat it to the ignition temperature (heat of a gas flame) and exothermic (with heat release) reactions, and the kinetic energy of cutting oxygen to remove oxides.

According to the nature and direction of the oxygen jet, three main types of cutting are distinguished: cutting, in which through cuts are formed; surface, in which the surface layer of the metal is removed; oxygen spear, which consists in burning deep holes in the metal.

Fig. 36 shows a diagram of cutting. Metal 3 is heated at the initial point of the cut to the ignition temperature (in oxygen for steel up to 1000...1200 °C) by a heating acetylene-oxygen flame 2, then a jet of cutting oxygen 1 is directed, and the heated metal begins to burn with the release of a significant amount of heat according to the reaction



The heat Q from the combustion of iron, together with the heating flame, heats the layers lying below and spreads over the entire thickness of the metal. The smaller the thickness of the metal being cut, the greater the role of the heating flame (at a thickness of 5 mm - up to 80% of the total amount of heat released during cutting, at a thickness of more than 50 mm - only 10%). The oxides 5 that are formed, as well as the partially molten metal, are removed from the cutting zone 4 under the action of the kinetic energy of the oxygen jet. Continuous supply of heat and cutting oxygen ensures continuity of the processes.

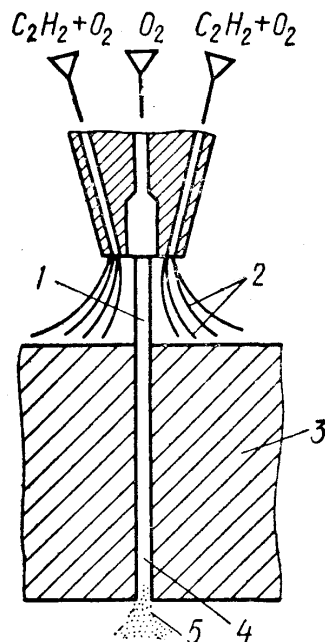


Figure 36 – Oxy-fuel cutting scheme

Cutting conditions and cuttability. To ensure a normal cutting process, the following conditions must be met.

1. The heat source must be of the required power to ensure heating of the metal to the required temperature of the metal combustion reaction, and the amount of heat released during the combustion of the metal in the oxygen jet must be sufficient to maintain a continuous cutting process (Tables 4, 5).

2. The melting point of the metal must be higher than the temperature of its oxidation (burning) in oxygen, otherwise the metal will melt when heated and be forcibly removed from the cut without oxidation characteristic of the cutting process, which is the main source of heat.

3. The melting point of the metal must be higher than the melting point of the oxides formed during the cutting process, otherwise refractory oxides will isolate the metal from contact with oxygen and complicate the cutting process.

4. The oxides and slags formed must be fluid and easily blown away by the cutting oxygen jet, otherwise the contact of oxygen with the liquid metal will be slowed down or completely impossible.

All of the above conditions are satisfied by carbon steel, so it can be cut with oxygen.

The first condition is not satisfied by copper in gas cutting due to its high thermal conductivity, which greatly complicates the start of the cutting process, and low heat release during oxidation. Therefore, the power of gas cutters is not enough to cut copper, and copper can be cut using a more powerful heat source - an electric arc.

The second and fourth conditions are not satisfied by cast iron. As the carbon content in iron increases, the cutting process deteriorates significantly due to a decrease in the melting point and an increase in the ignition temperature; cast iron containing more than 1,7% carbon cannot be processed by oxygen cutting. In addition, the viscosity of the slag increases significantly with increasing silicon content, which is necessarily contained in cast iron, which is also one of the reasons for the impossibility of oxygen cutting of cast iron.

The third condition is not satisfied when cutting aluminum, magnesium and their alloys, as well as steels with a high content of chromium and nickel. When these alloys are heated during cutting, a film of refractory oxide is formed on their surface, which prevents oxygen from reaching the unoxidized metal.

The main parameters of oxy-fuel cutting:

characteristics of the heating flame - power, combustible gas, ratio of the mixture of combustible gas and oxygen;

characteristics of the cutting oxygen jet - pressure, flow rate, shape, purity, cutting speed.

The heating flame during cutting has a neutral character

($\varepsilon = 1,1$ for acetylene, $\varepsilon = 3,5$ for a propane-butane mixture). The power of the heating flame increases with increasing thickness of the metal being cut.

The manual cutting modes of sheet metal are given in Table 5, and the machine cutting modes are given in Table 6.

Table 5 – Manual cutting modes for rolled sheet metal

Thickness of cut metal, mm	Mouthpiece number		Oxygen pressure, MPa	Approximate cutting speed, mm/min
	external	internal		
8...10	1	1	0,3	550...400
10...25	1	2	0,4	400...300
25...50	1	3	0,6	300...250
50...100	1	4	0,8	250...200
100...200	2	5	1,0	200... 130
200...300	2	5	1,2	130...80

Table 6 – Machine cutting modes for low carbon steel

Thickness of cut metal, mm	Cutting speed, mm/min	Cutting oxygen pressure, kg/cm ² (MPa)	Gas consumption, m ³ /h		Time for heating the metal to the ignition temperature, s
			Oxygen	Acetylene	
5	500...530	2,4(0,24)	0,4...0,3	0,25...0,3	10...12
10	400...450	2,6(0,26)	0,45...0,6	0,3...0,4	12...13
20	300...340	3,0(0,30)	0,45...0,6	0,3...0,4	14...15
30	260...290	3,7(0,37)	0,45...0,6	0,3...0,4	15...16
50	210...230	4,0(0,40)	0,5...0,6	0,35...0,4	16...18
80	170...190	5,0(0,50)	0,6...0,8	0,4...0,5	18...20
100	160...180	6,0(0,60)	0,6...0,8	0,4...0,5	20...25

Oxygen cutting quality. Cutting quality is characterized by the accuracy of the trajectory and the quality of the cut surface. The smallest deviations of the cut trajectory (line) from the specified one are obtained when cutting on

machines with software, photoelectric and electromagnetic control, the largest ones are obtained when cutting manually without guide devices. The magnitude of the deviations depends on the length, thickness, surface condition of the sheet, the shape of the cut workpiece, and the qualifications of the cutter.

The quality of the cut is characterized by the non-perpendicularity and roughness of its surface, the uniformity of the cut width, the presence of undercutting of the upper edge and burrs on the lower edge (Fig. 37, a).

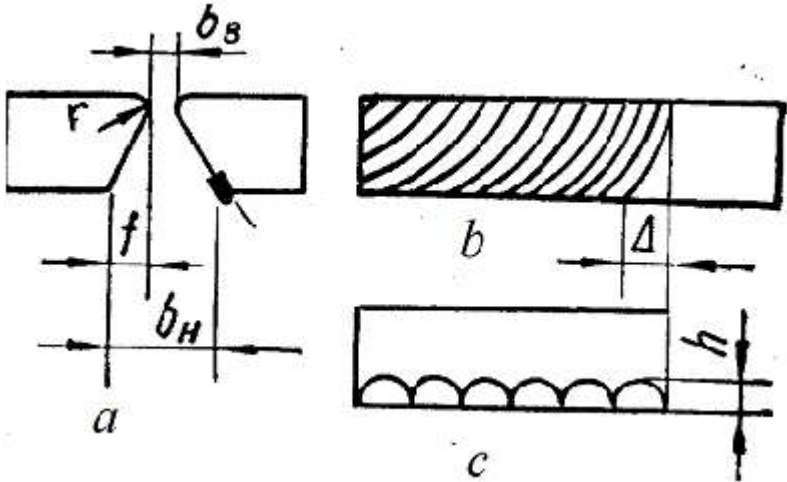


Figure 37 – Cut parameters:

- a – cross-section of the cut; b – view along the cut surface;
- c – top view along the cut; b_b – width of the cut at the top; b_H – width of the cut at the bottom; f – non-perpendicularity of the cut; h – depth of the grooves; Δ – lag; r – radius of melting of the upper edge

The non-perpendicularity of the cut surface is formed when the angle of inclination of the cutter to the sheet surface changes, as well as from the expansion of the cutting oxygen jet when it leaves the cut. The roughness of the cut surface is determined by the number and depth of the grooves left by the cutting oxygen jet (Fig. 37, c). The grooves usually have a curved outline due to the lag Δ from the axis of the cutting oxygen jet nozzle (Fig. 37, b). The greater the thickness of the metal, the lower the purity of the oxygen, the greater the lag, which is usually from 1 to 15 mm when cutting sheets with a thickness of 5 to 200 mm in a straight line. The depth of the grooves depends on the oxygen pressure, cutting speed, the uniformity of the cutter movement and the composition of the combustible gas. The amount of edge melting is directly dependent on the power of the heating flame and inversely dependent on the cutting speed.

To increase the productivity and quality of the cut, a number of varieties of oxy-fuel cutting are used.

High-speed oxy-fuel cutting is achieved by tilting the cutter by 45° to the side opposite to the direction of movement. The cutting speed of sheet steel with a thickness of 3...20 mm increases by 2...3 times, but the quality of the cut deteriorates.

High-quality high-speed oxy-fuel cutting (wash-out process) allows you to increase both the speed (by 1.5...2.5 times) and the quality of the cut. The first is achieved due to the sharp angle of the cutter - 25° , the second - by using special nozzles, which have three holes for cutting oxygen, located at the corners of an isosceles triangle. The main cutting jet moves in front, which cuts the metal through the entire thickness. Two other jets, located on the sides and behind the main one, "protect" the hot edges formed by the main jet. The disadvantage of the method with an acute angle is the impossibility of figured cuts and a large width of the cut.

Cutting with high-pressure oxygen up to 5 MPa provides an increase in the cutting speed of metal up to 50 mm thick by 30-50%.

Steel up to 300 mm thick is cut with conventional universal cutters. Welding of thick steels is associated with additional difficulties: the need to use high oxygen pressures, the difficulty of heating the lower layers of metal and removing slag at a considerable distance from the cutter. Therefore, thick steels (more than 300 mm) are cut with special cutters, the nozzles of which have increased cross-sections for cutting oxygen compared to universal cutters. A carburizing heating flame is used, because in this case it will be longer.

Oxy-flux cutting. For cutting chromium, chromium-nickel stainless steels, cast iron and non-ferrous metals that do not meet the conditions of oxygen cutting, the oxy-flux cutting method is used, the essence of which is that a special powdered flux is introduced into the cutting zone together with cutting oxygen, the combustion of which releases additional heat and increases the temperature in the cutting zone. In addition, the combustion products of the flux, interacting with refractory oxides, are easily removed from the cutting zone, without interfering with the normal course of the process. The main component of powder fluxes used in metal cutting is iron powder, which, when burned, releases a large amount of heat (about 180 kcal/kg). The best results when welding stainless steels are achieved by adding 10...15% aluminum powder to iron powder. For surface and cutting cutting of stainless steels, a mixture of aluminum-magnesium powder with ferrosilicon or silicate calcium is used as a flux. Aluminum-magnesium powder, which is part of the flux mixture, burning in a stream of oxygen, increases the flame temperature, and ferrosilicon or silicate calcium act on chromium oxides as a fluxing additive.

Table 7 – Composition of fluxes for oxy-flux cutting

Metal	Flux composition, %, by weight						
	iron powder	aluminum powder	aluminum-magnesium powder	Ferro-phosphorus	ferrosilicon	Silicocalcium	quartz sand
Cast iron	65...75			35...25			
	65...75	10...5	—	—	—		25...20
Stainless steel	100	—	—	—	—	—	—
	80...90	20... 10	—	—	—	—	—
	—	—	60...80	—	40...20	—	—
	—	—	25...30	—	—	75...70	—
Copper	70...80	30...20	—	—	—	—	—
Brass	70...80	10...5	—	—	—	—	20...15
Bronze	65...75	20...15	—	15...10	—	—	—

The main task of the flux when cutting cast iron is to dissolve the flux with iron in the cut area, reduce the carbon content in the alloy, and dilute the slag, which contains a lot of oxygen. The composition of fluxes for cutting cast iron includes iron and aluminum powders, quartz sand and ferrophosphorus.

Non-ferrous metals and alloys are subjected to oxy-flux cutting only with the use of fluxes. The composition of fluxes for oxy-flux cutting is given in Table. 7.

Installations for oxy-flux cutting consist of two main parts: a cutter (manual or machine) and a flux feeder, which provides supply and regulation of flux flow.

Surface oxy-cutting of metal. Surface oxy-cutting is the process of removing a metal layer with an oxygen jet. In this case, the oxygen jet is directed to the surface to be processed at an acute angle (15...40°), but unlike separate cutting, the direction of the jet coincides with the direction of cutting, and the metal placed in front of the cutter is heated by the heated slag (Fig. 38) that moves.

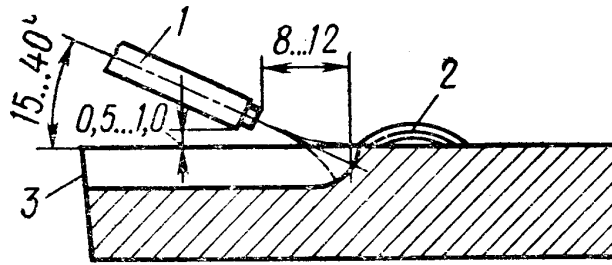


Figure 38 – Surface cutting scheme:
1 – nozzle; 2 – slag; 3 – groove

Cutting with an oxygen lance (Fig. 39) is performed with a thin-walled steel tube (lance) with an outer diameter of 20...35 mm. The tube is connected to a handle with an oxygen valve and oxygen is supplied through it to the cut site.

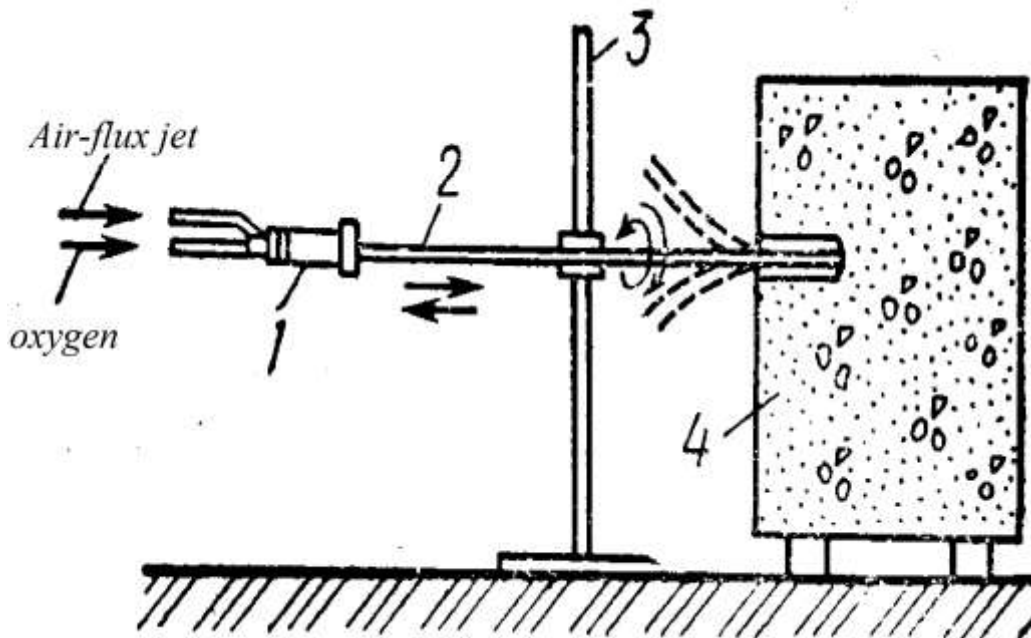


Figure 39 – Scheme of burning a hole in concrete with an oxygen spear:
1 – spear holder; 2 – spear; 3 – protective screen; 4 – concrete product

Before starting cutting, the end of the tube is heated with a gas burner or an electric arc to the ignition temperature. The hot end of the oxygen lance is pressed with a sufficiently large force against the product (metal, concrete, reinforced concrete) and thus burns out the hole.

The slag formed during the burning of the hole is carried out into the gap between the spear and the wall of the burning hole by the pressure of oxygen and gases. This process is facilitated by the reciprocating and rotational movements of the spear.

3.4 Arc and beam types of metal cutting

Intensive heating of metal by an electric arc is successfully used in technology not only for welding, but also for cutting metal (Fig. 40). The following methods of arc cutting have been used: manual arc with non-consumable and fusible covered electrodes used in welding; air-arc; oxygen-arc and compressed arc.

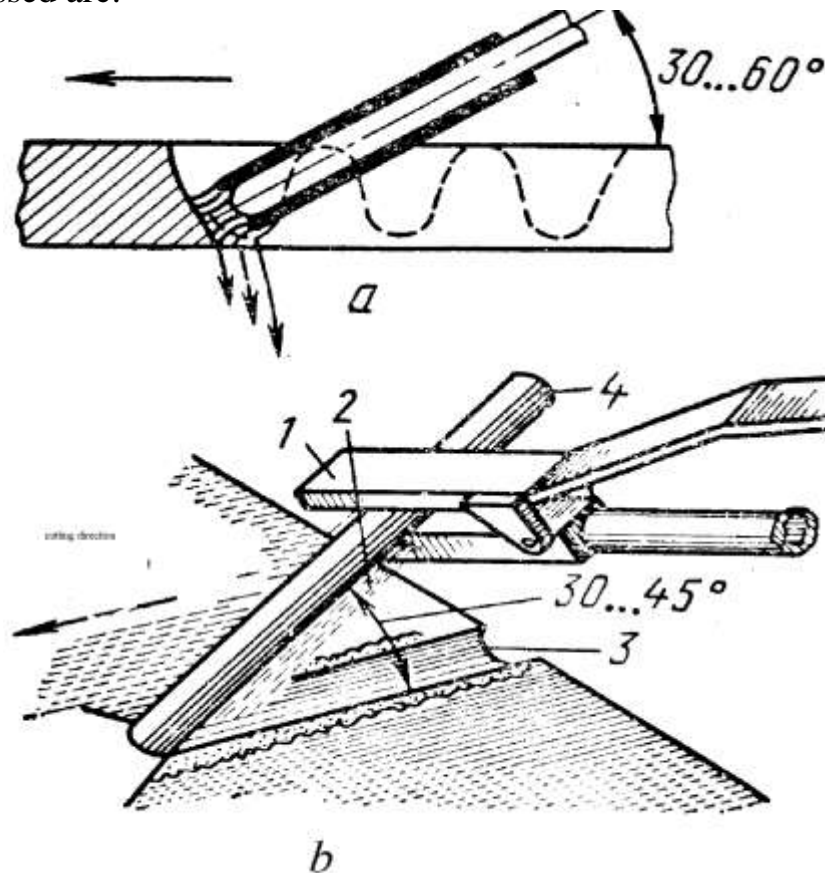


Figure 40 – Schemes of arc cutting of metal:

a – manual arc with a consumable electrode; b – air-arc; 1 – cutter; 2 – air jet; 3 – groove; 4 – electrode

Manual arc cutting with non-consumable and fusible electrodes is used as an auxiliary operation. In arc cutting with a non-consumable electrode, carbon and graphite electrodes are used. Cutting is ensured by melting the metal from the cut zone, and not by combustion in an oxygen jet, as in gas cutting. Due to the high heating temperature, it is possible to cut materials that are not amenable to oxygen cutting (cast iron, high-alloy steels, non-ferrous metals). Direct and alternating current of maximum power are used. This method is characterized by very low accuracy and cleanliness of the cut. When arc welding with a fusible electrode, the cut is obtained cleaner and narrower than when cutting with a non-consumable electrode. Cutting is performed by the resistance method. The electrode coating helps to increase the stability of the arc during cutting, slow down the melting of the electrode rod, isolate it from the walls of the cut, and

accelerate cutting due to the oxidation of the molten metal by the coating components.

The cutting current is 20...30% higher than welding. In air-arc cutting, the metal is melted by the temperature of the electric arc, and then blown out with compressed air from the cut zone. At the same time, a small part of the metal burns in the oxygen contained in the air. This method is used to remove defective areas for welding and separate cutting of stainless steel sheets up to 20 mm thick. Cutting is performed on a direct current (carbon, graphite) electrode using special cutters, usually with a side supply of compressed air under a pressure of 0.4...0.5 MPa.

Oxy-arc cutting consists in the fact that the metal to be cut is heated using an electric arc, and then burned by a jet of oxygen, which is supplied to the cut point parallel to the electrode. Oxides formed during the combustion of the metal are blown out of the cut point by this same jet of oxygen. Carbon and graphite electrodes are used, as well as special fusible tubular electrodes with oxygen supplied through an internal hole. The method is used to a limited extent.

Plasma jet cutting is based on melting the metal at the cut point and blowing it out with a plasma stream. The plasma jet is used to cut metal with a thickness ranging from particles to tens of millimeters. For cutting metal of small thickness, an intermediate-action plasma jet is used. With increased metal thickness, the best results are achieved with a direct-action plasma jet — a plasma arc (Fig. 41). Due to the high temperature and high kinetic energy of the plasma jet, all metals can be cut.

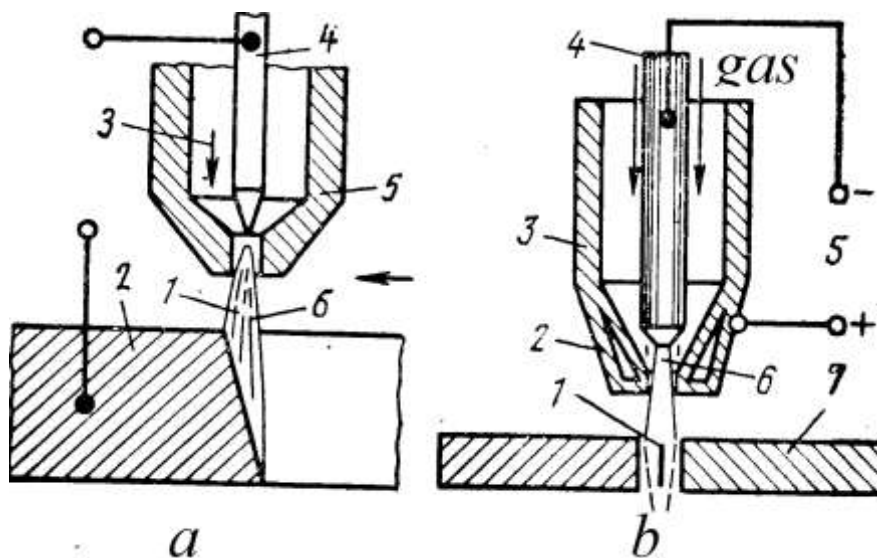


Figure 41 – Plasma arc cutting scheme:

- a – plasma arc: 1 – arc; 2 – cutting metal; 3 – gas; 4 – electrode;
 5 – cutter; 6 – plasma; b – plasma jet: 1 – plasma; 2 – nozzle; 3 – mouthpiece;
 4 – electrode; 5 – DC source; 6 – arc; 7 – cutting metal

Depending on the metal, nitrogen, hydrogen, argon-hydrogen, argon-nitrogen, nitrogen-hydrogen mixtures can be used as plasma-forming gases. The use of diatomic gases (H₂, N₂) for cutting is more energy efficient. The diatomic gas absorbs heat during dissociation in the plasma torch, which is transferred and released on the cut surface, where free atoms combine into molecules. When using electrodes with zirconium and hafnium alloys, air can be used as plasma-forming gases during cutting.

Aluminum and its alloys with a thickness of 5 to 20 mm are cut in nitrogen, with a thickness of 20 to 150 mm - in nitrogen-hydrogen mixtures (65...68% nitrogen, 35...38% hydrogen). Stainless steels with a thickness of up to 20 mm are cut using pure nitrogen, and with a thickness of 20 to 50 mm - a mixture of 50% nitrogen and 50% hydrogen. Compressed air is used as plasma-forming gases when cutting low-carbon steels with a thickness of up to 40...50 mm.

Table 8 – Approximate modes of plasma-arc machine cutting of stainless steels

Thickness of cut metal, mm	Nozzle diameter, mm	Current strength, A	Voltage, V	Power, W	Gas consumption, m ³ /h			Cutting speed, m/h
					argon	nitrogen	hydrogen	
10	3	300	150	45	—	1	—	180
20	5	500	75	38	—	1	—	160
30	1,4	100	165	17	0,7	—	0.5	—
40	5	350	120	42	—	1,6	—	18
50	4,5	490	80	40	0,9	—	—	14
75	4	500	85	43	—	1,5	—	10
100	7	700	145	100	0,4	—	—	17

When cutting copper and its alloys, a nitrogen-hydrogen mixture, nitrogen or atmospheric air are used as plasma-forming gases. Table 8 shows the modes of plasma-arc cutting of stainless steels. GOST 12221-79 establishes four types of equipment for plasma-arc cutting: PCR - for manual cutting, PLRM - for

manual and machine cutting, PLM - for machine cutting, PLMT - for machine precision cutting.

Laser beam cutting. High energy concentration allows the use of a laser beam for precision (accurate) cutting of metals and non-metals. The laser can cut glass, ceramics, diamonds and other materials. The essence of laser cutting is the local melting and evaporation of metal under the action of a focused beam. When cutting, as a rule, continuous lasers are used, which have high radiation energies in the infrared range. The main field of application of laser cutting is microelectronics.

3.5 Equipment and apparatus for gas welding and cutting

Acetylene generators. An acetylene generator is a device used to produce acetylene by decomposing calcium carbide with water.

Acetylene generators for welding and cutting are classified according to the following criteria:

by capacity - from 0,5 to 150 m³/h;

by pressure of produced acetylene - low pressure up to 10 kPa and medium pressure from 70 to 150 kPa;

by method of application - mobile with a capacity of 0,5 - 3 m³/h and stationary - 5 - 160 m³/h;

depending on the interaction of calcium carbide with water - generators of the KB system ("carbide in water"), in which the decomposition of calcium carbide occurs when a certain amount of calcium carbide is fed into the water in the reaction space, generators of the VK system ("water in carbide"), in which the decomposition of calcium carbide occurs when a certain amount of water is fed into the reaction space where calcium carbide is located; generators of the VV system ("water displacement"), in which the decomposition of calcium carbide occurs when it comes into contact with water depending on the change in the level of water in the reaction space and is displaced by the gas formed; combined generators. All acetylene generators, regardless of their system, have the following main parts: a gas generator, a gas collector, a safety valve, automatic regulation of the produced acetylene depending on its flow rate. Schemes of acetylene generators of different systems are shown in Fig. 42.

Safety valves are devices that protect acetylene generators and gas pipelines from the ingress of an explosive wave during backfire of a flame from a welding torch or cutter.

Backfire is the ignition of a combustible mixture in the channels of a torch or cutter and the spread of the flame along the combustible gas hose. The combustible mixture of gases during backfire is directed through the acetylene channel of the torch or cutter into the hose and, in the absence of a safety valve, into the acetylene generator, which can lead to an explosion of the acetylene generator. Backfire can occur when the rate of flow of the combustible mixture

becomes less than the rate of its combustion, and from overheating and clogging of the channel of the burner mouthpiece.

Safety valves are liquid and dry. Liquid valves are filled with water, dry ones are filled with a fine-pored cermet. Valves are classified by throughput – 0,8; 1,25; 2,0; 3,2 m³/h; by limiting pressure - low pressure, in which the limiting pressure of acetylene does not exceed 10 kPa, medium pressure - 70 and high pressure - 150 kPa.

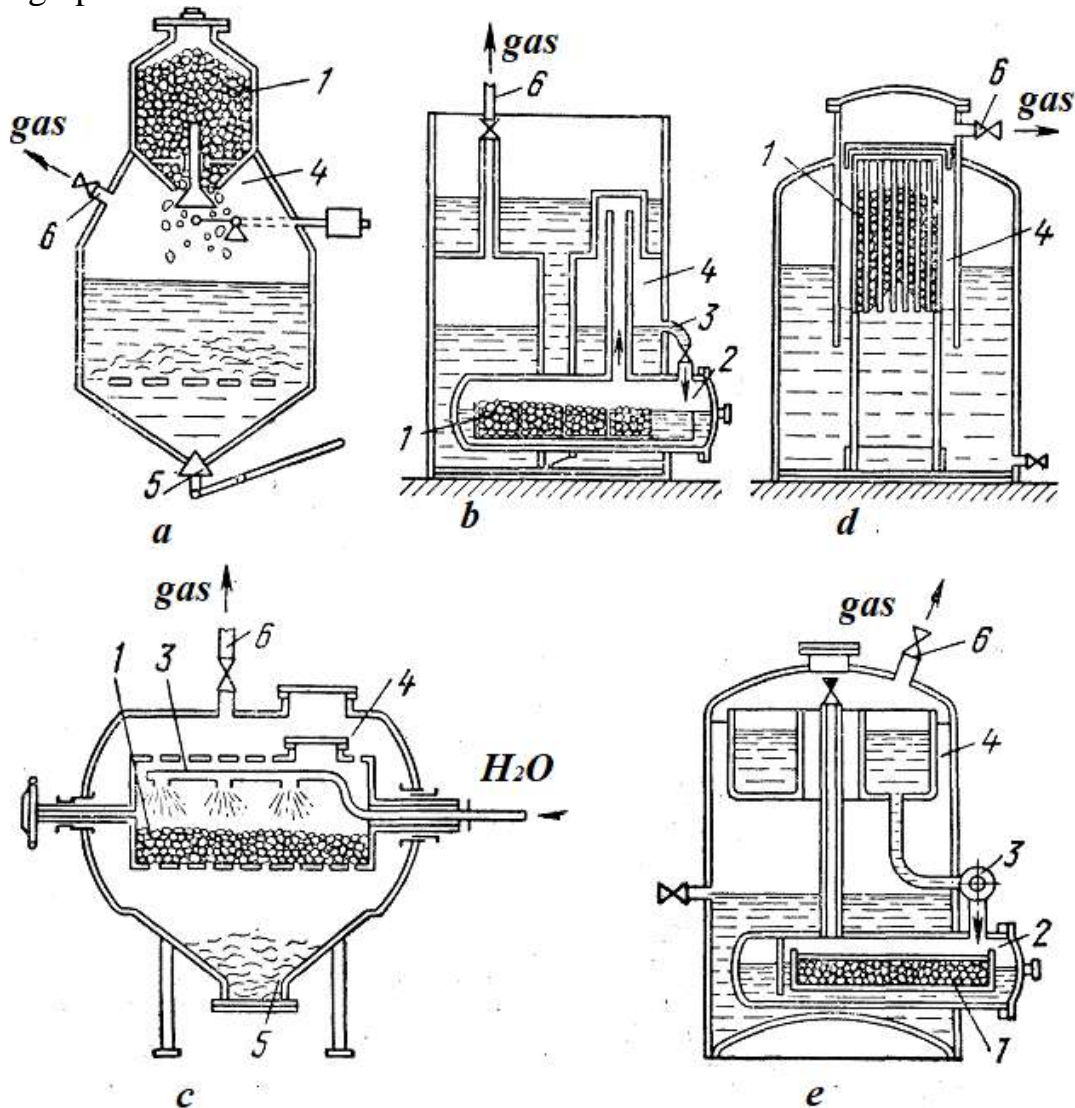


Figure 42 – Schemes of acetylene generators:
a – "carbide into water"; *b* – "water into carbide"; *c* – "dry decomposition";
d – "displacement"; *e* – combined system "water into carbide" and
 "displacement"; 1 – bunker or drum with calcium carbide; 2 – retort; 3 – water
 supply system; 4 – gas collector; 5 – sludge discharge;
 6 – gas sampling

Safety valves are installed between the acetylene generator or acetylene pipeline (with multi-station power supply) and the burner or cutter.

The principle of operation of the water valve is shown in Fig. 43. The valve body 3 is filled with water to the level of the control valve KK. Acetylene is supplied through the tube 1, passes through the check valve 2, located in the lower part of the body. The gas passes into the upper part of the body through the reflector 4. Acetylene is discharged to the place of consumption through the outlet valve. In the upper part of the body there is a tube closed by a membrane 5 made of aluminum foil. During a backlash, the membrane ruptures and the explosive mixture escapes. The explosion pressure is transmitted through the water 6 to the gas from the generator. After the explosive mixture is removed, the membrane is replaced.

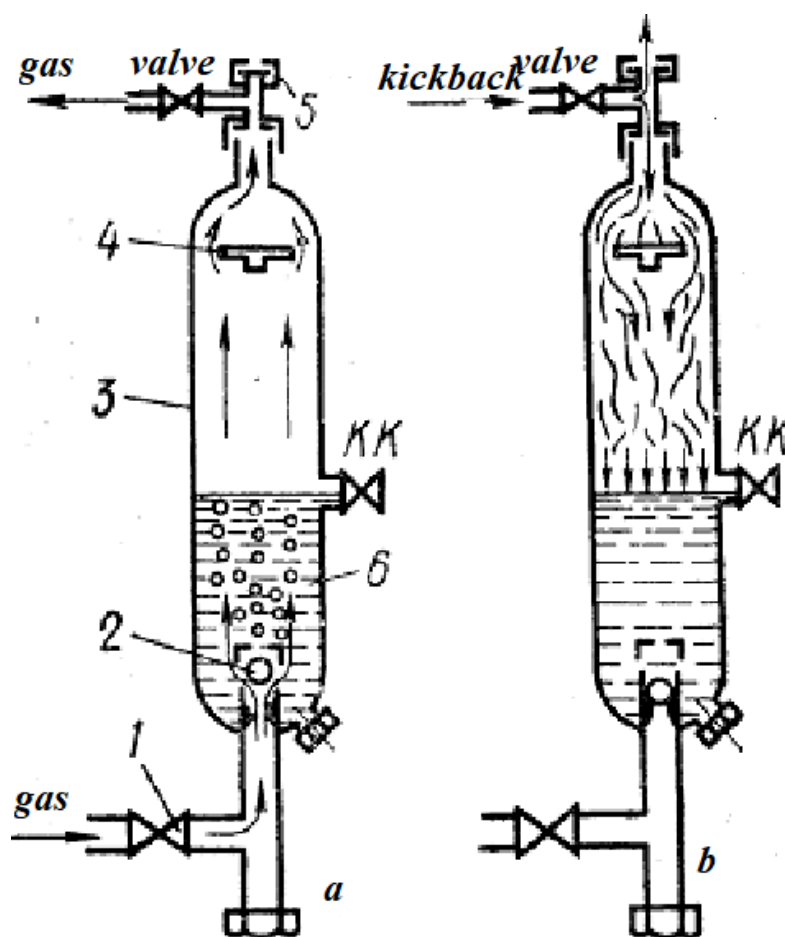


Figure 43 – Water valve diagram: a – during normal operation; b – during backlash

Cylinders for compressed gases. For storage and transportation of compressed, liquefied and dissolved gases under pressure, steel cylinders with a capacity of 0,4 to 55 dm³ are used.

Cylinders with a capacity of 40 dm³ are most often used in gas welding and cutting. Cylinders are steel cylindrical vessels, in the neck of which there is a conical hole with a thread, into which a shut-off valve of various designs for combustible gases and oxygen is screwed.

Each gas has its own conventional color of the cylinder and the color of the gas name, for example, oxygen cylinders are painted blue, the inscription is made in black paint; acetylene - in white and red paint, respectively; hydrogen - in dark green and red paint; propane - in red and white paint. Oxygen is filled into cylinders to a pressure of 15 MPa. A cylinder with a capacity of 40 dm³ at a gas pressure of 15 MPa contains 6 m³ of oxygen.

Powering gas welding and cutting stations from acetylene generators is associated with a number of inconveniences, so acetylene power from acetylene cylinders has become widespread. Acetylene cylinders are filled with a porous mass (charcoal, pumice, diatomaceous earth), which forms microcavities necessary for the safe storage of acetylene. The mass in the cylinder is impregnated with acetone (225...300 g per 1 dm³ of cylinder capacity), in which acetylene dissolves well. Under normal conditions, 23 volumes of acetylene dissolve in one volume of acetone. The pressure of dissolved acetylene in a filled cylinder should not exceed 1,9 MPa at 20 °C. To reduce acetone losses from the cylinder, acetylene should be withdrawn from the cylinder at a rate of no more than 1700 dm³/h.

Cylinders have valves - locking devices that allow compressed or liquefied gas to be stored in the cylinder. Each valve has a spindle that moves when the flywheel rotates, opening or closing the valve.

A gas plasma treatment reducer is a device for reducing the gas pressure in a cylinder or pipeline to the working pressure and automatically maintaining this pressure constant. It has a valve controlled by a flexible membrane, on which a spring force acts on one side and a gas pressure on the other. By adjusting the spring force, the set pressure and gas flow rate are ensured.

Reducers are classified according to the principle of action (direct and reverse), purpose and place of installation, according to the reduction schemes and the type of reduced gas.

Gas distribution ramps, pipelines, hoses. With a large flow rate of combustible gases, the supply is carried out from a gas distribution ramp consisting of two collectors, flexible connecting pipelines and a ramp reducer. Each collector has a shut-off valve that allows you to change cylinders on one of the collectors without disrupting the operation of the other. The gas pressure is reduced by a ramp reducer for oxygen, nitrogen and air from 1,5 to 0,03...0,15 MPa, and for acetylene, propane-butane and other combustible gases - from 1,9 to 0,01 MPa.

Oxygen gas distribution ramps are produced for 2x10 and 2x5 cylinders, acetylene - 2x6, 2x9, 2x12 cylinders. Along with stationary ones, mobile ramps are used.

Oxygen and combustible gases are supplied from gas distribution ramps to workplaces by pipelines. Acetylene pipelines are divided into three groups depending on the working pressure:

low pressure - up to 0,01 MPa inclusive;

medium - from 0,01 to 0,15 MPa;

high - above 0,15 MPa.

Oxygen pipelines are also divided into three groups depending on the working pressure:

low pressure - up to 1,6 MPa inclusive;

medium - from 1,6 to 6,4 MPa;

high - above 6,4 MPa.

Pipelines and fittings for acetylene are steel, painted white. Fittings for high-pressure oxygen pipelines are made of copper alloys (brass, bronze), specially designed for oxygen, painted blue.

Hoses are used to supply gas to the burner and cutter from cylinders and ramps. Hoses must be strong and flexible: they are made of vulcanized rubber and with fabric gaskets according to GOST 9356-75 of the following classes: I — for supplying acetylene and other combustible gases under pressure up to 0,63 MPa, red; II — for supplying liquid fuel (gasoline, etc.) under pressure up to 0,63 MPa, yellow; III — for supplying oxygen under pressure up to 2,0 MPa, blue.

Welding torch. The main tool of a gas welder is a welding torch, that is, a device that serves to mix combustible gas or vapor of a combustible liquid with oxygen and form a welding flame. Each torch allows you to adjust the power, composition and shape of the welding flame. Welding torches according to GOST 1077-79 are classified:

by the method of supplying combustible gas and oxygen to the mixing chamber—injector and non-injector; by the type of gas used; by purpose—universal and specialized; by the number of flames—single-flame and multi-flame; by power—low power (acetylene consumption 25...400 dm³/h), medium power (400...2800 dm³/h), high power (2800...7000 dm³/h); by the method of application—manual and machine.

The most widely used are injection burners that operate on a mixture of acetylene and oxygen. In injection burners, the combustible gas is sucked into the mixing chamber by a jet of oxygen, which is supplied to the burner at a higher pressure than the combustible gas. This sucking process is called injection. The diagram of the injection burner is shown in Fig. 44.

Oxygen under pressure enters the burner and through the connecting fitting 6 and the control valve 5 is supplied to the injector 4. Coming out at high speed from the narrow channel of the injector cone, oxygen creates a significant vacuum in the chamber 3 and sucks in the combustible gas, which enters through the acetylene channels of the burner to the chamber 3 of the mixer, where a combustible mixture is formed. Then the combustible mixture enters through the tip 2 to the mouthpiece 1, at the exit of which it forms a welding flame during combustion.

Burners of this type have interchangeable tips with different diameters of the injector and mouthpiece outlets, which allows you to adjust the power of the acetylene-oxygen flame.

In injector-free burners, combustible gas and oxygen are supplied at approximately the same pressure up to 100 kPa. In them, the injector is replaced by a simple mixing nozzle, which is screwed into the tube of the torch tip.

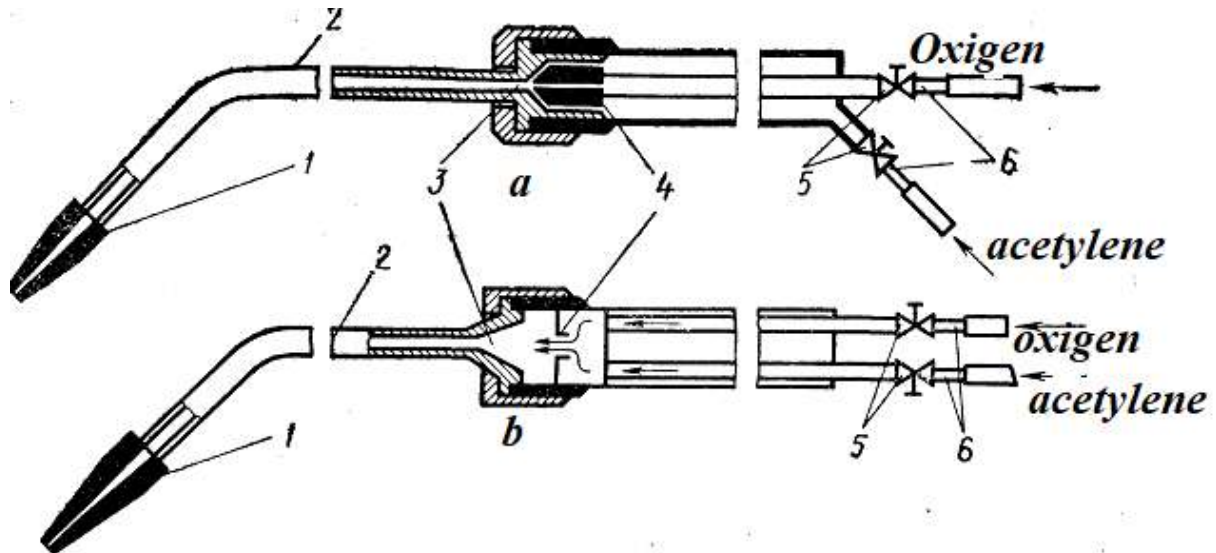


Figure 44 – Schemes of acetylene burners: *a* – injection; *b* – without injection

Gas cutting torches. Torches are used to mix combustible gas with oxygen to form a heating flame and supply a jet of cutting oxygen to the metal being cut.

Manual gas cutting torches are classified according to the following features:

- the type of combustible gas on which they operate - for acetylene, substitute gases, liquid fuel;

- the principle of mixing combustible gas and oxygen - into injector and injector-free;

- purpose - universal and special;

- type of cutting - for separate, surface, oxy-flux, spear.

Now widely used are injection cutters that allow cutting steel with a thickness of 3 to 500 mm. The cutter diagram is shown in Fig. 45. The cutter structurally combines the heating and cutting parts. The heating part is similar in structure to a welding torch. The cutting part consists of an additional tube 5 for supplying cutting oxygen and a valve 4 for regulating the supply. The mouthpiece 3 has two concentrically located holes for the exit of the heating flame 1 and the cutting jet 2. Gases are supplied to the mouthpiece and regulated using the appropriate valves. For gas flame processing of materials, along with universal ones, special burners and cutters are used for heat treatment, surface

cleaning, soldering, welding of thermoplastics, gas flame surfacing, cutters for surface, scribing, oxy-flux cutting, for cutting metal of large thicknesses, etc.

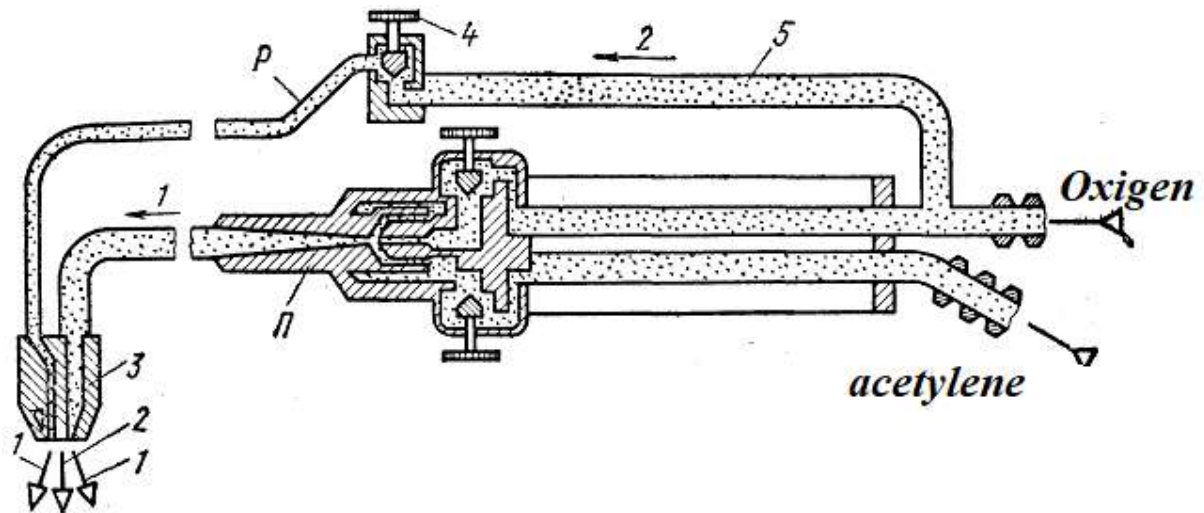


Figure 45 – Scheme of an oxygen-oxygen cutter: *P* - cutting part; *II* - heating part

Oxygen cutting machines. To increase productivity, cut quality and reduce heavy manual labor, machine cutting is used. Oxygen cutting machines are divided into two main types—stationary and portable. Stationary machines are divided:

- by design — into portal (*P*), which are located directly above the cut part; portal-console (*PC*), when only the console is located above the cut part; hinged (*W*);

- by cutting method - oxygen (*O*), oxygen-flux (*OF*), plasma-arc (*PA*) and gas-laser (*GL*);

- by the method of movement or contour control system - linear (*L*), for straight-line cutting, magnetic (*M*) on a steel copier for figured cutting, photocopying (*F*) according to a drawing for figured cutting, digital software (*C*) for figured cutting;

- by technological purpose - for cutting work, for precise straight-line and figured cutting of parts (*T*), universal - for straight-line and figured cutting of parts (*U*), for figured cutting of small-sized parts (*M*).

Portable machines are divided:

- by cutting method - oxygen (*O*), plasma-arc (*PA*);

- by the method of movement or contour control system - by marking (*P*), by compass (*C*), by guides (*N*), by flexible copier (*G*).

Each machine consists of a supporting part, a cutter (one or more), a control panel and a driving mechanism. In stationary machines, the main unit that automates the cutting process is the copying system. Such machines use the

principles of mechanical, electromagnetic, photoelectronic, remote-scale and program copying.

Portable machines are made in the form of a self-propelled cart moved by an electric motor, spring mechanism or gas turbine. The machine is installed on a sheet or pipe to be cut and guided by marking, a compass device, a guide or flexible copier.

The main working tool of an oxygen cutting machine is a machine gas cutter. The following main types of machine cutters are used: injection, equal pressure and internal nozzle mixing.

3.6 Occupational safety requirements for gas welding and cutting

The main sources of danger in gas welding and cutting are:

explosions of acetylene generators from backfires when the water seal does not work;

explosions of oxygen cylinders at the moment of their opening, if there is oil on the cylinder fitting or on the reducer valve;

danger of fire in the room, ignition of hair and clothing, burns of the welder if the torch is handled carelessly;

eye burns if welders do not use light filters;

poisoning by harmful gases that have accumulated when there is no exchange ventilation in the rooms.

Safe work in gas welding and cutting is possible only with proper handling of materials, equipment and apparatus in accordance with the "Rules of safety and industrial sanitation in the production of acetylene, oxygen and gas flame processing of metals". Workers at least 18 years of age who have undergone special training with a test of knowledge of safe work are allowed to perform gas welding and gas cutting work.

It is forbidden to work without a water seal or with a faulty water seal; it is impossible to connect several burners or cutters to one water seal.

It is necessary to strictly follow the rules for handling and maintaining acetylene generators in accordance with the operating instructions.

It is necessary to be careful when working with calcium carbide:

store it in dry, well-ventilated, fire-resistant rooms; at the place of work, store calcium carbide in undamaged drums with a tightly closed lid; open calcium carbide drums only with a special tool that prevents the possibility of sparks; drums must be protected from shocks and impacts.

Oxygen cylinders must be protected from shocks and impacts during transportation and storage. To ensure explosion safety, cylinders may be transported on spring-loaded vehicles, special hand trucks and stretchers, and in special containers. At workplaces, cylinders should be securely fixed in a vertical position at a considerable distance from heating devices, they should not

be exposed to sunlight. Joint storage of cylinders with combustible gases and oxygen is not allowed.

Operation of dirty, dented and scratched, untimely tested cylinders is not allowed. Particular attention should be paid to the absence of oil or dirt on the valve fitting of oxygen cylinders.

During gas flame processing, welders should work in overalls, gloves and safety glasses with G-1, G-2, G-3 glasses, and auxiliary workers - in glasses with B-1, B-2, B-3 glasses. With increasing flame power, glass with a higher number should be used, as the darkest.

When performing gas-flame work inside compartments, pits and tanks where accumulations of harmful gases are possible, portable supply and exhaust fans must be used. Only specially trained workers with appropriate certificates may be allowed to perform work with liquid fuels. The use of liquid fuels in slipway work and in closed rooms (boilers, tanks, etc.) is prohibited. The use of leaded gasoline and gasoline with a high octane number is unacceptable. When working with liquid fuel, only gasoline-oil-resistant hoses according to GOST 9356-75 with an internal diameter of 6 mm and a length of at least 5 m are allowed.

Control questions

1. Explain the structure and properties of a gas flame. What gases are used for gas flame processing?
2. Name the main parameters of the gas welding mode. What are the left and right welding methods?
3. What is the structure of a gas burner?
4. What is the essence of thermal cutting: oxy-fuel, arc, plasma, beam?
5. Name the conditions for cutting materials during gas cutting.
6. What is the structure of a gas-oxygen cutter?
7. How are the methods of obtaining acetylene classified? Explain the structure of an acetylene generator.
8. Name the main hazards during gas flame processing.

The flux protects the arc and the weld pool from the harmful effects of the environment, affects the metal of the weld pool and, in addition, prevents the splashing of liquid metal. Molten flux, having low thermal conductivity, slows down the cooling process of the weld, which makes it easier for slag inclusions and gases dissolved in the metal to rise to the surface of the bath, helping to clean the weld metal from contamination. Excess flux not melted during the welding process is sucked off from the weld with a pneumatic device and then used in the next welding.

The melted and hardened part of the flux forms a thick slag crust on the weld. After stopping welding and cooling the metal, the slag crust is easily separated from the weld metal. Welding is usually carried out on a substrate or a flux pad.

The advantages of submerged arc welding are:

high productivity due to the use of high currents, large penetration depth, as well as almost complete absence of metal losses due to burnout and spatter;

mechanization of the welding process;

high quality of welds due to good protection of the weld pool from air by the flux;

improvement of working conditions for welders.

The disadvantages of submerged arc welding are the possibility of welding only in the lower position (tilt up to 15°), difficulty of use in installation conditions, on short seams.

Table 9 – Strength and current density in the electrode during manual arc welding and submerged arc welding

Diameter of electrode rod or wire, mm	Manual arc welding		Automatic submerged arc welding	
	Current strength, A	Current density, A/mm ²	Current strength, A	Current density, A/mm ²
5	190...350	10...18	700...1000	35...50
4	125...200	10...16	500...800	40...63
3	80...130	11...18	350...600	50...85
2	50...65	16...20	200...400	63...125

When submerged arc welding, the process productivity in machine time increases by 6...12 times compared to manual arc welding. When welding in special, so-called forced modes, which are used in the manufacture of large-diameter pipes and wide-slab I-beams, the productivity increases by 15...20 times. An increase in productivity in automatic submerged arc welding is

achieved by using high currents and increasing the current density in the electrode (Table 9). A sharp increase in the absolute value of the current and its density in the electrode is possible due to the presence of a dense layer of flux around the welding zone; this prevents the liquid weld metal from blowing out of the weld pool and reduces losses due to scrap and spatter to 1...3%. An increase in current allows you to weld metal of considerable thickness without cleaning the edges on one or two sides and increase the amount of metal deposited per unit time. The deposition rate during submerged arc welding is 14... 18 g/(A·h) and more compared to 8... 12 g/(A·h) when welding with covered electrodes.

During submerged arc welding, high and stable quality of welds is ensured. This is achieved due to reliable protection of the weld metal from the action of oxygen and nitrogen in the air, uniformity of the weld metal in chemical composition, improvement of the weld shape and preservation of the constancy of its dimensions. At the same time, a lower probability of formation of non-welds, undercuts and other defects in the formation of the weld and the absence of interruptions in the welding process caused by changing electrodes is ensured.

Automatic and mechanized submerged arc welding is used in factory and assembly conditions for welding in the lower position of metal with a thickness of 2...100 mm. Steels of various compositions, copper, titanium, aluminum and alloys based on them are welded.

When welding aluminum, flux welding is used due to the fact that fluxes for aluminum have greater electrical conductivity. Currently, methods of welding aluminum and submerged arc welding have been developed.

Flux welding is automatic arc welding, in which a layer of flux is applied to the edges to be welded, the thickness of which is less than the arc gap. This is semi-open arc welding, which is characterized by such a flux dosage that the resulting layer, without completely covering the arc, creates sufficient protection and high stability of the arc process.

The main type of submerged arc welding is single-arc welding. To increase the productivity of the process and improve the quality of welded joints, submerged arc welding is used with an additional dosed additive in the form of granulated powder, pellets, chopped wire, which are fed into the welding zone by pre-filling into the gap, feeding into the tail part of the bath, directly together with the electrode into the melting space (Fig. 47).

To increase the melting speed of the electrode, submerged arc welding with an increased electrode extension can be used. In this case, preheating of the electrode by welding current in the extension area and its faster melting are achieved.

The productivity of the process and the quality of the welded joint can be increased by multi-arc automatic submerged arc welding with two or more electrodes. This method is mainly used in mass production of the same type of

parts (pipes, beams, tanks). There are multi-electrode and multi-arc welding. In multi-electrode welding, all electrodes are connected to one pole of the power source. In multi-arc welding, each of the electrodes is connected to a separate power source and they are electrically isolated from each other.

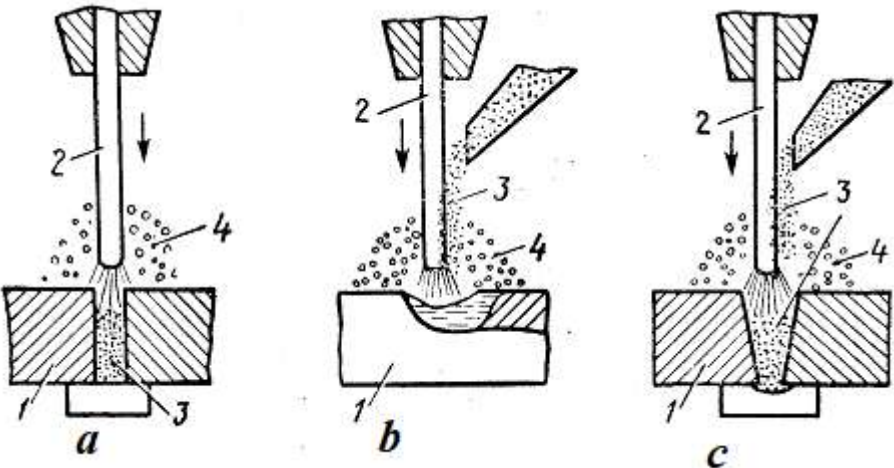


Figure 47 – Welding schemes with additional filler metal:

a – filling the gap with filler metal; b – feeding filler metal to the electrode; c – combined feeding filler metal; 1 – product; 2 – electrode; 3 – additional filler metal; 4 – flux

There are two types of multi-arc welding: welding in a common bath, when the metal melted by all arcs forms a single bath (Fig. 48), and welding in separate baths, when each arc forms its own bath and the next arc melts the layer that has already crystallized, welded by the previous arc. This method is also called welding with spread arcs. Multi-electrode welding is carried out in a common bath.

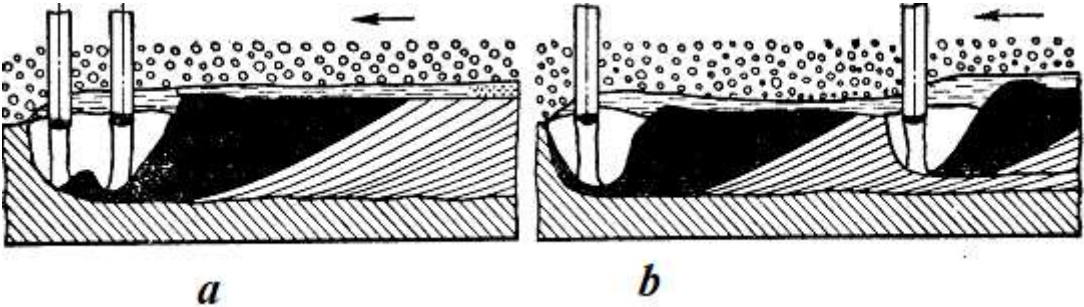


Figure 48 – Submerged arc welding with two arcs (the arrow shows the welding direction):

a – into a common bath; b – into separate baths

The following types of welding in a common bath are used in industry: welding with a paired electrode with a longitudinal and transverse arrangement of electrodes (Fig. 49).

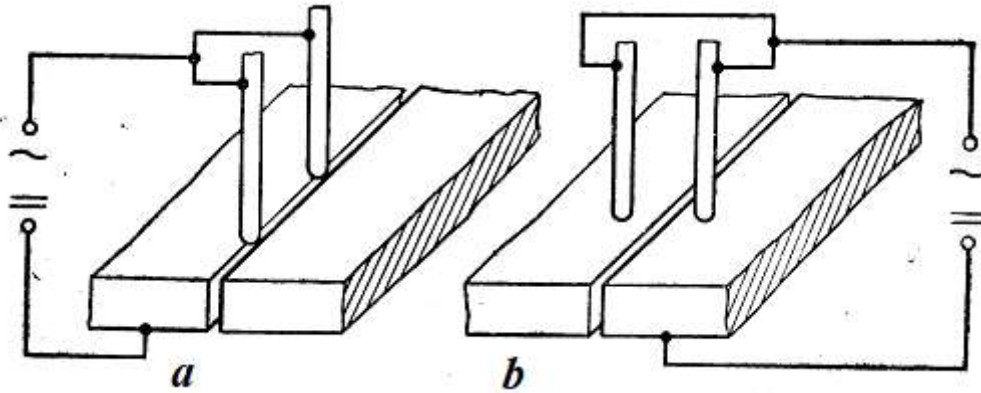


Figure 49 – Double electrode welding:

a – longitudinal arrangement of electrodes; *b* – transverse arrangement of electrodes

In this case, productivity is increased by increasing the amount of electrode metal introduced into the weld pool per unit of time. The paired electrode is used in gap welding, in double-sided welding of butt joints for penetration depth from the first layer, in welding of multilayer joints and surfacing works;

three-phase arc welding (Fig. 18, c), in which the deposition rate increases. This method is used for surfacing work, welding of multilayer seams and fillet welds of large cross-section;

arc or multi-arc welding at high speeds, in which two inclined electrodes or vertical and inclined electrodes are used (Fig. 50). Instead of one vertical electrode, a double electrode is also used. With such schemes, it is possible to increase the depth of penetration of the base metal and improve the formation of the seam, which allows significantly increasing the welding speed and its productivity. The speed when welding fillet welds reaches 90 m/h and higher, and when welding butt welds - 300 m/h.

When welding in separate baths, the electrodes are placed according to the scheme (Fig. 50, a). Welding with the second arc is carried out on the liquid slag from the first arc. The minimum distance between the arcs is determined by the length of the weld pool of the first arc, and the maximum distance is determined by the length of the slag pool. Along with increasing the productivity of welding with spread arcs, it allows significantly increasing the plastic properties of the welded joint and resistance to cold and hot cracks by reducing the cooling rate of the weld metal and the surrounding area, reducing the proportion of the base metal in the formation of the weld and remelting by the second arc of the metal layer formed by the action of the first arc.

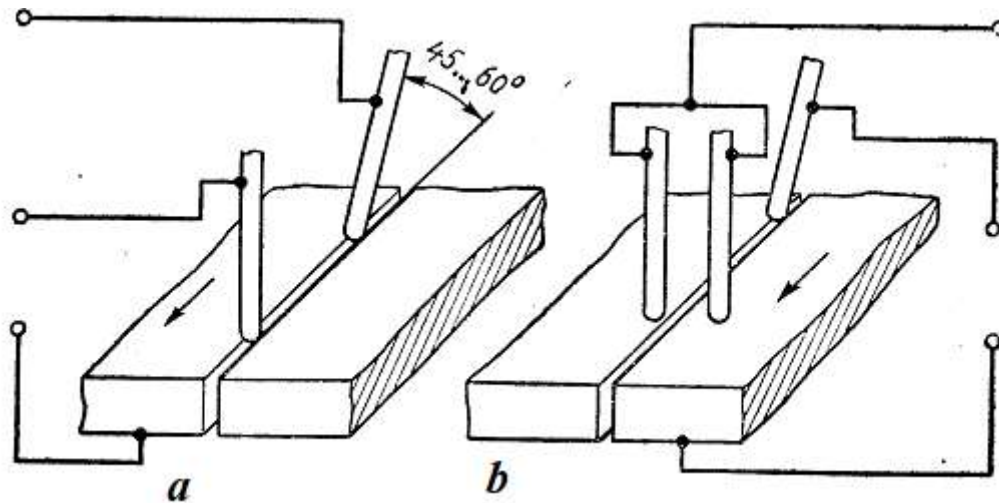


Figure 50 – Placement of electrodes when welding at high speeds: *a* – vertical and inclined electrodes; *b* – double vertical and inclined electrodes

4.2 Welding fluxes and wires

A welding flux is a non-metallic material, the melt of which is needed for welding and improving the quality of the weld.

According to the method of manufacture, fluxes are divided into fusible and non-fusible. Fusible flux is obtained by fusing its components. The fused mass is crushed into grains of the desired size after cooling. Non-fusible fluxes are a mechanical mixture of powdered and granular materials. These include ceramic fluxes for arc welding, which are obtained by mixing powdered materials with a binder.

The advantage of fusible fluxes over ceramic ones is their higher technological properties (protection, forming, separation of slag crust, etc.) and lower cost. The advantage of ceramic fluxes is the ability to widely alloy the weld metal through the flux. Currently, our industry mainly uses fusible fluxes.

Fusible fluxes are distinguished by the content of oxides of various elements in them. According to the content of silicon oxide SiO_2 , fluxes are divided into high-silica (up to 40...45% SiO_2), low-silica (up to 0.5% SiO_2) and silica-free. According to the content of manganese oxide MnO - into high-manganese (containing more than 30% MnO), medium-manganese (containing MnO within 15...30%) and low-manganese.

Low-silica fluxes are usually used for welding alloyed steels. For welding low-carbon steel, low-carbon welding wire is mainly used in combination with high-silica flux.

An example of modern high-silica manganese fluxes can be OSC-45 and AN-348A fluxes, the charge of which consists of manganese ore (MnO), quartz sand (SiO_2) and fluorspar (calcium fluoride CaF_2).

According to the grain structure, fluxes are divided into vitreous (dense) with a density of 1,3...1,8 kg/dm^3 and pumiceous (porous). Depending on the

diameter of the welding wire, flux of the same composition is used with grains of different sizes. For welding with a wire with a diameter of less than 3 mm, a vitreous fine-grained flux with a grain size of less than 0,25...1,0 mm is used, and for welding with a wire with a diameter of 3 mm and more - with a grain size of 0,35...3,0 mm (in diameter).

By purpose, fluxes are distinguished for welding low-carbon, alloyed, special steels and non-ferrous metals. Manganese high-silicon fluxes are used for welding carbon and low-alloyed steels with the appropriate welding wires;

low-silica fluxes with a high content of CaO, MgO and CaF₂, the slags of which are weakly acidic, - for welding high-alloy steels with a high content of easily oxidized elements such as Cr, Mo, Ti, Al, etc., silica-free fluxes based on CaO, CaF₂, Al₂O₃ compounds and oxygen-free fluoride fluxes consisting of 60...70% CaF₂ are used. The slags of these fluxes are basic or neutral in nature. Fluxes have been developed for non-ferrous metals and alloys taking into account chemical properties and weldability. For example, when welding Ti, fluxes of the CaF₂-BaCl₂-NaFe system are used, which do not contain oxygen compounds to prevent oxidation of titanium.

The same fluxes are used for automatic and semi-automatic submerged arc welding as for welding. The most common fusible fluxes are AN-348A, OSC-45, AN-20, AN-60, 48-OF-6, AN-26, AN-15M, AN-8, AN-25 in combination with alloyed wires.

Since the chemical composition of the weld metal is closely related to the chemical activity of the flux and the composition of the welding wire, the flux for welding different grades of carbon and low-alloy steel is selected simultaneously, that is, the flux-wire system is selected, based on the fact that the weld metal contains at least 0,2...0,4% Si and Mn to prevent the formation of pores. Three main systems are used:

1. Low-carbon wire (Sv-08, Sv-08A, etc.) and high-manganese (35...45% MnO), high-silica (40...45% SiO₂) flux. The alloying of the seam with silicon and manganese occurs due to the flux.

2. Low-carbon wire, alloyed up to 2% Mn (type Sv-10G2), and high-silica (40...42% SiO₂) flux, which contains no more than 15% MnO. In this case, the alloying of the seam with manganese occurs due to the wire, and with silicon - due to the flux.

3. Medium-manganese electrode wire (~1% Mn) and medium-manganese (~30% MnO) siliceous flux. The alloying of the seam with manganese occurs due to the wire and flux, with silicon - due to the flux.

The welding wire of a solid cross-section, which is used in submerged arc welding, is the same as in the manufacture of coated electrodes (see section 2.2). It is possible to use activated and cored wires.

4.3 Submerged arc welding technology

The main parameters of the submerged arc welding mode are the current value, its type and polarity, arc voltage, welding speed, diameter and feed rate of the electrode wire. Additional parameters of the mode are the electrode protrusion, the inclination of the electrode and the product, the flux brand, edge preparation and the type of welded joint.

The parameters of the welding mode are selected based on the thickness of the welded metal, the required shape of the weld seam, which is determined by the penetration depth and the width of the seam.

The welding mode is determined by experimental tables or approximately by simple calculation, when welding without stripping - by the penetration depth, when welding with stripping - by the amount of deposited metal.

The procedure for selecting the welding mode is as follows: depending on the thickness of the welded metal, the diameter of the electrode wire is selected, then depending on the diameter, the welding current is set, then the electrode wire feed rate and welding speed are set.

Automatic submerged arc welding is performed with a welding wire of solid cross-section with a diameter of 1...6 mm at a current strength of 150...2000 A and an arc voltage of 22...55 V, semi-automatic - with a welding wire with a diameter of 0.8...2 mm at a current strength of 100...500 A and an arc voltage of 22...38 V.

Example modes of automatic submerged arc welding of low-carbon steel are given in Table. 10.

The effect of changing the parameters of the welding mode on the penetration depth and the width of the seam is as follows. An increase in current due to an increase in thermal power and arc pressure increases the penetration depth, but has little effect on the width of the seam. With an increase in the arc voltage (arc length), their mobility increases and the proportion of the arc heat spent on melting the flux increases. At the same time, the width of the seam increases, and the penetration depth remains practically constant. This mode parameter is widely used in practice to adjust the seam width. Increasing the electrode diameter at a constant current leads to a decrease in the penetration depth and an increase in the seam width due to arc wandering.

Table 10 – Typical automatic submerged arc welding modes of butt joints on a flux pad without edge cleaning

Metal thickness, mm	Metal thickness, mm	Seam type	Wire diameter, mm	I_{zv}, A	U_{ϕ}, V		Welding speed, m/h
					alternating current	reverse polarity direct current	
3	0...1,5	Unilateral	2	275...300	28...30	26...28	48...50
5	0...2	The same	2	400...425	28...30	26...28	38...40
8	2...4	»	4	575...625	28...30	26...28	48...50
8	2...4	»	5	675...725	32...36	26...28	30...32
8	2...4	Bilateral	4	650...700	34...38	30...32	35...37
8	2...4	The same	5	625...675	34...38	30...34	35...37
10	2...4	Unilateral	5	700...750	34...38	30...32	28...30
10	1...3	Bilateral	5	650...670	34...38	30...32	32...34
10	1...3	The same	4	625...675	34...38	30...32	32...34
12	4...5	Unilateral	5	750...800	36...40	30...34	25...27
12	2...4	Bilateral	5	675...725	36...40	30...34	30...32
12	2...4	The same	4	650...700	36...40	30...34	30...32
14	4...6	Unilateral	5	850...900	36...40	30...34	25...27
14	2...4	Bilateral	5	700...750	36...40	30...34	28...30
14	2...4	The same	4	675...725	36...40	30...34	28...30
16	5...7	Unilateral	5	900...950	38...42	30...34	20...22
16	2...4	Bilateral	5	725...775	36...40	30...34	27...29
16	2...4	The same	4	700...750	36...40	30...34	27...29
20	5...7	Unilateral	5	950... 1000	40...44	32...36	18...20
20	2...4	Bilateral	5	775...825	38...42	32...26	22...24
20	2...4	The same	4	750...800	38...42	32...36	22...24
30	6...8	»	5	950...1000	40...44	—	16...18
40	8...10	»	5	1100...1200	40...44	—	12...14
50	10...12	»	5	1200...1300	44...48	—	10...12

The type and polarity of the current also significantly affect the shape and dimensions of the weld, which is explained by the different amount of heat released at the cathode and anode of the arc. When welding with direct current of direct polarity, the penetration depth is 40...50%, and with alternating current, it is 15...20% less than when welding with direct current of reverse polarity. Therefore, welds that require a small amount of metal and a large penetration depth (butt and fillet welds without edge cleaning) should be performed with direct current of reverse polarity. An increase in the welding speed leads to a decrease in the main dimensions of the weld.

With an increase in the electrode extension, the intensity of its heating and the melting speed increase. As a result, the thickness of the layer of molten metal under the arc increases and, as a result, the penetration depth decreases. This effect is sometimes used to increase the productivity of surfacing and filling seams.

In some cases, especially with automatic surfacing, the electrode is subjected to oscillations across the seam with different amplitudes and frequencies, which allows you to change the shape and dimensions of the seam within wide limits. When welding with transverse oscillations of the electrode, the penetration depth and the height of the reinforcement decrease, and the seam width increases. This method is convenient for preventing burns when welding butt joints with an increased gap or reduced blunting of the edges. The same effect can be obtained when welding with a paired electrode, when the electrodes are placed across the welding direction. When they are placed sequentially, the penetration depth, on the contrary, increases.

The inclination of the electrode and the product has a certain effect on the dimensions of the seam. When welding with a forward angle, due to the flow of metal into the welding zone, the penetration depth decreases and the seam width increases. When welding with a backward angle, due to the extrusion of molten metal by the pressure of the arc into the tail part of the pool, the penetration depth increases, the seam width decreases. Accordingly, when welding with a downward angle, the penetration depth decreases, the seam width increases, and when welding with an upward angle, the relationship is the opposite.

The technique of automatic submerged arc welding depends on the thickness of the metal and the type of connection. Metal of increased thickness is welded with multi-pass seams with the necessary displacement of the electrode from the seam axis. To ensure the quality of the end sections of the seam, welding begins at the input and ends at the output strips up to 150 mm wide and up to 250 mm long, which are fixed on the tacks before the start of welding, after welding the strips are removed.

When automatically welding butt joints "on the scale" it is difficult to obtain a seam with penetration along the entire length due to the leakage into the gap between the edges of the molten metal and flux with the formation of burns. To prevent this, various techniques are used that contribute to the formation of

the seam root. To maintain the weld pool, the following technological techniques are used: welding on a flux pad, copper-flux backing, temporary steel backings and those that remain, manual welding of the root of the weld, welding "on a scale" with a gap of less than 1 mm (Fig.51).

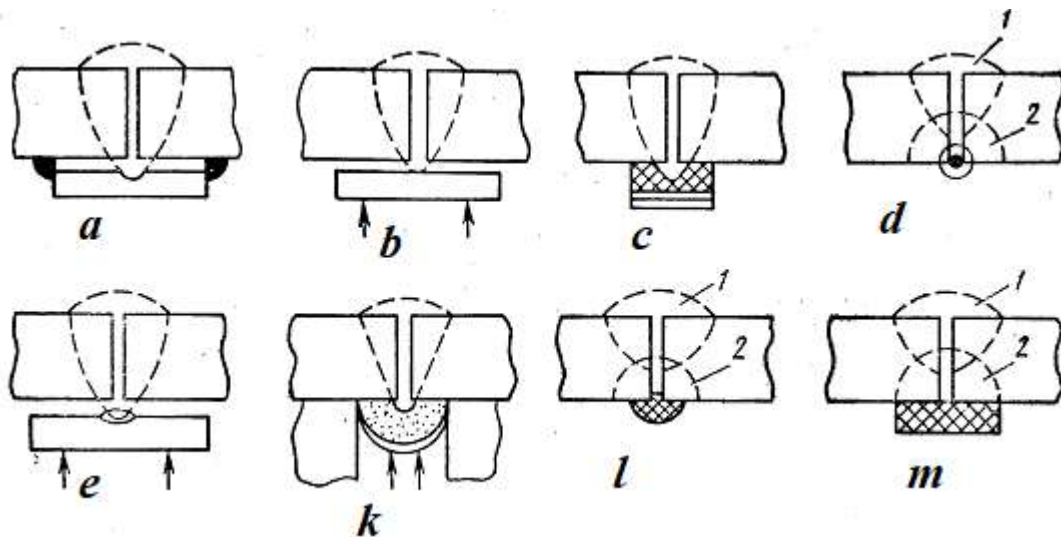


Figure 51 – Schemes of devices for holding the weld pool and slag and forming a return roller during submerged arc welding:

a – remaining backing; *b* – temporary backing; *c* – flexible tape; *d* – manual welding; *e* – copper-flux backing; *k* – flux cushion; *l* – packing the gap with fire-resistant material; *m* – asbestos backing; *a-c, d, e* – one-sided seam; *k, l, m* – two-sided seam; 1 – first seam; 2 – second seam

Welding of one-sided seams can be performed with preliminary manual or automatic welding. One-sided welding on the remaining steel substrate is used when it is allowed by operating conditions. For single-layer seams, the thickness of the substrate is 30...40% of the metal thickness, for multi-layer seams - equal to the thickness of the first layer. When using removable copper substrates for welding, the quality of the seam depends on the reliability of pressing the edges to them. With gaps above 0,5 mm, molten metal can flow out of it, which leads to the formation of defects in the seam. At the same time, it is difficult to lay the edges of a long joint along the forming groove of a fixed copper substrate.

To improve the formation of the root of the seam, flux can be poured into the deepened forming groove in the copper substrate - this is how welding is performed on a copper-flux substrate. One-sided welding on a flux pad with tight flux pressure ensures complete penetration of the edges and good formation of the root of the seam with less accuracy of folding edges with a thickness of 2 mm and above. The flux under the joint is pressed with air supplied to the hose, and when welding annular seams - with a special flexible tape. The welded sheets must be held from skewing when pressing the flux with special clamps, weights or magnets on special magnetic stands. Substrates made

of heat-resistant synthetic and ceramic disposable tapes are beginning to be used.

In one-sided seams, good formation of the root of the seam is not always ensured. Therefore, welding from both sides is used in critical structures. In this case, the first rollers at the root of the seams should overlap each other by 2...5 mm. To prevent the molten metal from flowing into the gap between the edges, the best results are obtained with preliminary manual underwelding, which often serves as a gripping seam during assembly. After the product is canted, the underwelding seam must be completely overwelded during the first main pass.

The main position when welding corner seams is “in a boat” (symmetrical and asymmetric, Fig. 31). This position provides technological convenience, good formation and high quality of the seam, but requires additional measures to keep the weld pool from leaking (underwelding, asbestos and copper-flux linings) or a gap of less than 1,5 mm. “In a corner” welding is performed with an inclined electrode. With this method, it is difficult to maintain the direction of movement of the electrode, especially with multi-pass welding. The maximum leg of the seam in one pass is 8 mm, but this method imposes lower requirements on the quality of assembly, a gap of up to 3 mm is allowed.

When welding T-joints with an inclined electrode, it is difficult to avoid undercutting on the vertical wall of the joint. To prevent this, the electrode is shifted to the wall. Lap joints with a thickness of the upper sheet up to 8 mm are welded with a vertical electrode with melting of the upper edge.

Automatic submerged arc welding is widely used both for restoration surfacing and for surfacing to obtain surfaces with special properties (wear-resistant, corrosion-resistant, etc.).

The surfacing technique when using electrode wire involves the application of filament rolls with an overlap of the previous roll by 1/3 of its width or rolls with transverse oscillations of the electrode. Welding can also be carried out with thread rollers at some distance from each other; after removing slag from all rollers, the rollers are welded in the free spaces.

When surfacing flat surfaces, it is advisable to use wide rollers, i.e. to conduct the process with oscillatory movements, and also to use electrode tapes. For surfacing, it is more expedient to use flux-cored wires and tapes.

Surfacing of bodies of revolution is performed along the generator or with circular rollers along a helical line. To reduce deformation and stresses, forging is used after surfacing.

The productivity of submerged arc surfacing with one electrode is 9...15 kg/h, with a tape - 5...30 kg/h.

The use of automatic submerged arc welding is not always feasible and expedient. Welding in places difficult to reach for automatic machines, as well as short and curved seams, can be performed with hose semi-automatic machines (see section 5.5). The essence of the method of mechanized submerged arc welding is that the electrode wire is fed into the submerged arc

welding zone from a cassette located at a distance of 1,5...3 m from the torch (holder) through a special hose wire, which simultaneously serves to supply welding current to the electrode wire through the torch mouthpiece. The arc is moved along the welded edges manually. The flux is supplied to the welding zone either from a small hopper or through a flexible rubber hose using compressed air. A hollow flexible cable is used to supply welding current and guide the electrode wire, which connects the welding torch with the feed mechanism.

For mechanized submerged arc welding, a hose semi-automatic machine of the PSh-5 type with a universal DSh-6 holder is used.

Depending on the thickness and type of connection, metal with a thickness of 2-30 mm (sometimes more) is welded with or without beveling of the edges, one- and two-sided butt, single- or multi-pass corner seams, slotted seams, seams in lap joints and with through-melting of the upper sheet are performed, and electric rivets are used.

A characteristic feature of mechanized submerged arc welding is the use of an electrode wire with a diameter of 1.6...2 mm at a high current density, which ensures deep penetration of the base metal and welding of metal of great thickness. Mechanized submerged arc welding can be performed both on alternating and direct current. However, when performing butt seams of thin metal and corner seams with a small leg, it is more expedient to use direct current of reverse polarity.

4.4 Automatic welding equipment

According to the degree of mechanization of individual operations, arc welding can be automatic and mechanized.

Automatic is usually called welding or surfacing with mechanized excitation and maintenance of the arc process, mechanized supply of welding materials to the melting zone and mechanized movement of the arc along the line of the welded joint.

Mechanized is usually called welding or surfacing with mechanized supply of wire and other welding materials to the melting zone and manual movement of the arc along the line of the welded joint.

A mechanized device consisting of a power source, a welding machine or welding machine and mechanized auxiliary equipment is called a welding installation (Fig. 52).

The welding machine is a structural combination of a welding head with a mechanism for moving it along the seam, mechanisms for setting movements, a device for supplying flux or shielding gas, coils or cassettes for wire, control panels and other devices. If the welding machine is moved in a mechanized manner relative to the product during welding, then it is called a welding machine.

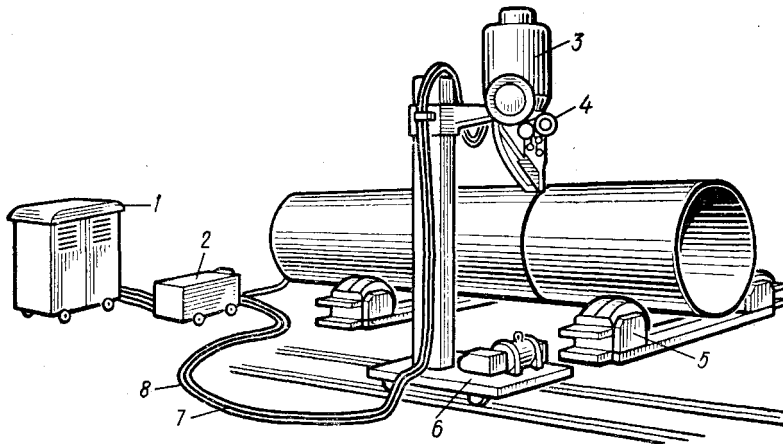


Figure 52 – Installation diagram for automatic submerged arc welding of longitudinal and annular seams:

- 1 – power source; 2 – control cabinet; 3 – flux equipment;
- 4 – welding machine; 5 – device for rotating the product;
- 6 – device for fastening and moving the welding machine;
- 7 – control wires; 8 – wires for supplying welding current

The main part of the welding machine is the welding head. This electromechanical device supplies a consumable electrode to the arc zone, supplies welding current to it, maintains a stable arc process, and also terminates the welding process. The welding head can move along a special track (usually along guide rails) or directly along the product. If the design of the welding head provides a mechanism for moving it above the welded product, the head is called self-propelled. A welding head fixedly fixed on a stand above the welded product is called suspended. In suspended heads there is no mechanism for moving the head itself, usually the product is moved relative to the arc using an auxiliary mechanism or stand on which the head is fixed.

A portable welding machine (automatic machine) for arc welding with a self-propelled cart that moves it along the welding edges along the surface of the product or a portable track, placed on the product, is called a welding tractor.

In industry, many different general-purpose (universal) and specialized welding machines are used, which are classified according to the following features:

- by the method of movement along the welded joint line - non-self-propelled (suspended) and self-propelled, including tractors;

- by the method of protecting the arc zone - for welding under flux (F), in shielding gases (G), without external protection (O), over flux, under flux and in shielding gases (FG);

- by type of electrode - for welding with consumable and non-consumable electrodes (without filler metal and with filler metal);

by type of consumable electrode - for welding with wire, (solid cross-section or powder), strip (solid cross-section or powder) and artificial (rods or plates) electrodes;

by number of electrodes with common welding current supply - single-, double- and multi-electrode;

by number of arcs with separate supply of electrodes with welding current - single-, double- and multi-arc;

by technological purpose - for welding, for surfacing;

by type of current used - for welding with direct current, alternating current, direct and alternating current;

by method of electrode wire supply - with supply independent of arc voltage and with dependent supply;

by the method of regulating the welding speed (for self-propelled machines) and the electrode wire feed - with smooth, with smooth-step, step regulation;

by the method of forming the weld metal: for welding with free formation (as a rule, in the lower position) and with forced (as a rule, on vertical, inclined and curved surfaces).

The composition of welding and surfacing machines includes welding nozzles or torches (welding tool); mechanisms for feeding electrode or filler material, movement along the connection line, adjustment, auxiliary and corrective movements; devices for placing electrode or filler material; flux equipment; gas equipment; control systems; welding current sources; safety equipment.

When welding under flux, the heads of ABS, ADS-1000-2, ADF-500, etc., which have a separate electrical wire for feeding the electrode wire, can be used as hanging heads. Tractor-type welding machines for welding at currents from 500 to 1600 A (ADS-1000-2, TS-17M-U, TS-35, ADF-500, etc.) are becoming increasingly popular.

Automatic machines for multi-arc welding mostly consist of a set of two or three single-electrode welding heads, they provide simultaneous feeding of the corresponding number of electrode wires with separate power supply (double-arc machine DTS-38; A-639). Double-arc machines allow you to use a three-phase power supply scheme and weld with a three-phase arc.

Let us consider for example the TS-35 tractor-type welding machine, designed for submerged arc welding of butt joints with and without edge cleaning, for performing corner seams with vertical and inclined electrodes and for welding lap joints. During welding, the tractor can move directly along the product or along a guide line.

The TS-35 welding machine consists of a welding tractor (Fig. 53), a hardware box and a power source. The tractor is a self-propelled mechanism consisting of a welding head and a running cart with individual electric drives. The feed mechanism 1 provides the feed of electrode wire with a diameter of

1.6...5.0 mm using notched rollers. The wire feed speed is adjustable within 50...500 m/h.

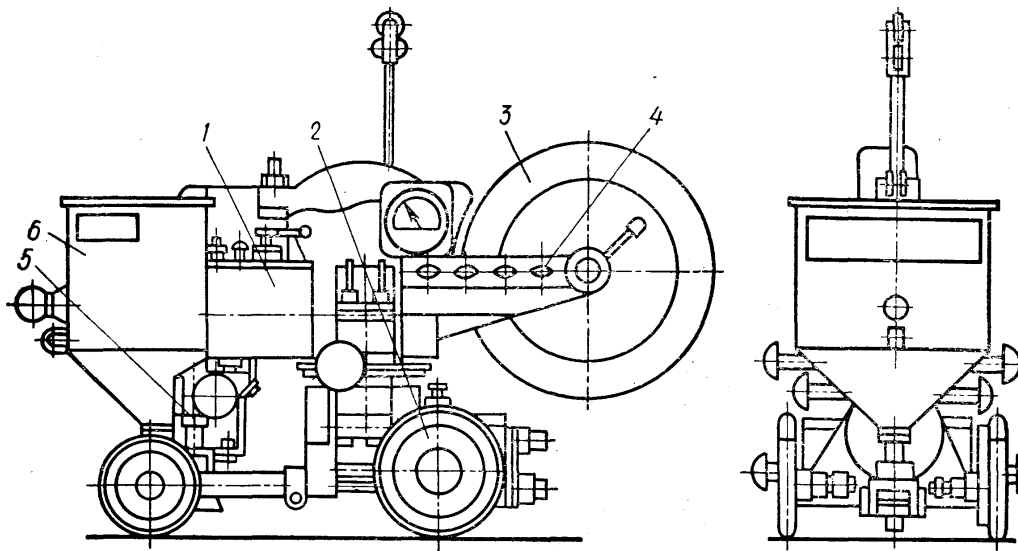


Figure 53 – General view of the welding tractor TS-35

The welding head has two types of conductive nozzles 5. For welding with an electrode wire with a diameter of 3...5 mm at currents up to 1000 A, contact rollers are used. For welding with a thin wire with a diameter of 1.6...2 mm at currents up to 600 A, tubular nozzles with a tip in the form of a sliding contact are used.

A stable welding process and good quality of the weld are ensured by the correct selection and maintenance of constant welding modes. The main parameters of the mode include welding current, voltage and welding speed. Modern welding heads use two principles of regulating the arc mode according to its voltage - arc self-regulation and automatic arc regulation.

A constant arc length is ensured when the electrode wire feed speed v_e is equal to its melting speed v_n . If $v_e > v_n$, this will lead to short circuits, and when $v_e < v_n$ - to arc breakage and termination of the welding process.

Violation of the equality $v_e = v_n$ during welding is possible for the following reasons: voltage fluctuations in the network; irregularities, waviness, tacks on the welded surfaces; uneven electrode wire feed speed; magnetic blast that deflects the arc, and other reasons.

Most arc welding machines operate on the principle of self-regulating the arc.

Arc self-regulation is the property of a welding arc when welding with a consumable electrode to restore its length at random deviations, due to a change in the melting rate of the electrode. The more the arc length changes, the more the current changes and, consequently, the melting rate of the electrode. If the arc length decreases, the current and melting rate increase and the arc length returns to its original value.

The essence of this principle can be understood when considering the change in welding mode parameters depending on the external characteristics of the power source and the change in the arc length (Fig. 54).

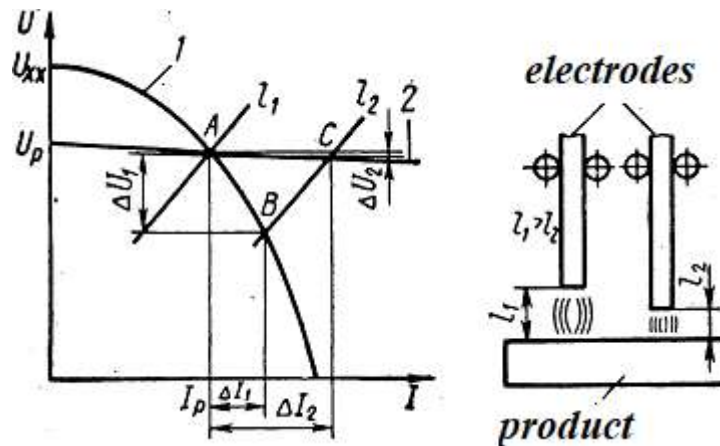


Figure 54 – Changing the welding mode parameters depending on the external characteristics of the power source and the arc length

Fig. 54 shows the steeply falling 1 and hard 2 characteristics of the power sources and the increasing volt-ampere characteristic of the arc 1, 2 corresponding to section III of the I-V characteristic, characteristic of mechanized welding methods (see Fig. 21). Point A of the intersection of the characteristics of the arc and the source is the point of stable arc burning, to which the operating current I_p and voltage U_p correspond, l_1 is the initial arc length for stable burning.

Let us assume that the arc length has changed and has become equal to l_2 , that is, the arc has become shorter. A smaller arc length corresponds to a smaller voltage, a larger arc length to a larger voltage. With a steeply falling characteristic 1, as can be seen from the figure, the arc voltage ΔU_1 will change significantly and the arc current ΔI_1 to a lesser extent. With a rigid characteristic 2, on the contrary, a change in the arc length leads to a sharp increase in the current ΔI_2 and to a slight change in the voltage ΔU_2 .

An increase in the current will lead to an increase in the melting rate of the electrode, as a result of which the melting rate will be greater than the electrode feed rate ($v_n > v_e$) and the arc length will recover after a certain period of time, while the melting and electrode feed rates will be compared.

An mechanized welding methods, the self-regulation process is most effective when using sources with rigid (shielded gas welding) and sloping (submerged arc welding) characteristics. In manual arc welding, when changes in the arc length are most frequent, and when welding in hard-to-reach places the welder has to artificially change the arc length himself, it is most convenient to use power sources with a steeply sloping characteristic, because changes in

current at given modes will be insignificant, and therefore the main dimensions of the seam will change insignificantly. Automatic and semi-automatic machines that use the principle of self-regulation of the arc operate with a constant electrode wire feed speed, which does not depend on the arc voltage (Fig. 55, a). In these devices, an asynchronous three-phase current motor 1, which has a constant rotation frequency, rotates the feed roller 3 through a gearbox 2, which feeds the electrode wire 4 into the arc zone at a constant speed. One of the advantages of welding machines with a constant wire feed speed is the simplicity of their electrical circuit and reliability of operation.

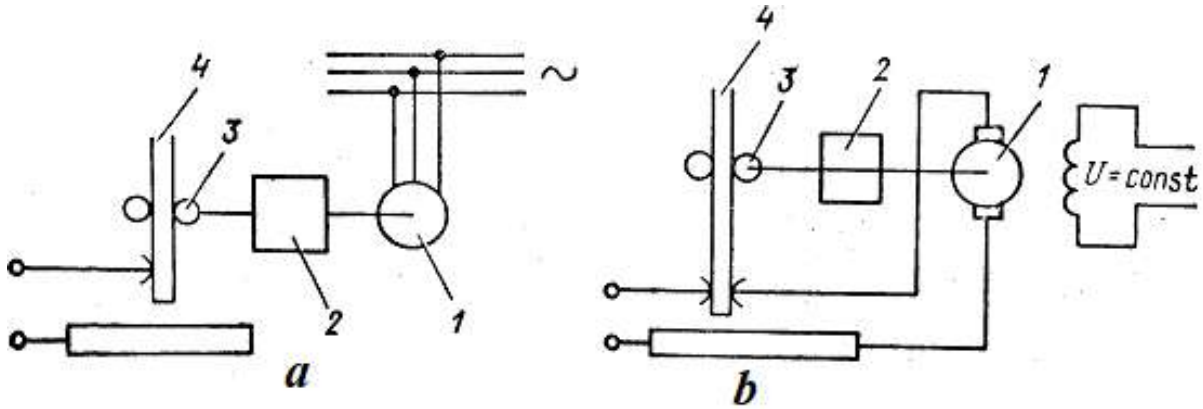


Figure 55 – Schematic diagram of the structure of the welding head:
a – with a constant electrode feed speed; *b* – with an automatically regulated electrode feed speed; 1 – electric motor; 2 – gearbox; 3 – roller; 4 – electrode wire

Automatic arc regulation is based on changing the electrode wire feed speed depending on the voltage on the arc. Fig. 55, b shows a simplified diagram of the welding head built on the principle of automatic regulation. The armature of the DC electric motor 1 rotates the feed roller 3 through the gearbox 2, which feeds the electrode wire 4 into the arc burning zone. The arc voltage is applied to the winding of the armature of the electric motor. If for some reason the arc length increases, then the arc voltage applied to the armature also increases. As a result, the armature will begin to rotate faster, and the wire feed speed will increase to the initial value. On the contrary, if for some reason the arc length decreases, the voltage on it will drop. The armature of the electric motor will reduce its revolutions, and the wire will begin to be fed more slowly. With automatic regulation, the equality $v_e = v_n$ is ensured by changing the electrode wire feed speed.

With particularly high requirements for the quality of the seam, as well as for welding products of small thickness, serially produced converters PS-500, PSO-500, PS-100 are used, as well as welding rectifiers VS-500, VS-1000-2, VDU-504, VDU-1001, VDU-1601.

In practice, more advanced schemes for automatic regulation of the arc length are used, for example, in the ADS-1000-2 welding machine. Systems for automatic regulation of the welding mode from several parameters of the mode are being developed.

For submerged arc welding, alternating and direct current sources with a sloping characteristic are used. Alternating current sources are mainly used due to their greater efficiency and good stability of the submerged arc. For this purpose, TSD-500-1, TSD-1000-4 and TSD-200 transformers are mass-produced in a single-body design and with built-in chokes and remote control.

4.5 Electroslag welding

Electroslag welding is a fusion welding process in which the heat released when an electric current passes through molten conductive slag is used to heat the metal. In electroslag welding, almost all the electrical power is transferred to the slag bath, and from it to the electrode and the base metal. In this case, the molten flux serves as protection against the harmful effects of the environment and a means of metallurgical action on the molten metal. The amount of heat — Q , released during the electroslag process, is proportional to the current I , voltage U , slag resistance R and time t of current flow, $Q = I \cdot U \cdot t$. This heat is spent on melting the metal, heating the slag and heat removal. The temperature of the molten slag is about 2000 °C, which ensures the melting of the base and electrode metal.

The electroslag process as a source of energy for welding is characterized by the largest heating area and the lowest concentration of energy in the heating zone.

According to GOST, electroslag welding is classified:

by the type of electrode - wire electrode, plate electrode, fusible mouthpiece;

by the number of electrodes with a common welding current supply - single-, double- and multi-electrode;

by the presence of electrode oscillations - without oscillations and with oscillations.

The scheme of electroslag welding with a wire electrode is shown in Fig. 56. The electrode 1 and the base metal 2 are electrically connected through molten slag 3. Due to the heat released in the slag bath when an electric current passes through, the electrode metal and the edges of the base metal melt and flow to the bottom of the melt, forming a metal bath 4. At the beginning of the welding process, an electric arc is excited, after the flux melts under the action

of the arc and the formation of a slag bath, the liquid flux fills and extinguishes the arc, and the arc process turns into an electroslag process.

The parts to be welded are stacked vertically without beveling the edges, with a gap of 20... 40 mm. To form the seam and keep the liquid metal and slag from flowing out, special forming devices are used - movable or stationary copper sliders 5, cooled by water b, or plates that remain. The molten metal, crystallized in the lower part of the metal bath, forms a seam 7.

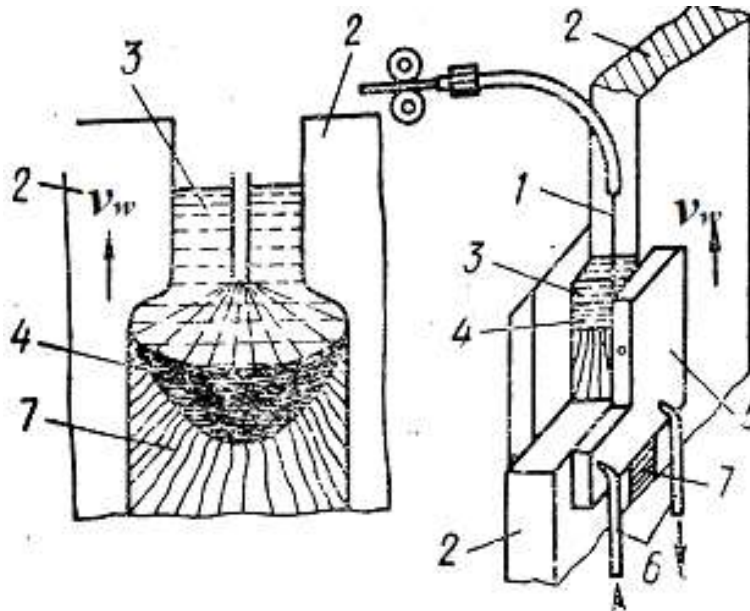


Figure 56 – Electroslag welding process diagram

Electroslag welding has the following features and advantages:

- metal of almost any thickness can be welded in one pass, so the welding productivity is 5...15 times higher than with multi-layer automatic submerged arc welding, while, as a rule, edge cleaning is not required;

- the vertical position of the metal bath, the increased temperature of its upper part and a significant time of the metal in the molten state contribute to the removal of gases and non-metallic inclusions from the weld metal;

- low flux consumption, usually no more than 5% of the mass of the deposited metal.

The disadvantage of electroslag welding is significant overheating of the metal of the near-weld zone, which leads to a decrease in plastic properties, so subsequent high-temperature treatment is usually necessary to obtain the required mechanical properties of the welded joint.

Electroslag welding is technically possible with a metal thickness of more than 16 mm and, as a rule, economically advantageous when welding metal with a thickness of more than 25 mm. This type of welding allows you to perform only vertical seams. Electroslag welding is used for welding steels, aluminum

and titanium alloys. The main types of welded joints performed by electroslag welding are shown in Fig. 57.

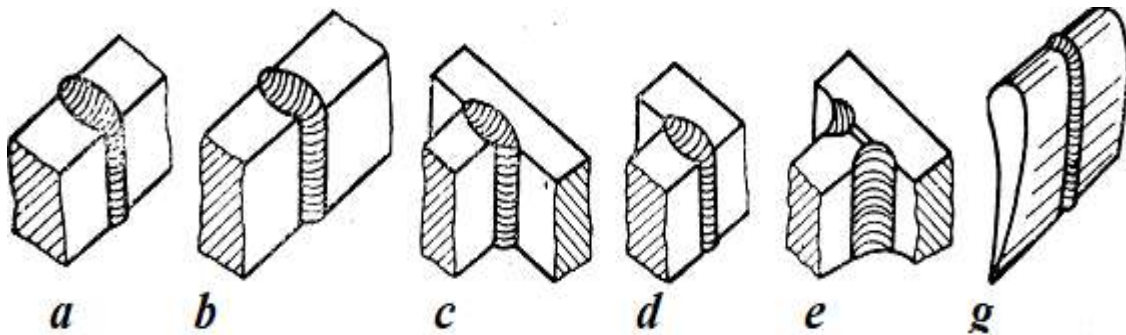


Figure 57 – The main types of welded joints performed by electroslag welding:
a, b – butt; *c, d* – T-shaped; *e* – angular; *g* – variable cross-section

The use of electroslag welding introduces fundamental changes in the technology of manufacturing large-sized products, it becomes possible to replace large cast or forged parts with welded-cast or welded-forged parts from smaller parts.

The main parameters of electroslag welding include: welding speed, welding current, electrode feed rate, welding voltage, metal thickness per electrode, distance between electrodes. Auxiliary parameters of the mode: gap between the edges, depth of the slag bath, flux composition, speed of transverse oscillations of the electrode, electrode extension, wire cross-section, etc. Welding current, the value of which is determined by the type of electrode (wire, plate, fusible nozzle), the number of electrode wires, their diameter and cross-section of plate electrodes or fusible nozzles, electrode feed rate and other parameters are selected so as to obtain the welding speed and voltage that will ensure the stability of the process and the required dimensions and shape of the seam. Approximate values of the main parameters of the mode are given in Table. 11. When using an electrode wire, the depth of the slag bath is usually 25...70 mm, the wire feed rate is 100...150 m/h, the speed of reciprocating movement of the electrodes is 25...40 m/h, the dry electrode extension is 60...80 mm.

For electroslag welding, conventional fluxes are used, for example AN-348A, FC-7, as well as special fluxes that form an electrically conductive melt with specified technological properties: viscosity, electrical conductivity, melting point, etc. (AN-8, AN-22, etc.).

Table 11 – Approximate parameters of the electroslag welding mode of low-carbon steel with wire electrodes

Thickness of welded metal, mm	Welding current per electrode, A	Voltage on the slag bath, V	Number of electrodes, pcs.	Electrode diameter, mm	Distance between electrodes, mm	Speed, transverse movement of the electrode, m/h	Electrode feed rate, m/h	Shutter speed near sliders, s	Clearance, mm	Welding speed, m/h	Dry electrode travel, mm	Slag bath depth, mm	Flux brand
30	350...370	32...34	1	2.5	-	-	172	—	30	0.9...1	40...50	20...25	AH-8
70	640...660	46...48	1	3		31	371..400	5	26...30	1.0...1.1	90...95	60...65	AH-8
90	600...620	42...46	2	3	45...50	26...32	300	4...6	24...27	1.6	60...80	50...70	ΦЦ-7
250	500...550	50...55	2	3	125	31	230...250	5	28...32	0.4...0.5	60...70	45...50	ΦЦ-7
300	400...450	46...48	3	3	110	31...36	200...220	5	30	0.35	60...70	45...50	AH-8
450	200	36...38	9	3	50	—	60...80	—	30...33	0.6	50...70	40...45	AH-8

Welding with a plate electrode is used for relatively short seams up to 1.5 m high. Instead of plates, consumable electrodes can be used, i.e. rods of round, square and other sections. In this case, the welding equipment is greatly simplified.

Welding with a fusible mouthpiece seems to combine the methods of welding with wire and plate electrodes. Grooves are made in the plate electrode or tubes are welded to it for feeding electrode wires. During welding, the plate remains stationary and is a fusible mouthpiece through which the wire is fed. This method allows you to weld seams of a complex curved profile.

The workpieces for welding are stacked with a gap, usually 30 mm, taking into account the shrinkage of the etik during and after welding. For a tight fit of the sliders and forming devices to the edges of the etik, the latter are cleaned of burrs and scale to a width of up to 100 mm. To remove the shrinkage cavity beyond the seam, starting strips are installed at the end of the seam, and to remove non-welds at the beginning of the seam, starting strips are installed, which are removed by cutting after welding. To start welding, flux is poured into the pocket formed by the starting strips, an arc process is excited until a slag bath of the required size is obtained. After that, the arc is shunted with slag, and the process switches to arc-free - electroslag.

Electroslag welding is carried out with special electroslag machines that provide electrode feed into the welding zone, maintain a stable electroslag process, and move along the seam as it is formed.

Automatic and semi-automatic machines are used in electroslag welding. Semi-automatic machines are not widely used, because it is difficult for a welder to move heavy equipment vertically. Installations for automatic electroslag welding have the following main components: a self-propelled welding machine, to which copper water-cooled shoes are connected, which form the seam; a hopper with flux; cassettes with electrode wire; power sources; control equipment.

The machines are divided into suspended and self-propelled, rail and railless types. During arc welding in the lower position, the weight of the machine itself is sufficient to engage the running rollers with the rail or surface of the product. During vertical movement, the machines must be equipped with special mechanisms that will hold them in a vertical plane - due to friction forces with a spring or magnetic clamp that moves along the seam together with the machine at the speed of seam formation.

The safety requirements for submerged arc welding and electroslag welding meet the requirements set out in clause 2.8. Additional requirements are as follows:

- when working with suspended machines and welding tractors, the power supply is carried out by wires that move;
- the voltage in the network of automatic equipment is higher than in manual arc welding, therefore all fixed wires are placed in metal tubes, and

moving ones are placed in rubber sleeves, sheathed with tarpaulin or wrapped in two layers with a keeper (rubberized) tape.

All parts of machines and semi-automatic machines that may become live in the event of insulation damage must be grounded; all bolted and contact connections must be tightly tightened, and the tips must be tinned.

The flux hopper must be tightly closed with a lid. When pouring flux into the hopper and removing used flux, one must try not to raise dust, and monitor the operation of the ventilation.

During electroslag welding, a significant volume of liquid metal and slag is formed. If the technology is violated, emissions of liquid metal are possible, therefore, it is necessary to strictly monitor the level of the bath and the condition of the water supply system. It is strictly forbidden to be under the slider, backing or mold during welding, so that liquid metal or slag does not get on clothes and body when leaking. Overalls and light filters for eye protection are the same as for manual welding.

The protective gases used in welding (argon, helium, nitrogen and carbon dioxide) are stored in cylinders under an excess pressure of 15 MPa, therefore, handling of cylinders during their transportation, storage and operation must comply with the rules of the State Committee for Technical Supervision.

Control questions

1. What is the essence of submerged arc welding?
2. What fluxes are used in submerged arc welding?
3. What does a welding machine for automatic welding contain? What components does a submerged arc welding machine consist of?
4. What is self-regulation and automatic regulation of arc parameters?
5. Name the parameters of the submerged arc welding mode and their effect on the formation of the seam.
6. What is the essence of electroslag welding?
7. What is a welding machine, automatic machine, head, tractor? Give a classification of welding machines.

5 FUNDAMENTALS OF ARC WELDING TECHNOLOGY IN PROTECTIVE GASES AND EQUIPMENT FOR IT

5.1 General information

The essence and characteristic feature of arc welding in protective gases is the protection of the molten and heated to a high temperature base and electrode metal from the harmful effects of air by protective gases, which provide physical isolation of the metal and the welding zone from the air and a given atmosphere in the welding zone.

Types of welding in shielding gases can be classified according to the following features:

- type of electrode - fusible and non-fusible electrodes;
- type of shielding gas - inert, active, their mixtures;
- protection method - jet, in a controlled atmosphere;
- character of arc burning - stationary, pulsed;
- mechanization - manual, semi-automatic, automatic.

Classification of welding types by electrode type and degree of mechanization is shown in Fig. 58.

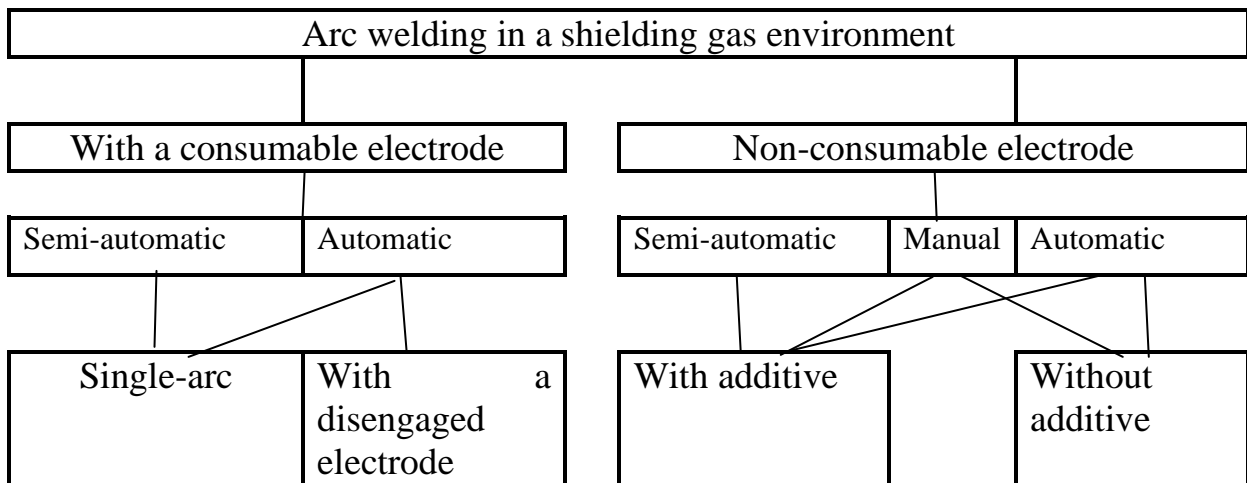


Figure 58 – Classification of arc welding methods in shielding gases

As a consumable electrode, welding wires are used, which in chemical composition correspond to the welding materials described in section 2.2.

Non-consumable electrodes are used to excite and maintain arc burning. Tungsten electrodes are mainly used, less often carbon and graphite electrodes (when welding in active gases). To increase the stability of arc burning and electrode stability, usually 1.5...3% of activating rare-earth metal oxides (thorium, lanthanum, yttrium) are added to the tungsten electrode, which increase the emissivity of the electrode.

As electrodes for welding, tungsten rods with a diameter of 0.2...12 mm are used, which are produced by industry: pure tungsten (EVCh), thoriated tungsten (EVT5, EVT10, EVT15), lanthanated tungsten (EVL10, EVL20), yttriated tungsten (EV130).

Carbon and graphite electrodes (rods) are made of electrical coal or synthetic graphite with a diameter of 4...18 mm and a length of 250...700 mm. Graphite electrodes have better electrical conductivity and are more resistant to oxidation at high temperatures than carbon electrodes. Shielding gases protect the arc and the weld pool from the harmful effects of the environment. Inert and active gases, as well as their mixtures, are used as shielding gases.

Inert gases are gases that do not chemically interact with the metal and do not dissolve in it. Argon (Ar), helium (He) and their mixtures are used as inert gases. Inert gases are used for welding chemically active metals (titanium, aluminum, magnesium, etc.), as well as in all cases where it is necessary to obtain welds that are homogeneous in composition with the base and filler metal (high-alloy steels, etc.). Inert gases provide protection for the arc and the welded metal without exerting a metallurgical effect on it

Argon and helium are supplied in cylinders with a capacity of 40 liters under a pressure of 15 MPa. The argon cylinder is painted gray, the inscription is green; the helium cylinder is brown, the inscription is white. Due to the fact that helium is 10 times lighter than argon, the helium consumption during welding increases by 1.5...2 times.

Nitrogen (N₂) is also inert in relation to copper.

Active shielding gases are gases that enter into a chemical interaction with the welded metal and dissolve in it (carbon dioxide, hydrogen, water vapor, etc.). Welding carbon dioxide with a purity of 99.5% is used for welding.

Carbon dioxide is stored and transported in liquid form, mainly in steel cylinders with a capacity of 40 liters under a pressure of 6,0...7,0 MPa. The cylinder contains 60...80% liquid carbon dioxide, and the rest is evaporated gas. The color of the cylinder is black, the inscription is yellow.

Gas mixtures in some cases have better technological properties than individual gases. For example, a mixture of carbon dioxide with oxygen (2...5%) promotes fine-droplet metal transfer, reduces spatter (by 30...40%), and improves weld formation. A mixture of 70% He and 30% Ar increases the welding performance of aluminum, improves weld formation, and allows welding of large thicknesses of metal in one pass.

According to the method of protection, local and general protection of the welding unit are distinguished (welding in a controlled atmosphere). The main method of local protection is jet protection of the seam. With this method, the protective environment in the welding zone is created by a gas flow with central, lateral or combined gas supply. With central gas supply, the arc (Fig. 59, *a*), burning between the electrode and the base metal, is surrounded on all sides by gas, which is supplied under a small excess pressure from the burner nozzle located concentrically to the electrode axis. This method of protection is the

most common. In some cases, in order to save inert gases, as well as to obtain optimal technological and metallurgical properties of the protective environment, burners are used, the design of which provides combined protection with two concentric gas flows (Fig. 59, *b*).

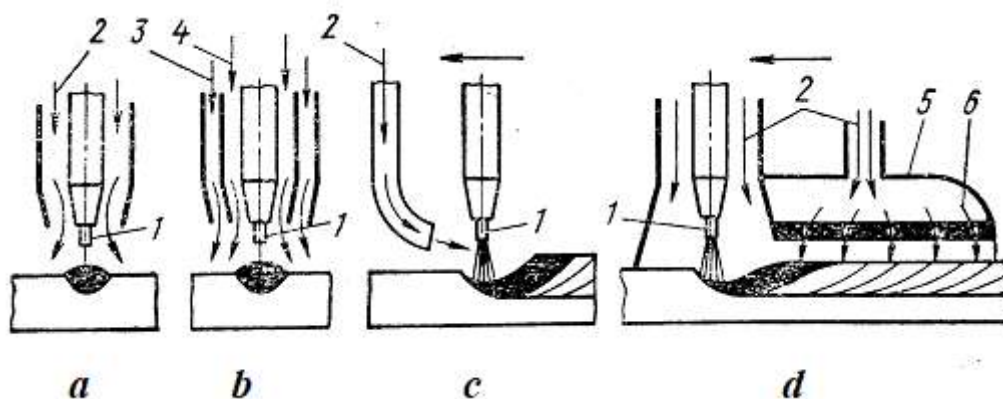


Figure 59 – Supply of shielding gases to the welding zone:

a – central with one concentric flow; *b* – central with two concentric flows; *c* – lateral; *d* – into a moving chamber (nozzle);

1 – electrode; 2 – shielding gas; 3, 4 – external and internal flows of shielding gases; 5 – nozzle; 6 – gas distribution system

For example, the inner flow is formed by argon, and the outer flow is formed by carbon dioxide. When welding highly active metals (Ti, Zr, Ta, Nb, Mo, W), it is necessary to protect not only the molten metal, but also the metal zone heated during welding to a temperature of more than 300 °C on the front and back sides of the weld. To expand the jet protection on the front side of the weld, additional caps-attachments are used, which are put on the torch nozzle (Fig. 59, *d*). Protection of the back side of the weld is provided by blowing in protective gas. Side gas supply is used to a limited extent (Fig. 59, *c*).

The most effective protection of the weld metal and the heat-affected zone is provided when welding in chambers with a controlled atmosphere. The chambers are pre-blown or evacuated, and then filled with protective (inert) gas of a given composition under low pressure.

The advantages of welding in shielding gases are:

high productivity (approximately 2,5 times higher than in manual arc welding with covered electrodes);

simplicity of mechanization and automation;

the possibility of welding in various spatial positions;

a small heat-affected zone and relatively small deformations of the product due to the high degree of arc concentration;

high quality of protection, there is no need to clean the seam in multi-layer welding;

availability of monitoring the welding process;

the possibility of welding metal of different thicknesses (from tenths of a millimeter to tens of millimeters).

The disadvantages of welding in shielding gases are an open arc, which increases the risk of eye damage by light radiation and the need to protect the welding zone from drafts (with jet protection), which makes it difficult to use this type of welding in outdoor installation conditions.

5.2 Welding in protective gases with a consumable electrode

Welding in protective gases with a consumable electrode is carried out using a consumable electrode and a shielding gas supplied to the arc zone. Inert and active gases are used for protection, as well as their mixtures (Ar, He, CO₂, Ar + CO₂, CO₂ + O₂, Ar + O₂, etc.). The main types of welding are carbon dioxide welding and argon-arc welding. This welding is mechanized, it is performed by semi-automatic and automatic machines. The scheme of the station for welding in protective gases with a consumable electrode is shown in Fig. 60.

Welding in protective gases with a consumable electrode has a number of features. Stable combustion is ensured at a high density of direct current (100 A/mm² and above) on an increasing branch of the volt-ampere characteristic (see Fig. 21). The stability of the weld parameters (its depth and width) depends on the constancy of the arc length, which is ensured by the processes of self-regulation of the arc length by maintaining a constant electrode wire feed rate equal to its melting rate.

High welding current density determines the use of small-diameter electrode wire (usually $d_e = 0,8...2,5$ mm), which leads to the need to use high electrode wire feed rates. Under these conditions, the process of self-regulation by power sources with falling characteristics is not ensured. Therefore, to maintain a stable arc length and ensure the process of self-regulation of the arc length, it is necessary to use direct current power sources with a rigid and increasing external characteristic (PSG-500 converters or VS-300, IPP-500 rectifiers, etc.). Welding is usually performed on direct current of reverse polarity with continuous electrode wire feed by semi-automatic and automatic machines. The most widely used semi-automatic machines are A-547, PDG-500, etc. Automatic machines for welding in shielding gases are mainly tractor-type - ADPG-500, ADG-500, etc.

The main parameters of welding with a consumable electrode include current strength, polarity, arc voltage, diameter and feed speed of the electrode wire, composition and flow rate of the shielding gas, electrode throw, welding speed. Welding with a consumable electrode is usually performed with reverse polarity. With direct polarity, the melting speed is 1,4...1,6 times higher than with reverse, but the arc burns less stably with intense spattering. The welding current, on which the dimensions of the seam and welding performance depend, depends on the diameter and composition of the wire, it is set according to the wire feed speed.

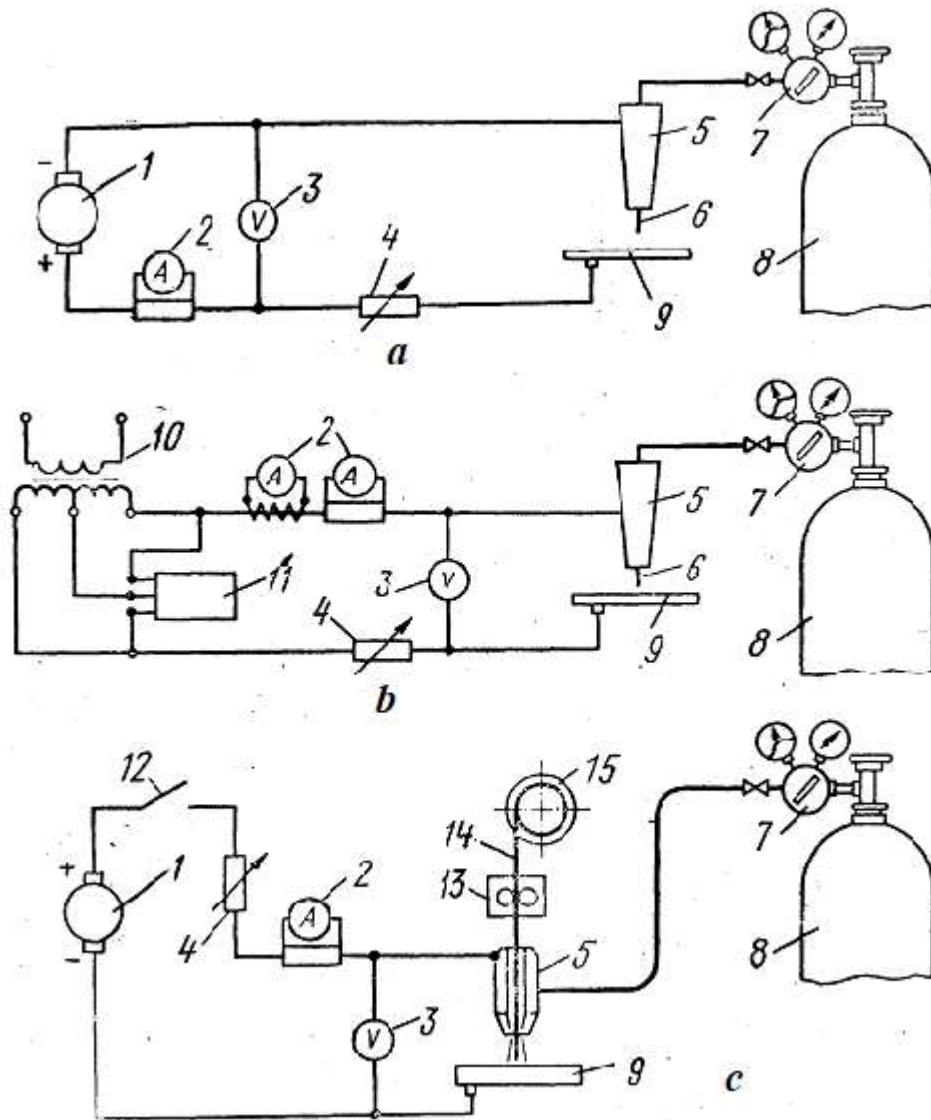


Figure 60 – Electric and gas welding scheme in protective gases:

a – non-consumable electrode in inert gases at direct current of direct polarity; *b* – the same, at alternating current; *c* – fusible electrode at direct current of reverse polarity; 1 – welding converter; 2 – ammeter, 3 – voltmeter; 4 – ballast rheostat; 5 – burner; 6 – tungsten electrode; 7 – reducer-flowmeter for protective gas; 8 – gas bag; 9 – product; 10 – welding transformer; 11 – oscillator; 12 – contactor; 13 – wire feed mechanism; 14 – fusible welding wire; 15 – spool with wire

The welding speed is usually 15...80 m/h, it is selected taking into account the productivity and quality of the seam formation. High-quality joints can be obtained with a metal thickness for automatic welding > 0.5 mm, mechanized > 1 mm, usually weld thicknesses > 3 mm.

Welding technique. Metals up to 4 mm thick are welded without edge cleaning. To improve the formation of the seam with a metal thickness > 2...3 mm, welding is carried out on a copper substrate with a forming groove or on

the remaining substrate of the base metal. For welding thin sheet metal, a wire with a diameter of 0,5...1,2 mm is used. Metal with a thickness of 4... 12 mm is usually welded in two passes on both sides without cleaning, with a thickness of 15... 20 mm - in two or three passes with a cleaning angle of 60° and a blunting of 2...4 mm.

At a thickness of 20...30 mm, double-sided edge cleaning with an angle of 60° and a blunting of 2...4 mm is used. Metals of greater thickness are advisable to weld with a narrow gap edge cleaning in several passes. Mechanized welding is usually performed at lower currents than automatic. Welding can be performed in different spatial positions using methods of holding the weld pool. The technique of welding metal with a thickness of > 2 mm during mechanized welding is similar to the technique for manual arc welding with covered electrodes. Welding of seams with a consumable electrode in different spatial positions is performed with a wire with a diameter of up to 1,2 mm, seams located in the lower position – 1,2...3,0 mm. The cycle diagram of welding in a protective gas with a consumable and non-consumable electrode is shown in Fig. 61.

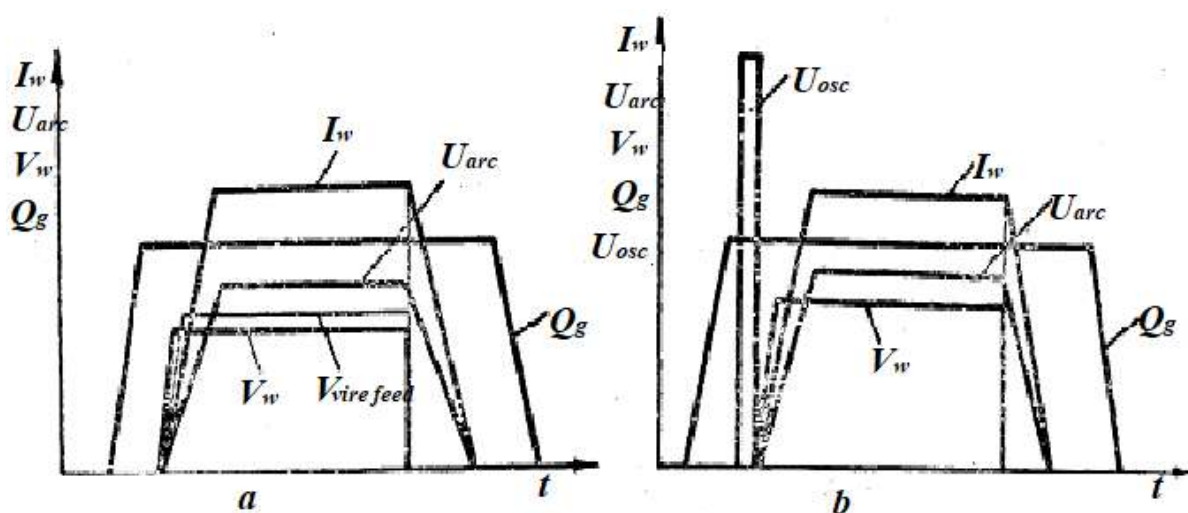


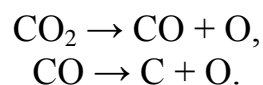
Figure 61 – Cyclogram of the welding process in shielding gases:

a – with a consumable electrode; *b* – with a non-consumable tungsten electrode; I_w – welding current; U_d – arc voltage; V_w – welding speed; Q_g – shielding gas flow rate; $V_{wire\ feed}$ – welding wire feed speed; U_{osc} – oscillator voltage

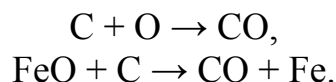
The cycle diagram shows the change in the main parameters of the manual welding process: welding current I_{zv} , arc voltage U_d , filler wire feed speed $v_{p.d}$, welding speed v_{zv} , argon flow rate Q_g and an additional parameter - oscillator voltage U_{osc} , during the welding cycle t . Gas is supplied 10...15 s before the start of arc burning, the gas pressure is $(1,1...1,3) \cdot 10^5$ Pa, the average gas flow rate for protecting the welding zone is 10...15 l/min, for the reverse side of the weld - 30...50% of the main flow rate.

Welding in carbon dioxide gas, along with other advantages that are characteristic of welding in protective gases, is characterized by high productivity and low cost. Its disadvantages include increased spatter and not always satisfactory appearance of the weld.

The main feature of welding in carbon dioxide gas with a consumable electrode is the need to use electrode wires with a high content of deoxidizing elements - silicon and manganese, which compensate for their burnout in the welding zone and prevent additional oxidation of the metal during welding and the formation of pores. For carbon steels, welding wires of solid cross-section Sv-10GS, Sv-08G2S, as well as flux-cored wires containing FeSi, FeMn ferroalloy powders are mainly used. The reasons for oxidation and the formation of pores during welding in carbon dioxide gas are as follows. During welding, carbon dioxide dissociates in the arc zone with the formation of atomic oxygen by the reaction

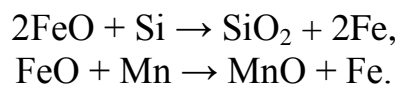


Atomic oxygen oxidizes iron and alloying impurities contained in steel, $\text{Fe} + \text{O} \leftrightarrow \text{FeO}$. As a result, the weld pool metal is saturated with oxygen, and its properties deteriorate. When the molten metal is cooled, the carbon contained in the steel, being oxidized, will contribute to the formation of carbon monoxide by the reaction



During the crystallization of the weld metal, the CO formed is released in the form of bubbles, some of which, not having time to be removed, are retained in the weld metal, forming pores.

In the case when the welding wire is alloyed with Si and Mn, iron oxides are deoxidized not due to carbon, but mainly due to Si and Mn from the welding wire, thus preventing the formation of carbon oxide during crystallization and the formation of pores. The deoxidation of iron oxides occurs by the reaction



Silicon and manganese oxides in the form of slag accumulate on the surface of the weld pool.

Let's consider the main parameters of the welding mode in carbon dioxide gas. The diameter of the welding wire is selected depending on the thickness of the metal; a stable process is ensured at a high current density, therefore, a wire of small diameter from 0,5 to 3,0 mm is used.

The welding current is determined depending on the diameter of the wire by its feed speed. The wire feed speed is set so that during welding there is a stable process of melting the electrodes, without its shorting and without arc breaks. The arc voltage should be less than 32 V, because with increasing voltage and arc length, spattering and oxidation increase. Usually $U_d = 20...30$ V, welding speed from 20 to 80 m/h, gas consumption 6...25 l/min.

The electrode projection and the distance from the torch nozzle to the metal surface increase with increasing electrode wire diameter. When welding with a very small projection, it is difficult to observe the welding process and frequent burning of the gas nozzle and current-carrying contact tip occurs. With an increase in projection, the stability of the arc burning and the formation of the weld deteriorates, and spatter also increases.

Welding in carbon dioxide is performed on a direct current of reverse polarity. Alternating current without special activation of the arc space is not used due to the low stability of the welding process, unsatisfactory formation and poor quality of the weld.

The properties of the weld metal are affected by the quality of carbon dioxide. With an increased content of nitrogen and hydrogen in it, as well as moisture, pores may form in the welds. When welding in carbon dioxide gas, the effect of rust is insignificant, but better quality of the seam is ensured by cleaning the edges from rust, oil contamination, and moisture. Approximate modes of semi-automatic welding in carbon dioxide gas of low-carbon steel are given in Table 12.

Table 12 – Typical modes of butt welding in carbon dioxide gas

Metal thickness	Number of layers	Clearance, mm	Wire diameter, mm	I_w, A	U_{arc}, B	V_w , one layer, m/h	Gas consumption per layer, l/min
0,6... 1,0	1	0,5...0,8	0,5...0,8	50...60	18...20	20...30	6...7
1,2...2,0	1...2	0,8...1,0	0,8...1,0	70...120	18...21	18...25	10...12
3...5	1...2	1,6...2,0	1,4...2,0	180...320	22...30	20...25	14...16
6...8	1...2	1,8...2,2	2,0	280...380	28...35	18...24	16...18
8...12	2...3	1,8...2,2	2,5	280...450	27...35	16...3	18...20

5.3 Argon arc welding

Argon arc welding is arc welding in which argon is used as a shielding gas. Argon arc welding is used with non-consumable tungsten and fusible electrodes. Argon arc welding with a tungsten electrode can be manual and automatic. Welding is possible without feeding and with feeding of filler wire. This process is intended mainly for metals with a thickness of less than 3...4 mm. Most metals are welded with direct current of direct polarity. Welding of aluminum, magnesium and beryllium is carried out with alternating current.

With direct polarity (plus on the product, minus on the electrode), the best conditions for thermionic emission, higher resistance of the tungsten electrode and permissible limiting current are provided. The permissible current when

using a tungsten electrode with a diameter of 3 mm is approximately 140 – 180 A with direct polarity, only 20 ... 40 A with reverse polarity, and an intermediate value of 100 ... 160 A with alternating current. The arc with direct polarity is easily ignited and burns stably at a voltage of 10 ... 15 V a wide range of current densities. With reverse polarity, the arc voltage increases, its burning resistance decreases, the resistance of the electrode decreases sharply, and its heating and consumption increase. These features of the reverse polarity arc make it unsuitable for direct use in the welding process. However, the reverse polarity arc has important technological properties: when it acts, oxides and dirt are removed from the surface of the welded metal. This phenomenon is explained by the fact that with reverse polarity, the metal surface is bombarded with heavy positive argon ions, which, moving under the action of an electric circuit from plus (electrode) to minus (product), destroy the oxide films on the welded metal, and electrons coming out of the cathode (product surface) contribute to the removal of destroyed oxide films. This process of removing oxides is called cathodic sputtering. This property of the reverse polarity arc is used when welding Al, Mg, Be and their alloys, which have strong oxide films. But because with direct current of reverse polarity the stability of the tungsten electrode is low, alternating current is used for this. In this case, the removal of the film, i.e. cathodic sputtering, occurs when the welded product is the cathode. So, when welding with a non-consumable electrode on alternating current, the advantages of the arc of direct and reverse polarity are realized to a certain extent, that is, both the stability of the electrode and the destruction of oxide films are ensured. The simplest electrical and gas circuits for argon-arc welding are shown in Fig. 60, *a, b*.

The technology of argon-arc welding with a tungsten electrode. Fig. 61, *b* shows a characteristic cycljgram of the argon-arc welding process with a tungsten electrode. The arc is excited by closing the electrode and metal using a carbon rod or by a short-term discharge of high frequency and voltage using an oscillator/ Manual welding is performed with an inclined torch at an angle forward, the angle of inclination to the surface of the product is 70 ... 80°. The filler wire is fed at an angle of 10 ... 15° (Fig. 62). After welding, the arc is gradually broken to seal the crater, in manual welding – by gradually stretching it, in automatic welding – by a special crater sealing device, which is provided by a gradual decrease in the welding current. To protect the cooling metal, the gas supply is stopped 10 ... 15 s after the current is turned off.

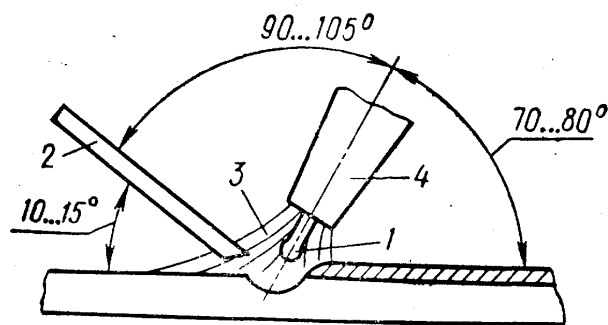


Figure 62 – Placement of the torch and the filler rod in manual argon-arc welding:

1 – electrode; 2 – filler rod; 3 – shielding gas; 4 – torch nozzle

An example of a manual argon-arc welding mode with a tungsten electrode of a butt joint made of high-alloy steel with a thickness of 3 mm: tungsten electrode diameter 3...4 mm, filler wire diameter 1.6...2 mm, welding current 120...160 A, arc voltage 12...16 V, argon flow rate 6...7 l/min. Argon-arc welding is used to weld butt, T- and corner joints. With a sheet thickness of up to 2.5 mm, it is advisable to weld with edge trimming, with a small gap (0,1...0,5 mm) it is possible to weld thin sheet metal with a thickness of 0,4 to 4 mm without edge trimming. The smaller the thickness of the welded material, the smaller the permissible gap. Sheets with a thickness of more than 4 mm are butt welded with edge cleaning, while the permissible gap should be no more than 1,0 mm.

Several types of argon-arc welding with a tungsten electrode have been developed, which are based on increasing the intensity of the thermal and force action of the arc on the metal being welded. These types include: submerged arc welding, using flux, at increased pressure of the protective atmosphere, pulsed arc and plasma welding.

Submerged arc welding. With an increase in the diameter of the electrode and the current strength, the arc pressure and the specific amount of heat input increase. Under the pressure of the arc, the liquid metal is clamped under the electrode. The arc is then deepened into the weld pool, and maintaining the specified voltage (arc length) is achieved by lowering the electrode below the surface of the welded metal. The penetration depth reaches 10...12 mm and above, the argon flow rate into the torch nozzle is 15...20 l/min, into the attachment for protecting the cooling seam 15...30 l/min and to the reverse side of the seam 6...10 l/min.

Welding with the use of flux. Applying a thin layer of flux (0,2...0,5 mm) to the surface of the welded metal, which consists of fluorine, chlorine and some oxide compounds, helps to increase the concentration of the heat flux in the heating spot and increase the penetration capacity of the arc. At the same time, due to the concentration of thermal energy, the penetration efficiency increases and the consumption of direct energy during welding decreases.

Welding at increased pressure of the protective atmosphere. The arc power increases with increasing pressure of the protective atmosphere at constant current and arc length. The arc is compressed, which increases its penetration capacity by approximately 25...60%. This method can be used when welding in chambers with a controlled atmosphere.

Pulsed arc welding with a tungsten electrode consists in using a pulsed (pulsating) arc as a heat source in order to concentrate the thermal and force action of the arc on the base and electrode metal in time. With a compressed heat sink, the heat for melting the base metal is used more fully than with continuous arc welding.

The arc pulses with a given pulse-pause ratio (Fig. 63). A continuous seam is obtained by melting individual points with a certain overlap. Repeated excitation and arc stability are ensured by burning a low-power secondary arc (10...15% of the current strength in the pulse). Along with current strength, voltage, and welding speed, the main parameters of pulsed arc welding include the pulse duration t_w and pause t_p , the welding cycle duration $t = t_w + t_p$ and the spot pitch $S = v_w(t_w + t_p)$, where v_w is the welding speed. The ratio $t_p/t_w = G$ is called the regime stiffness.

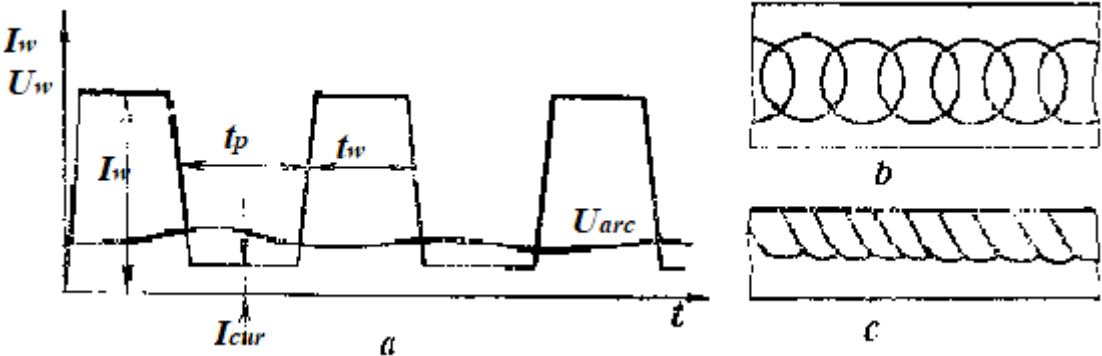


Figure 63 – Change in welding current and voltage during pulse welding with a tungsten electrode (a) and appearance of the welds (b, c):

I_w – welding current; I_{cur} – current of the next arc; t_p – pause time;
 t_w – welding time

The rigidity of the mode at a given pulse energy and cycle duration characterizes the penetration ability of the arc. By changing the parameters of the pulse arc welding mode, it is possible to change the crystallization of the metal within wide limits and thus influence the properties of welded joints. The technological advantages of pulse arc welding with a tungsten electrode are most evident when welding thin-sheet materials: there are practically no defects in the formation of the seam, sagging and undercuts, the conditions for forming the seam in different spatial positions are improved, and the requirements for the welder's qualification in manual welding are reduced. Since much less linear energy is required to weld a metal of a certain thickness, deformations and losses of thin-sheet materials are significantly reduced. Therefore, pulse arc

welding with a tungsten electrode is intended mainly for regulating the penetration of the base metal and the formation of the seam when welding thin-sheet metal.

Argon-arc welding with a consumable electrode. The field of application of this type is welding of non-ferrous metals (Al, Mg, Cu, Ti and their alloys) and alloyed steels.

Welding occurs with droplet and jet transfer. With increasing current, droplet transfer of the electrode metal changes to jet and the depth of penetration increases. The critical current value at which droplet transfer changes to jet is: when welding steels - from 60 to 120 A per 1 mm² of the electrode wire cross-section, when welding aluminum - 70 A.

For example, for wire of the Sv-12XI8N9T brand of various diameters, when burning an arc in an argon environment, the critical current has the following values:

electrode diameter, mm	1,0	2,0	3,0
critical current, A	190	280	350

In argon arc welding with a consumable electrode, more stringent requirements are imposed on assembly than in welding with a tungsten electrode; before welding, the edges of the materials to be welded and the wire must be thoroughly cleaned.

5.4 Technology of mechanized welding with flux-cored and self-shielded wire

Flux-cored wire welding is arc welding performed with a consumable electrode made of flux-cored wire.

Flux-cored wire welding can be performed with an open arc without additional protection, in carbon dioxide gas and under flux. Flux-cored wire welding with an open arc is the main way to mechanize welding when it is difficult to use mechanized methods of welding in carbon dioxide gas and under flux, primarily in installation conditions, on open construction sites. Flux-cored wire is a tubular (often with a complex internal cross-section) wire filled with a powdered filler - a charge (Fig. 64). The sheath of the flux-cored wire is made of steel (most often low-carbon) tape with a thickness of 0,2...0,5 mm. The filler is a mixture of powders from gas and slag-forming components, as well as alloying components, which provide protection of the welding zone and the required properties of the weld. The most widely used is a flux-cored wire with a diameter of 1,6 to 3,0 mm.

When welding with such a wire, both the tube and the core components are melted. As a result of the melting of the slag-forming and decomposition of the organic components of the charge, gas-slag protection of the molten metal from the air is provided. According to the composition of the core charge, flux-cored wires are divided into two main groups - rutile and basic types.

The basis of the slag-forming components of the charge of rutile-type wires is titanium oxide (IV) (the mineral rutile), gas protection is carried out by introducing organic materials. These wires are insensitive to moisture and rust, but relatively inefficient, they are more expedient to use for welding thin metal. The basic type of wires uses slag- and gas-forming components of the charge with basic and amphoteric properties (marble, magnesite, etc.). Wires of this type are more sensitive to moisture and rust, do not allow a long arc due to the formation of porosity in the seam, but they are more productive and provide higher mechanical properties.

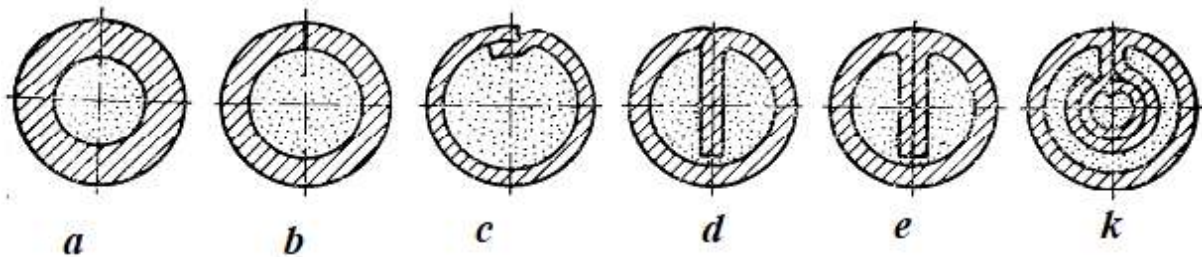


Figure 64 – Flux-cored wire designs:
a-c – simple tubular; *d* – with one sheath bend; *e* – with two sheath bends;
k – two-layer

Welding with flux-cored wires of all types is usually performed on a direct current of reverse polarity using power sources with rigid external characteristics. The disadvantages of self-shielded wire are a narrow range of welding mode parameters, deviation from which leads to a sharp deterioration in the quality of the welded joint. This disadvantage is compensated for when welding with flux-cored wires with additional protection with carbon dioxide.

Depending on the composition of the charge, flux-cored wire can be used for mechanized welding and surfacing of steels and cast iron both without protection and with additional protection (flux, shielding gas) from air.

For welding of carbon and alloy steels with an open arc, flux-cored wires PP-AN1 PP-AN3, PP-AN6, SP-3, SP-9, PPT-9, PP11, etc. are used, when welding in carbon dioxide - PP-AN4, PP-AN5. PP-AN8, PP-AN9.

The advantage of flux-cored wire is the ability to regulate the chemical composition of the weld used during surfacing within wide limits due to the filler. They can be used to surfacing products under flux, in protective gases and with an open arc. The following flux-cored wires have been developed: PP-AN120, PP-AN121, PP-AN122 - for surfacing machine parts made of carbon steels, PP-AN105 - for surfacing high-manganese steels, PP-AN170 - for surfacing high-chromium steels, and powder ribbons PL-AN101, PL-AN102, etc. When arc surfacing with flux-cored wires and ribbons, a lower current density is used compared to electrodes of a solid cross-section, which provides a smaller penetration depth and less mixing of the surfacing metal with the base metal.

Preparation and assembly of the metal for welding is performed in the same way as when welding in carbon dioxide gas and under flux. The surfaces to be welded must be cleaned of dirt, oil and rust. Tack is performed semi-automatically with flux-cored wire or manually with electrodes. The parameters of the welding mode and technique are basically the same as when welding in carbon dioxide gas: the diameter of the wire, the strength of the welding current and the associated wire feed speed are set depending on the thickness of the welded metal, the number of layers to fill the edge clearance and the position of the seam in space. Welding is performed with a short arc to reduce splashing of liquid metal, improve its protection from oxygen and nitrogen in the air, and reduce burnout of alloying elements. If the arc is too short, the stability of the arc and the quality of the seam deteriorate due to the voltage drop in it. With an increase in the wire diameter from 1.4 to 3 mm, the electrode protrusion increases from 7...10 to 20...25 mm.

The approximate modes of mechanized welding of low-carbon steel are given in Table 13.

Table 13 – Approximate welding modes of low-carbon steels with open arc flux-cored wire PP-AN1

Position of the seam in space	Wire diameter, mm	Arc voltage, V	Welding current strength, A	Welding speed, m/h	Electrode extension, mm
Bottom	2,5	22...36	250...300	12...16	10...20
	3,0	23...37	300...360	12...18	15...20
Horizontal	1,8	20...23	220...250	14...20	10...15
	2,0	22...25	240...270	16...20	12...18
	2,5	23...26	270...320	16...22	15...20
Vertical:					
Top to bottom	1,6	19...21	180...200	—	10...15
Bottom to top	1,6	20...21	160...180	—	10...15

Welding with self-shielding wire of solid cross-section is intended for mechanization of welding during installation on open sites, as well as in factory conditions, when welding in carbon dioxide gas is unsuitable.

During open arc welding, intensive oxidation of the welded and filler metal occurs, burnout of alloying elements, and pore formation. To prevent these processes, the welding wire is alloyed with elements that have a greater affinity for oxygen than the elements that burn out. Al, Ti, Zr and rare earth elements

(cerium, lanthanum, etc.) are used as such alloying elements. These elements actively bind O₂, N₂, S into stable non-metallic compounds and due to this it is possible to obtain properties of welded joints in terms of strength and plasticity at the level of the weld metal, which are obtained when welding with coated electrodes of type 346, 350. Microalloying of the wire with cerium increases the stability of the welding process and the plasticity and viscosity of the weld metal. For welding low-carbon steels in this way, Sv-15GSTUCA and Sv-20GSTUA wires are used. Preparation of metal edges, assembly, welding technique, and productivity are similar to welding in carbon dioxide. Welding is performed with direct current of both direct and reverse polarity. Approximate modes of mechanized welding are given in Table 14.

Table 14 – Approximate modes of mechanized welding with self-shielding wire of solid cross-section Sv-15GSTUTSA

Metal thickness, mm	Wire diameter, mm	Position of the seam in space	Welding current, A	Arc voltage, V
≥2	1,0	In all positions	150...170	23...25
≥4	1,2	Same	170...190	23...25
	1,6	Bottom, vertical		
		horizontal	180...220	23...25
≥6	2,0	Bottom	260...300	27...29

The technological properties of the arc when welding with this method are somewhat worse than when welding in carbon dioxide; the seam is covered with a thick film of oxides that are tightly bonded to its surface.

5.5 Semi-automatic welding machines

A welding semi-automatic is a welding machine with a mechanized feed of the welding wire, but moved manually during the welding process.

For mechanized welding and surfacing, hose semi-automatic machines with various burners are used, as well as special types of semi-automatic machines, which use additional devices, such as clamping mechanisms for welding with electric rivets. Hose semi-automatic machines are used for welding with both fusible and non-fusible electrodes. Mechanized welding is characterized by high maneuverability, the ability to weld all types of joints in almost all spatial positions, including in hard-to-reach places.

Hose semi-automatic machines are classified according to the following features:

by the method of arc protection - for welding in protective gases, under flux, without external protection (when welding with flux-cored and self-shielding wires), universal, adapted for welding with several different methods of arc protection;

by type of electrode or filler wire used - for welding with solid steel (hard) wire, aluminum alloy wire (soft), flux-cored wire, universal;

by method and speed of wire feed adjustment - push, pull, pull-push type; with smooth, step and mixed feed speed adjustment;

by layout - single-body (with a feed mechanism built into the power source housing) with a remote feed mechanism; with control equipment built into the arc power source or into a special control cabinet;

by transportability - stationary with transportation during welding by a feed mechanism, which can be mobile and portable (suitcase type, backpack, manual with a feed mechanism and a wire spool built into the torch holder);

by the method of cooling the torch - with natural (air) and artificial (water or gas).

The most common semi-automatic machines - hose - for welding in protective gases include (Fig. 65): torch 1 or a set of torches with a hose 2, electrode wire feed mechanism 3, coil 4 or other devices for electrode wire, cabinet or control unit 5 (if it is not connected to the power source), as well as wires for the welding circuit and control circuits, equipment for regulating the supply of protective gas and measuring parameters (composition, flow rate, pressure), gas hose, power source.

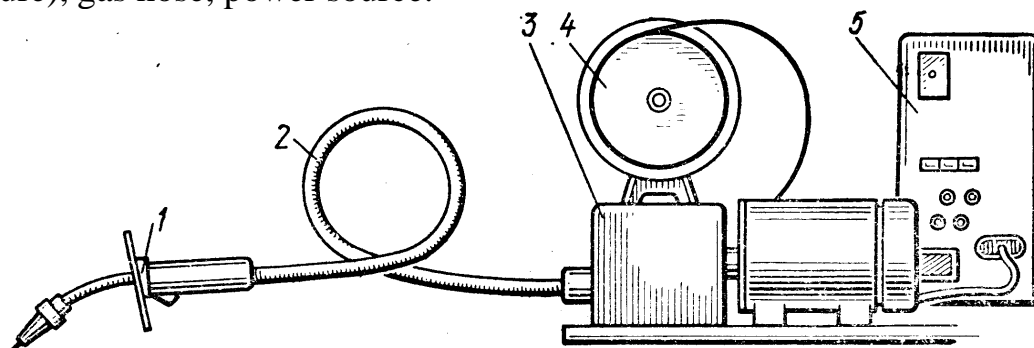


Figure 65 – Semi-automatic arc welding machine:

- 1 – torch; 2 – flexible hose; 3 – feed mechanism; 4 – wire cassette;
5 – control unit

Semi-automatic machines for submerged arc welding consist of the same components, but instead of gas equipment they have devices for supplying flux. A distinctive feature of semi-automatic machines for welding without external arc protection is the absence of gas equipment and devices for supplying flux.

The majority of torches used (~90%) are torches with natural (air) cooling of current-carrying parts and those heated by the heat of the arc. Water cooling is usually used in torches designed for currents above 400 A. According to the nature of the mutual arrangement of the main body and handle, hammer and

pistol-type torches are distinguished, the latter making up no more than 10% of the total number of torches.

The most common semi-automatic machines are push-type semi-automatic machines, i.e. those in which the electrode wire is pushed through hoses (flexible guide channels) from the feed mechanism.

The vast majority of torches have hoses up to 3 m long, usually for steel electrode wire. For welding with thin wire (diameter 0,6...1 mm) and wire from soft aluminum alloys, torches are equipped with hoses 1,5...2 m long.

Electrode wire feed mechanisms or feed mechanisms usually consist of an electric motor, a gearbox and a system of feed and pressure rollers. The drive roller, which is driven into rotation by an electric motor through a gearbox, pushes the wire through the hose into the welding zone.

The wire feed speed is regulated by step-changeable gears or rollers, as well as by smooth adjustment of the rotation frequency when using a DC motor.

Depending on the purpose, schemes with one drive roller (thin steel wire), two drive rollers (steel wire 1,6...2,0 mm, sometimes aluminum wire) and four drive rollers (aluminum and flux cored wires) are used.

The set of devices and fittings for supplying shielding gas from a cylinder or network to the electromagnetic gas valve of the semi-automatic machine includes a gas reducer and a flow meter, which are sometimes combined in one device - a reducer-flow meter. When welding in carbon dioxide gas, this set also includes a gas heater, which can be built into the reducer-flow meter (Fig. 60).

The requirements for occupational safety during welding comply with the requirements set out in clauses 2.8, 4.5.

Control questions

1. What is the essence of welding in shielding gases?
2. What methods of protecting the welding zone are used when welding in shielding gases?
3. Name the main parameters of the mode when welding with a consumable electrode in protective gases.
4. What are the features of welding in carbon dioxide gas?
5. Why is a power source with a rigid characteristic used for welding in protective gases with a consumable electrode?
6. What types of argon-arc welding with a tungsten electrode do you know?
7. What is a welding semi-automatic machine? Give a classification of semi-automatic machines.

6 FUNDAMENTALS OF CONTACT WELDING TECHNOLOGY AND EQUIPMENT FOR IT

6.1 Physical foundations and types of contact welding

Contact welding is welding using pressure, in which heating is performed by the heat released when an electric current passes through the parts to be joined that are in contact. Contact welding is the main type of pressure welding of the thermomechanical class.

The main feature of all types of pressure welding (contact, diffusion, cold, friction, etc.) is the plastic deformation of the metal in the contact zone of the parts to be joined, which is necessary for the formation of welded joints. During welding, interatomic bonds are forcibly formed between the crystal lattices of the parts to be joined. There are three main stages in the process of forming a welded joint during pressure welding: the formation of physical contact, the formation of chemical bonds, and the development of subsequent processes at the boundary of the resulting joint and in the volume of the parts.

At the first stage, the atomic surfaces are brought closer together. Irregularities and surface films are eliminated, physical contact is formed, that is, such contact of bodies at which atoms are at a distance sufficient for the beginning of interatomic interaction.

At the second stage, the electron shells are combined, chemical (for metals - metallic) bonds arise and a welded joint is formed.

At the third stage, mutual diffusion of atoms begins through the joint boundary, various processes accompanying welding develop, associated with the deformation of the metal, its heating, with structural changes in the joint zone and adjacent areas.

The main parameters of the technological process in pressure welding are the magnitude of the pressure (deformation), the heating temperature, the welding time, as well as the magnitude and speed of the mutual movement of the parts to be welded and the environment (composition of the gas phase) in which welding takes place.

The joint in contact welding is heated by an electric current passing through the metal (Fig. 66). The amount of heat Q (J) released is determined by the Joule-Lenz law:

$Q = I^2 R t$, where I is the welding current, A; R is the total resistance between the electrodes of the welding machine, Ω ; t is the current flow time, s.

The resistance R increases with increasing length l , resistivity ρ and decreasing cross-section of the conductor $F: R = m \rho l / F$, where $m \leq l$ is the surface effect coefficient due to the uneven distribution of current along the conductor.

The total resistance R consists of the resistance of the parts R_d , the resistance between the electrode and the part $R_{e.d}$ and the resistance of the welding contact R_k between the parts, i.e.

$$R = 2R_d + R_{e.d} + R_k$$

The resistance of the welding contact R_k is the largest, because the surfaces of the workpiece joints, even after careful processing, have micro-unevenness and touch only at individual points (Fig. 66, b). Due to this, the actual cross-section of the contact through which the current passes is sharply reduced, the resistance increases sharply and high current densities arise in the contact zone. In addition, on the surface of the welded metal there are oxide films and contaminants with low electrical conductivity ρ , which also increase the resistance R_k during the welding process.

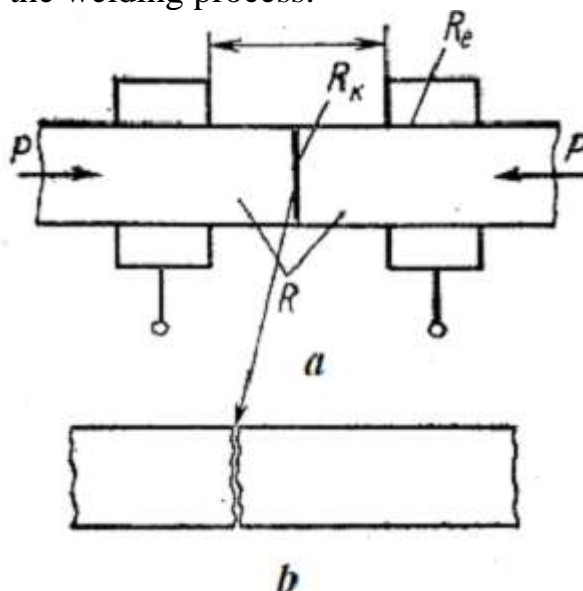


Figure 66 – Schematic diagram of contact welding:
a – welding diagram; *b* – physical contact at the joint;
 P – compression force

As a result of the high current density at the contact points, the metal is heated to a thermoplastic state or to melting. With continuous compression of the heated parts, new points of contact are formed, and so on until complete convergence to interatomic distances occurs, i.e. welding.

Contact welding is carried out without melting and with melting of the metal. In the first case, the connection occurs during deformation of the metal with the creation of physical contact between the particles of the joined surfaces and the subsequent formation of a common structure due to thermoplastic deformation, in the second case, mixing of the melt in a closed volume (spot welding) and its partial displacement (butt welding by melting) with subsequent crystallization of the melt and plastic deformation of the crystallized metal is possible.

High rates of heating, plastic deformation and cooling significantly affect the structure of the metal and the properties of the welded joint: hardness and strength increase. Joints with high hardness and unfavorable structure that do not meet operational requirements after welding are subjected to heat treatment.

Local heat treatment of the welding area can be carried out directly in the welding machine.

Due to its high productivity, reliability of joints, high level of mechanization and automation, resistance welding is used in industry. It is believed that about 30% of all welded joints are obtained using resistance welding.

Depending on the profile of the welded materials (sheet, profiled rolled metal, pipe), type of welded joint, thickness and metal, different types of resistance welding are used. The classification of resistance welding is presented in Fig. 67.

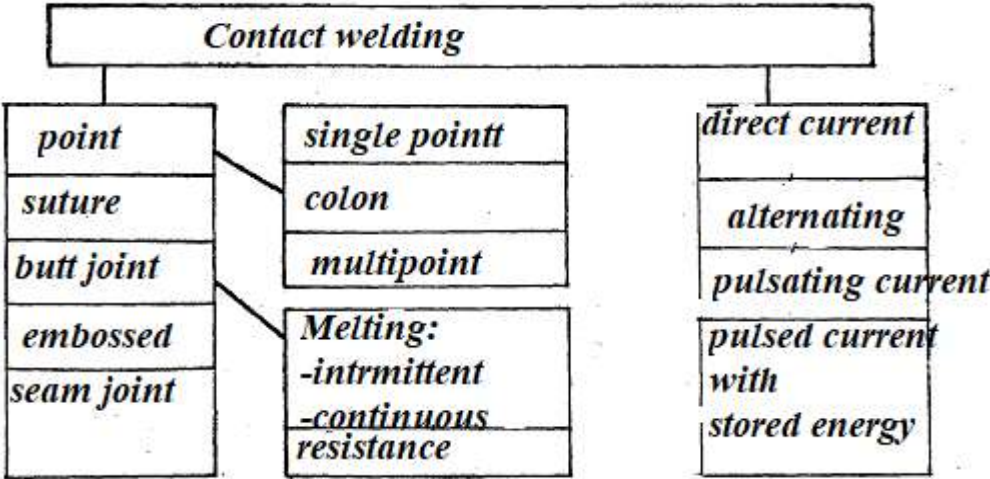


Figure 67 – Classification of resistance welding

The main types of resistance welding are butt, spot and seam.

6.2 Butt welding technology

Butt contact welding is a type of contact welding in which the connection of the welded parts occurs on the surface of the joined ends (Fig. 68). Butt welding is used to connect wire, rods, pipes, staffs, rails, chains and other parts.

During butt welding, the workpieces 1 are fixed in the clamps 2 of the butt welding machine. One of the clamps is movable, the other is stationary. The electric current is supplied from the welding transformer 3, the secondary winding of which is connected to the plates by flexible tires, and the primary is powered from the AC network through the switching device. Using the draft mechanism, the movable plate is moved, the welded parts are compressed under the force P.

A distinction is made between resistance butt welding (Fig. 68, a) and fusion welding (Fig. 68, b). Resistance welding is called butt welding with heating of the joint to a plastic state with subsequent shrinkage. Fusion welding is called butt welding with heating of the joint to fusion and subsequent shrinkage. Continuous and intermittent (pulse) fusion welding are distinguished, as well as fusion with heating.

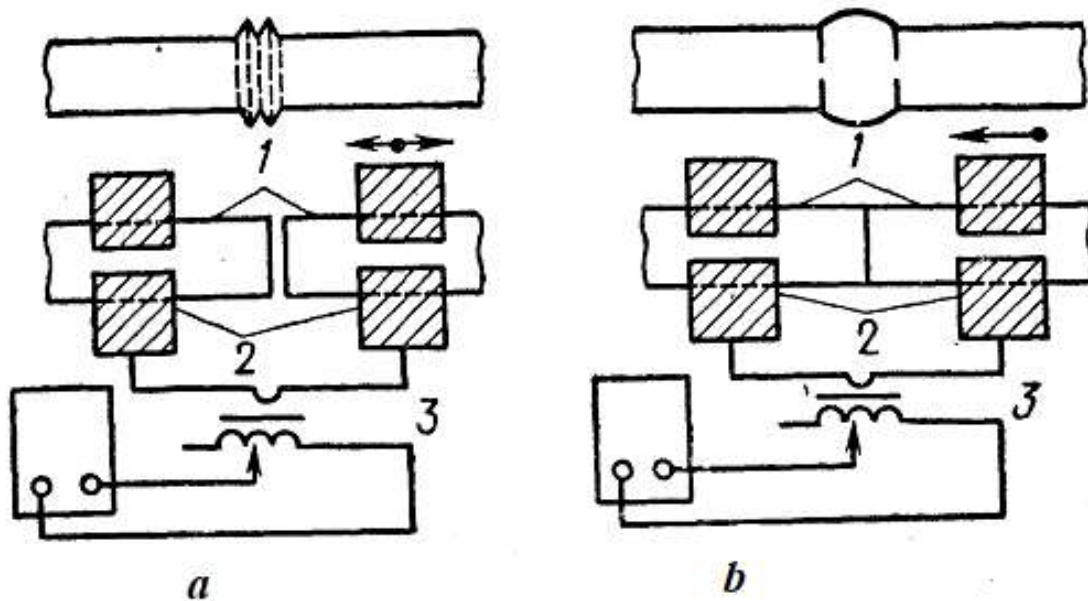


Figure 68 – Contact arc welding:
a – resistance; *b* – fusion; 1 – part; 2 – clamps; 3 – welding transformer

The parameters of the contact welding mode are the current I , A and its density j , A/mm^2 , the compressive force of the welded parts P , Pa, the current flow time t , s, the set length l , mm. The set length is the distance from the end of the workpiece to the inner edge of the electrode of the butt welding machine, measured before the start of welding.

For the correct formation of the welded joint and high mechanical properties of the joint, the process must take place in a certain sequence. A combined graphic representation of the change in parameters during welding is called a welding cycle. The contact butt welding cycle is shown in Fig. 69.

Preparation of parts for butt welding consists of operations such as shaping the contact surfaces of parts, straightening, processing the ends, and cleaning the contact areas.

Uniform heating of parts without careful preparation or pulsed current switching on during resistance welding is difficult. Therefore, the ends are made with protrusions (ring, conical, spherical), the presence of which localizes heating, facilitates resistance welding and removal of oxides. Specially prepared parts with parallel ends are well welded by fusion. Parts after mechanical or thermal cutting with cleaning of surfaces from burrs and slag are suitable for fusion welding. The skew of the contact surfaces should be no more than 15% of the reflow tolerance. Scale is removed by metal shot, etching, gas flame heating, cutting. Small parts are cleaned in tumble drums. Cleaning is automated in many industries. Rust is also removed because it decomposes in the heating zone, increases the oxidizing ability of the environment and leads to welding defects.

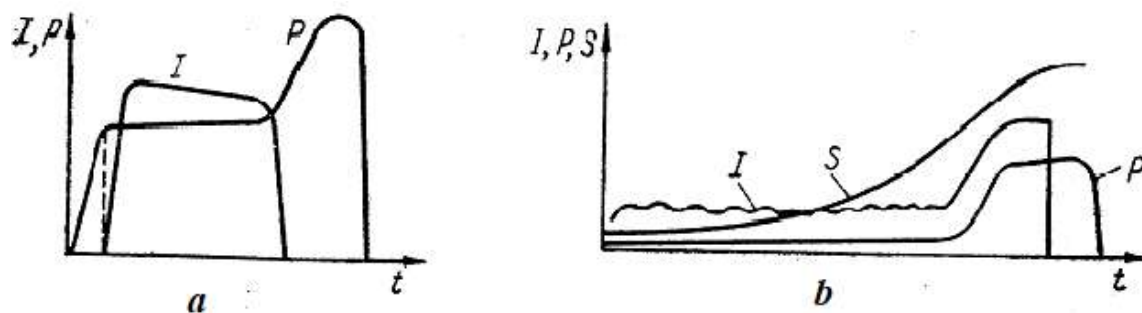


Figure 69 – Cyclograms of butt contact welding:
a – resistance; *b* – fusion; *I* – welding current; *P* – compressive force;
S – movement of the moving plate; *t* – time

In resistance welding, the cleanly machined surfaces of the parts to be welded are brought into contact, tightly compressed, and then the welding current is turned on. The passage of current through the parts leads to the gradual heating of the metal in the joint to a temperature close to the melting point. Then the force is increased (the parts are deformed). This leads to plastic deformation of the metal in the joint and the formation of a solid-state joint. In resistance welding, sufficiently complete removal of oxide films is not ensured, it is difficult to achieve uniform heating of the parts over the entire cross-section, therefore resistance welding is used only for products with a relatively small cross-section (up to 200... 250 mm²).

Butt welding by fusion is most widely used in the creation of various structures of both small and large cross-sections (up to 100,000 mm² and more). Typical products that are welded by butt welding are elements of tubular structures, wheels, rings, rails, reinforced concrete reinforcement, etc.

Continuous fusion welding is used to weld parts with a compact cross-section of up to 1000 mm², as well as sheets and pipes up to 10000 mm². When programming the voltage and using regulators, it is possible to weld parts with a compact cross-section of up to 20,000 mm². Heating, reducing the required power, allows welding products with a large area. Pulse fusion welding is used to weld parts with a compact cross-section of up to 400,000 mm² or more.

When welding with continuous fusion, the parts are brought closer together with the welding current turned on and very little effort. The parts first touch individual small areas through which a high-density current passes, which causes the parts to melt as a result of the continuous formation and destruction of bridge contacts between their ends. As a result of fusion, a layer of liquid metal is formed on the end, which, when deposited, is squeezed out of the joint along with contaminants and oxide films. The connection is formed in a solid state.

In intermittent fusion, the clamped workpieces are brought closer under current with a slowly increasing speed in a reciprocating motion.

The fusion butt welding mode is determined by the set length of the welded parts $l_1 + l_2$, the fusion allowances z_{aw} and the shrinkage z_s , the fusion speeds

vopl and shrinkage vos, the fusion currents I_{aw} and shrinkage I_s (or the voltage on the welding circuit), the shrinkage duration under current $t_{s,c}$ and the clamping force P . Heating is set by the temperature T_H or the duration t_H and the number of pulses and pauses.

Two types of process are used: with limited power W and long melting time t_{pl} or with limited t_{pl} and large W . In the first case, parts of compact cross-section, thick-walled pipes and profiles are welded, and in the second - strips, small-diameter pipes, rods and other mass-produced parts. The exact calculation of the welding mode parameters is difficult. Therefore, the parameters are selected based on experimental data with subsequent verification of the quality of the connection. For low-carbon steel, short-term continuous melting of thin-walled parts is carried out approximately at a power of 0,15...0,25 kV A/mm², with a melting current density $j_w = 10...20$ A/mm², and a deposition current $j_{oc} = 40...60$ A/mm². The heating and melting allowances must be sufficient for uniform heating of the parts and the creation of a melt layer at the ends. The speed of vopl and the duration of melting of topl depend on the voltage on the welding circuit, the required current density, the degree of heating, and the grade of the material. The speed gradually increases, sometimes reaching 6...10 mm/s. The average vopl for low-carbon steel is 1...2.5 mm/s, for alloyed steel – 2,5...3,5 mm/s and more. During productive work, the topl of parts of compact cross-section is 1 s per 30 mm², and sheets and pipes - 2...4 s per 1 mm of thickness. The deposition speed voc is chosen based on the conditions for preventing crystallization and oxidation of the melt. During productive work, the initial voc for low-carbon steel is 30...60 mm/s, for high-alloyed steels - 80...100, for aluminum and other metals that are easily oxidized, and alloys 100...200 mm/s. The approximate pressure R_s when welding low-carbon steel by continuous fusion is 50...100 MPa, when welding with heating - 40...60 MPa, for high-alloy steel - 120...200, 100...140 MPa, respectively.

Pulse fusion localizes heating and expands the high-temperature zone, thereby preventing rapid crystallization of the melt. After fusion of the entire cross-section, the current is turned off and the workpieces are deposited. Pulse fusion reduces the power required for fusion by 10...15 times to 0,02...0,03 kV A/mm² and the fusion allowance by 5...6 times. Pulse fusion is carried out at a current density $j_{aw} = 5...10$ A/mm², and to expand the heating zone in parts with a large cross-section - at $j_{aw} = 1$ A/mm². Increasing the current density localizes the heating. Pulsed fusion is 1,5...2 times faster than continuous fusion. Pulsed fusion welds both ordinary carbon and various alloyed steels and alloys.

To protect the metal from interaction with gases during butt welding of chemically active metals, protective environments (inert gases) are used.

A serious problem in butt welding is the need to remove burrs - metal squeezed out by the deposit. Burrs are cleaned manually or with mechanical devices - burr removers - immediately after welding, after cooling the joint or after heat treatment.

6.3 Spot welding technology

Spot welding is a contact welding process in which the elements are joined in areas limited by the heating area of the electrodes, which conduct current and transmit compressive forces (Fig. 70).

Spot welding is usually used to connect sheet metal structures made of homogeneous or heterogeneous ferrous and non-ferrous metals of the same or different thicknesses or sheets with rolled, pressed, forged or machined parts. Spot welding is used in the manufacture of automobile and tractor parts, agricultural machinery components, refrigerators, railway cars, microelectronics parts, household items, etc.

By the number of simultaneously welded points, spot welding can be single-, double- and multi-point. In spot welding, the parts are folded in a lap, clamped between electrodes connected to a welding transformer, when turned on, the parts are heated by a short-term (0,01...0,5 s) current pulse until a molten zone appears at the point of contact of the parts or the core of the spot. The force is maintained for some time after the current is turned off so that the crystallization of the molten metal of the spot occurs under pressure, which prevents the appearance of shrinkage defects - cracks and holes. Spot welding, depending on the location of the electrodes relative to the parts being welded, can be double-sided and single-sided. In double-sided welding (Fig. 70, a), two or more workpieces 1 and 2 are compressed between the electrodes of the spot machine. In single-sided welding (Fig. 70, b), the current is distributed between the upper and lower sheets 3 and 4, and heating is carried out by the current passing through the lower sheet. To increase this current, a conductive copper substrate 5 is provided. By one-sided welding, parts can be connected simultaneously at two points.

Preparation of parts for welding is of great importance for ensuring the stability of the welding process and obtaining high-quality joints. Before welding, parts are cleaned, straightened, adjusted and assembled in a device or clamped. Parts made of low-carbon steels are degreased with acetone, gasoline or other organic oil solvents and treated with felt or vulcanite grinding wheels, brushes, abrasive cloth or etched. Thick oxide films can be removed with rollers with a helical notch, shot blasting or metal shot treatment, flame heating, orienting of welding areas, as well as vacuum shot treatment. Prepared surfaces are passivated.

In mass production, etching is usually used, and in small-scale production and when re-welding defective areas, cleaning with brushes or sandpaper.

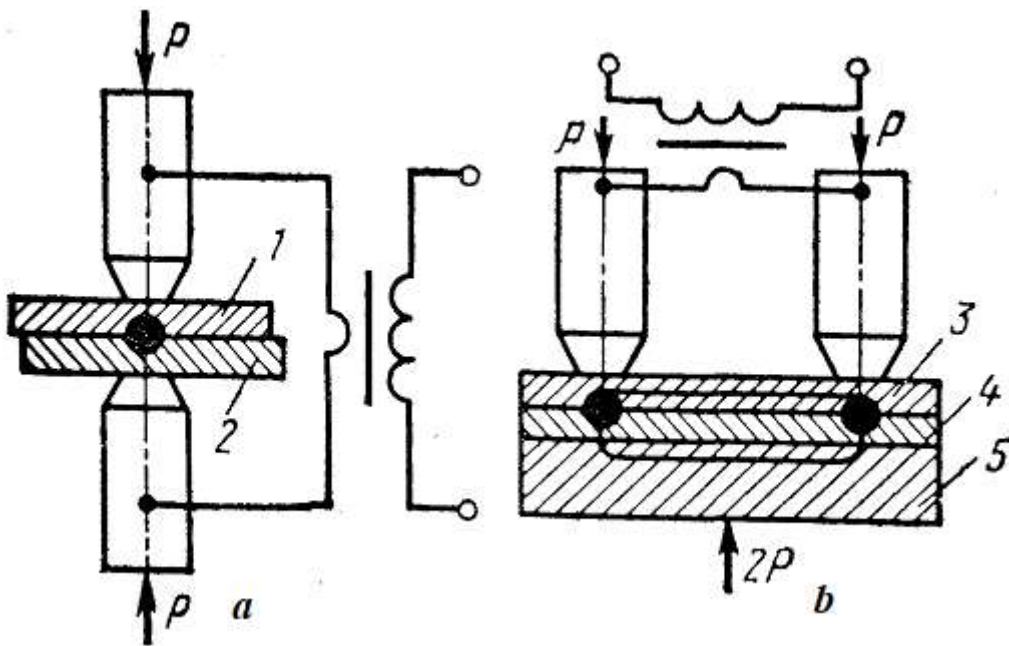


Figure 70 – Scheme of spot resistance welding:
a – double-sided; *b* – single-sided

The parts are cleaned completely or in the area of the seam. After mechanical cleaning, dust, abrasive inclusions and oxides are removed from the surfaces. Parts with metal coatings are usually not cleaned and are tacked in welding modes. Small parts and assemblies that are rigidly fixed in devices are welded without tacking. The distance between tacks in steel is 50...80 mm, in light alloys - 70...150 mm. Large assemblies are sometimes tacked by arc welding with subsequent cutting out of the tacked areas. The paired parts are straightened on presses or by local heating, which eliminates protrusions. The parameters of the spot welding mode are: compression force, current density and current flow time. One of the spot welding cycle diagrams is shown in Fig. 71.

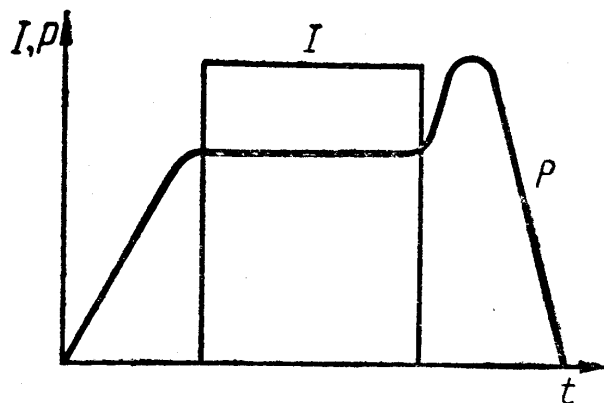


Figure 71 – Spot welding cycle diagram:
I – welding current; **P** – compression force; **t** – time

The entire welding cycle consists of the following stages:

compression of the welded parts between the electrodes;
switching on the current and heating the contact point to the melting temperature with the formation of a molten core of the spot;
switching on the current and increasing the compression force to improve the structure of the welded spot;
removing the force from the electrodes.

The mode parameters are selected taking into account the equipment that is available, according to the technological map, tables of approximate modes, nomograms or experimental work is performed.

Spot welding is carried out in soft and hard modes. The soft mode is characterized by a relatively low current density (70...160 A/mm²), a long cycle duration (0,5...3 s) at a relatively low pressure (15...40 MPa). The hard mode is characterized by high current densities (160...400 A/mm²), high pressures (up to 150 MPa) and a short welding cycle duration (0,1...1,5 s). Soft modes are used mainly in welding carbon and low-alloy steels, aluminum and copper alloys.

The approximate values of soft and hard modes of welding low-carbon steel are: current density — $j = 80... 160$ and $200...400$ A/mm²; compressive force $P = (100...200)S$, where S is the thickness of the welded sheets, electrode diameter $d_e = 2s + 2,5$ mm.

The approximate modes of spot welding of low-carbon steel are given in Table. 15. When spot welding parts of different thicknesses, the asymmetric core formed is displaced towards the thick part and, with a large difference in thickness, does not capture the thin part. The displacement is increased in soft modes, and in hard modes the danger of internal and external spatter increases. Therefore, various technological techniques are used that ensure the displacement of the core to the surfaces that are joined, increase the heating of the thin sheet due to overlays, create a relief on the thin sheet, use more massive electrodes on the side of the thick part, etc.

Table 15 – Approximate modes of spot welding of low-carbon cold-rolled steel

Thickn ess of welded sheets, S, mm	Regime									
	hard				mid			limp		
	d_e, MM	P_{wp}, H	I_{wp}, KA	T_{wp}, s	P_{wp}, H	I_{wp}, KA	T_{wp}, s	P_{wp}, H	I_{wp}, KA	T_{wp}, s
0,6+0,6	4	1250	7	0,1	1000	6	0,1	1000	5,5	0,2
0,8+0,8	4,5	1800	9	0,12	1250	8,5	0,12	1250	7	0,3
1+1	5	2250	10,5	0,16	1500	9,5	0,2	1500	7,5	0,4
1,2+1,2	6	3000	11,5	0,2	1800	10	0,24	1800	8	0,44
1,5+1,5	6,5	3500	13	0,24	2500	10,5	0,3	2500	8,5	0,54
1,8+1,8	7	—	—	—	3000	11,5	0,4	3000	9,5	0,5
2+2	7,5	—	—	—	3500	12,5	0,44	3500	10,5	0,6
2,5+2,5	8	—	—	—	3500	13,5	0,5	3500	11,5	0,8

Different materials are welded in soft modes, which makes it easier to obtain a high-quality connection by adjusting the mode parameters. For a more symmetrical placement of the core, heating is increased and heat conduction into the heat-conducting material is reduced by reducing the diameter and thermal conductivity of the electrodes.

A type of spot welding is relief welding (Fig. 72), when the initial contact of the parts occurs along previously prepared protrusions (reliefs). During relief welding, workpieces 2 and 4 are clamped between flat electrodes 5 and 1. In the initial period of welding, the presence of relief 3 makes it possible to provide concentrated heating at the point of contact at high current densities. Then the reliefs are gradually deformed and at a certain stage melting and formation of the core of the spot occur.

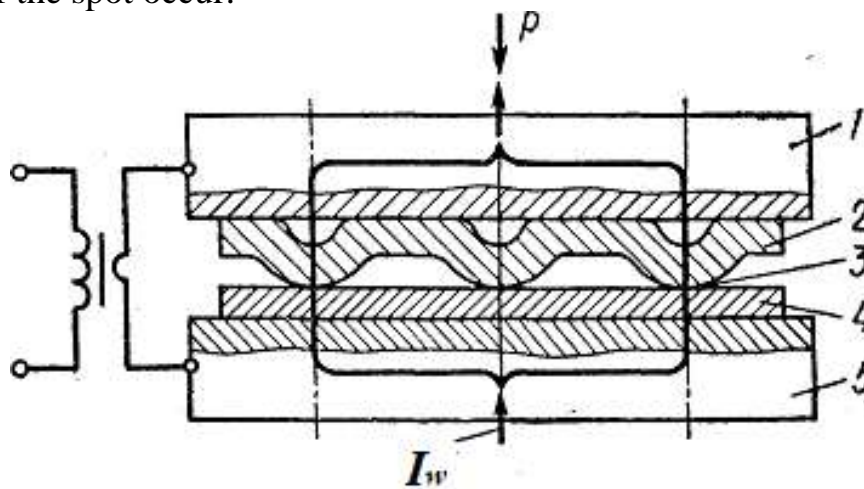


Figure 72 – Relief welding scheme

6.4 Seam resistance welding technology

Seam contact welding is a contact welding in which the elements are joined by laps using rotating disk electrodes in the form of a continuous or intermittent seam. In seam welding, a continuous joint (seam) is formed by successive overlapping of points one after another. In seam welding, the electrodes are made in the form of rotating disk rollers, which are used to transfer force to the parts, supply current, and move the parts (Fig. 73). As in spot welding, the parts are usually placed laps and heated with current without the use of special means of protecting the heated metal from interaction with the atmosphere. Seam welding, like spot welding, can be performed with one-sided and two-sided positions of the electrodes (rollers).

Seam welding is used in mass production in the manufacture of capacious products with a wall thickness of 0.3...3 mm, where hermetic seams are required - gas tanks, pipes, barrels, bellows, etc. In practice, the following methods of seam welding are used: continuous, intermittent with continuous rotation of rollers, intermittent with periodic rotation of rollers.

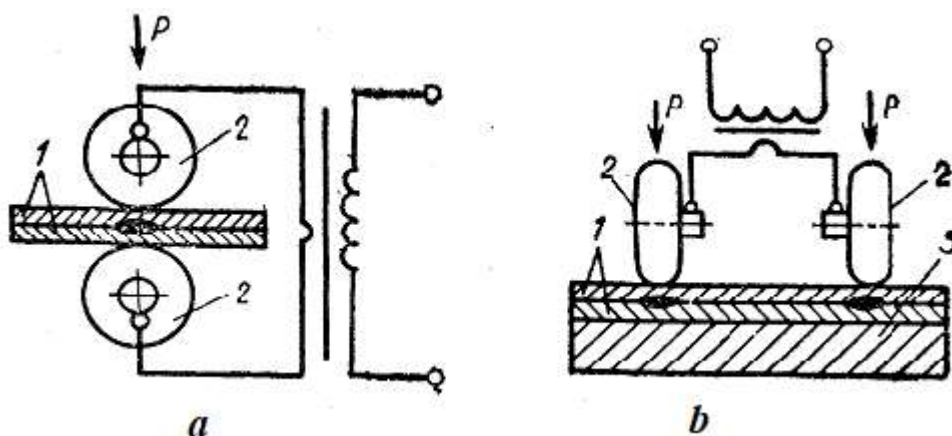


Figure 73 – Scheme of seam welding:
a – double-sided; *b* – single-sided; 1 – workpieces; 2 – electrodes;
 3 – copper lining

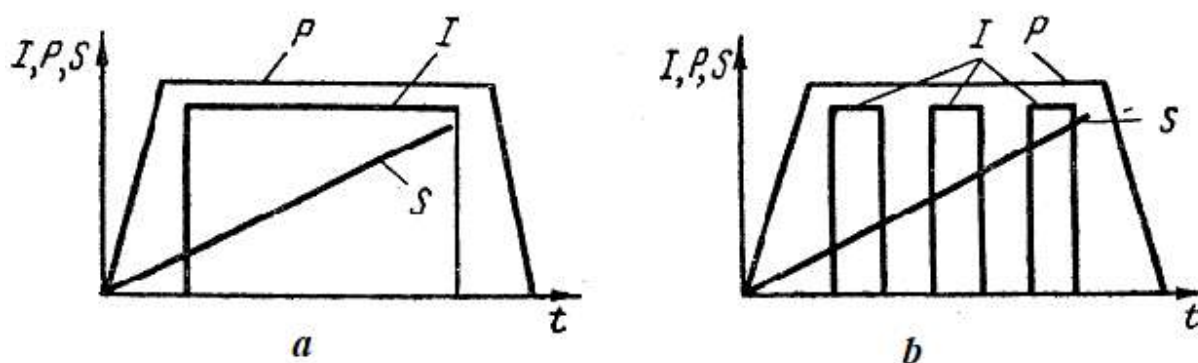


Figure 74 – Seam welding cycle diagrams:
a – continuous; *b* – pulsed current switching; *I* – welding current; *P* – pressure;
S – roller movement; *t* – time

Continuous seam welding is performed with a continuous seam with constant pressure of the rollers on the part to be welded and the welding current is constantly turned on throughout the welding process. The disadvantages of the method are increased requirements for surface preparation, uniformity of thickness and chemical composition of the metal of the welded parts.

Intermittent welding with continuous rotation of the rollers is also performed with constant compression pressure, and the welding current is applied periodically, while the seam is formed in the form of welded spots that overlap each other. The seam will be of high quality.

In intermittent welding with periodic rotation of the rollers, the welding chain is closed at the moment the rollers stop (step welding). This method provides the highest quality seam, because the formation of the welded spot occurs under compressive pressure. However, machines for this welding method are very complex and less productive.

The cycle diagrams of seam welding with continuous and intermittent current are shown in Fig. 74.

The parts for seam welding are prepared in the same way as for spot welding. If the parts are poorly cleaned, the shunting current decreases and the quality of the seam deteriorates. The groove of the parts is reduced by tacking along the seam axis with points without deep dents with a step of 50-100 mm. Very tight assembly increases the shunting of the current, and assembly with large gaps leads to metal run-in and violation of the tightness of the connection, especially on ring parts.

The mode is set by the current I_{zv} , pressure P_{zv} , diameter and profile of the electrode, welding speed v_{zv} . When step welding and welding with individual points, the welding time t_{zv} and pauses t_n are indicated.

The current during seam welding is 15...14% higher than during spot welding due to shunting and more stringent modes, the pressure is practically the same, and the welding time is shorter. The welding speed is selected according to t_{zv} and t_n taking into account the overlap of points. Approximate welding modes are given in Table. 16.

Table 16 – Approximate modes of seam welding of parts of the same thickness

Metal group	Metals	$S, \text{ mm}$	$I_w, \text{ A/mm}^2$	$P_w, \text{ kГ/mm}^2 \text{ (MПа)}$	$t_w, \text{ c}$	$s_n, \text{ c}$	$X_w, \text{ м/хв}$
1	Low carbon steel	1+1	850	22 (220)	0,06	0,06	0,85
		3+3	280	15 (150)	0,26	0,30	0,45
2	Austenitic grade steel	1+1	630	38 (380)	0,08	0,10	0,65
		3+3	210	20 (200)	0,20	0,34	0,35
3	Non-heat-hardenable	1+1	3500	35 (350)	0,12	0,28	0,25
		3+3	970	21 (210)	0,24	0,52	0,35
4	Titanium alloys	1+1	500	22 (220)	0,12	0,6	0,50
		3+3	190	14 (140)	0,32	0,46	0,30

Condenser welding. The disadvantage of contact welding is the significant short-term power consumed from the power grid at the time of welding, which creates difficult conditions for the power supply network. Types of stored energy welding have been developed. This is welding in which energy is accumulated in special devices with subsequent use for heating the parts to be joined. After accumulation in any receiver, energy is spent on welding through a welding transformer or directly for a short time. After the welding cycle, the process of energy accumulation and welding again takes place.

There are four types of stored energy for welding: electrostatic (or capacitor), electromagnetic, inertial and battery. The energy is respectively stored in a capacitor bank, the magnetic field of a special welding transformer, the rotating parts of a generator or a battery.

The most widely used is capacitor welding - welding with stored energy stored in electric capacitors. The energy in capacitors is stored when they are charged from a constant voltage source (generator or rectifier), and then, during

the discharge process, it is converted into heat used for welding. The energy stored in capacitors A can be adjusted by changing the capacitance and charging voltage; $A = CU_2/2$, where C is the capacitance of the capacitors, F; U is the charging voltage, V.

There are two types of capacitor welding: transformerless, when the capacitors are discharged directly onto the parts to be welded, and transformerless, when the capacitor is discharged onto the primary winding of a welding transformer, in the secondary circuit of which there are pre-compressed welded workpieces. Transformerless capacitor welding is intended mainly for butt welding, transformerless - for spot and seam welding, but can also be used for butt welding. The advantages of capacitor welding are: point dosing of the amount of energy, which does not depend on external conditions, in particular on the voltage in the network, short current passage time (0,001...0,0001 s) at high current density, which provides a small heat affected zone; the possibility of welding materials of very small thicknesses (up to several microns); low power consumption (0,2...2 kV A). Capacitor welding is used mainly in instrument making.

6.5 Equipment for resistance welding

Resistance welding is performed on special machines, the electrical part of which consists of a welding transformer, a welding current interrupter, a regulator (or switch) of the current of the primary circuit of the transformer and power supply devices, and the mechanical part consists of mechanisms and assemblies that create the necessary pressure to compress the parts being welded. Depending on the type of connection performed, the resistance machines are divided into butt, spot and seam, seam-butt. The schematic diagram of the resistance welding machine is shown in Fig. 75.

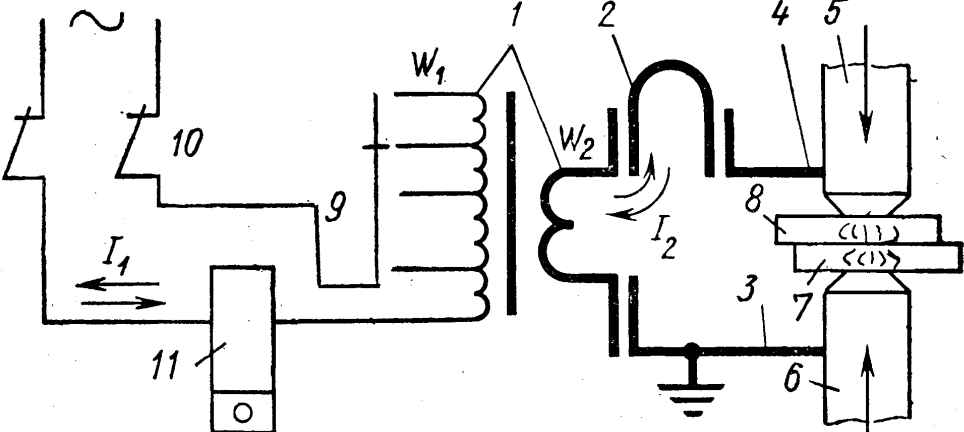


Figure 75 – Schematic diagram of a contact machine:

- 1 – transformer; 2 – flexible jumper; 3, 4 – power supply lines; 5, 6 – electrodes;
- 7, 8 – parts; 9 – switches; 10 – contactor; 11 – time controller

Each type of machine has:

an electrical part consisting of a transformer (or other energy converter), a power switch and a current switch, power cables and electrodes;

a mechanical part consisting of a frame, devices for fastening electrodes and parts, clamping units and moving parts;

control equipment with mechanical, electrical, hydraulic, pneumatic and other devices.

Structurally, typical spot and relief machines are similar. Seam welding machines have an additional drive for rotating electrodes, and butt welding machines have a drive for approaching parts at low speeds during melting and high speeds during deposition.

Alpha-numeric numbering is used to designate machines. The first letter characterizes the type of machine; U – installation, A – automatic, M – machine, K – complex, P – semi-automatic; the second – type of welding; the first two digits – rated current, kA, and the last two – machine model. For example, a model of a 5-point machine with a rated current of 20 kA is designated MT-20.05. Sometimes after the first two letters a third is added, which specifies the type of machine: M – multi-point, K – capacitor, B – with current rectification in the circuit.

Contact machines operate on alternating current from transformers. The primary winding of the transformers is connected to a network with a voltage of 220...380 V, it is made in sections to change the number of working turns when switching power levels. The secondary winding of the transformer consists of one or two turns (secondary voltage 1...12 V). The secondary current strength is 1000...100,000 A.

When the number of turns of the primary winding changes, the transformation ratio changes: $K = W_1/W_2 = U_1/U_2$, where W_1 and W_2 are the number of turns of the primary and secondary windings; U_1 and U_2 are the primary and secondary winding voltages, respectively.

Secondary voltage $U_2 = U_1 W_2/W_1$, where $W_2 = 1$, U_1 is a constant value.

Therefore, to change U_2 , it is necessary to change the number of turns of the primary winding W_1 turned on, and the secondary welding current will change accordingly. To increase the secondary current, it is necessary to reduce the number of turns of the primary winding of the transformer.

Contact machines are turned on and off from the side of the primary winding of the transformer. During welding, it is necessary to periodically turn on and off the current. For this, several types of interrupters are used: simple mechanical contactors, electromagnetic and electronic devices.

Mechanical contactors are used mainly on butt and spot machines of non-automatic action of low power, electromagnetic contactors - for butt and seam welding on machines of low and medium power. Electronic interrupters provide synchronous switching on and off of the current with a strictly defined duration of pulses and pauses, they are used for all types of automatic contact machines.

Pressure mechanisms are used to compress the workpieces between the electrodes of the machine. Depending on the type of drive, the compression mechanisms can have spring, electromechanical, pneumatic, pneumohydraulic,

hydraulic drives, as well as manual, which is sometimes used in low-power butt and spot machines.

Butt welding machines are produced with a capacity of 0,8...800 kVA (MS-403, MS-502, MSMU-150, etc.). Butt welding machines with a capacity of up to 25 kVA are used for resistance welding, with a capacity of 25...250 kVA - for resistance and fusion welding, with a capacity of 150...800 kVA - for automatic fusion welding of products with a large cross-section.

Spot welding machines (MT-601, MT-1220, MT-1616, MT-4001, MT-8002, MTV-16002, MTK-1601, etc.) are produced with a power of 0,1...25 kVA, used for welding parts with a thickness of 0,1...2 mm.

Seam welding machines (MSh-1001, MSh-1601, MSh-2001, etc.), unlike spot welding, have a roller electrode drive mechanism and a special sliding current supply. Seam welding machines are produced with a power of 25...200 kVA.

Condenser welding machines consist of a capacitor bank, rectifiers, a welding transformer (for transformer welding), a welding current switch, auxiliary devices and a welding table. Depending on the type of welded joint, spot, seam, and butt condenser machines are produced, which can be universal (automatic and mechanized) and specialized.

6.6 Safety requirements for resistance welding

When working on contact machines, the following are dangerous: electric current, molten metal particles flying out at high speed from the connection zone, and moving parts of the machines.

Contact welding is performed at low (up to 36 V) voltages, high-voltage electric shock is possible when the machine is not grounded, or in the event of a transformer breakdown, when switching the voltage without disconnecting the transformer from the network. Modern contact machines have locking systems that prevent high-voltage electric shock, for example, access to the switch is closed when the primary circuit is not switched off; doors of cabinets, panels, and frames with open live parts that are under voltage have locks that ensure voltage relief when they are opened. Operation of machines with faulty locks is not allowed. All work related to voltages of 220 and 380 V must be performed by a specialist electrician. A welder is allowed to perform such work only after special training and passing an exam.

Protection from molten splashes and prevention of burns are provided by working in overalls - this is a fire-resistant cotton or canvas jacket, gloves, colorless closed-type glasses, and for butt welding - additionally a helmet.

Contact welding machines for fusion welding must be equipped with a transparent shield that protects workers from splashes and sparks and allows you to observe the welding process. Spot and roller contact machines must have folding transparent screens that protect the electrodes from the service side.

Most accidents are associated with air or oil leaks in drive systems, with burning contact devices, with unskilled repair and improper operation. Therefore, machines must be operated strictly in accordance with the instructions and with compliance with welding technology.

Control questions

1. What is the essence of pressure welding?
2. How is a joint formed during resistance welding? Give a classification of resistance welding.
3. What are the main components of contact machines?
4. What are the essence and technological features of butt, spot, seam, and contact welding?
5. What is the essence of stored energy welding?
6. Basic safety requirements for contact welding.

7 SPECIAL TYPES OF WELDING

7.1 General information

Modern technology is characterized by the increasingly widespread use of new structural materials that have special properties: high heat resistance, heat resistance, corrosion resistance, radiation resistance, etc.

For this purpose, refractory metals Ti, Zr, Nb, Mo, W and alloys based on them, multilayer (composite) materials, as well as non-metallic materials based on ceramics and polymers are used.

Welding of these materials with high quality of welded joints can in principle be carried out under the following conditions: short-term heating of the metal to high temperatures, ideal protection of the metal from atmospheric air, the use in some cases of high speeds of the welding process. Most of these metals are distinguished by very high chemical activity not only in the molten state, but also in the solid state and at temperatures of more than 200...300 ° C, react intensively with all known fluxes used for conventional structural materials. Therefore, for these materials, such types of welding as manual arc welding with a consumable electrode, submerged arc welding, gas welding, and limitedly used welding in inert gases turned out to be unacceptable. The disadvantages of these types of welding are a relatively small concentration of energy in the heat source and insufficient protection of the metal from the action of oxygen and nitrogen in the air. Prolonged exposure to high temperatures on the metal of the welded joint with insufficient protection leads to loss of plasticity, anti-corrosion and other properties, high energy consumption, significant final deformations, saturation of the weld metal with gases, etc. These disadvantages can be eliminated by using special types of fusion welding and pressure welding in the solid state. As special types of fusion welding in welding technology, radiant heat sources are used, the energy concentration in which is 100...1000 times higher than in traditional sources. Radiant energy sources are used in electron beam welding, laser and light welding. In electron beam welding, the energy carrier is electrons, in laser and light welding, photons. High energy density in the heating spot is achieved by concentrating the energy flux using focusing devices. The heating area of an electron beam can be 1000 times smaller than that of a gas flame and an arc (see Table 1) with an energy density 1000 times higher. When using a photon beam, this difference is even greater. High energy density in a small heating spot determines the main advantages of electron beam and laser welding - a favorable form of penetration (knife, dagger and the possibility of obtaining precision joints. However, when welding with a deeply buried beam, additional difficulties arise: a high risk of

formation of pores and hot cracks, fluctuations in the depth of penetration and undercuts, high requirements for the quality of assembly and preparation of the metal for welding. Plasma and microplasma welding can also be attributed to special types of fusion welding. Special types of pressure welding (cold, ultrasonic, friction, explosion, diffusion) in contrast to contact electric welding are carried out, as a rule, without melting the contact surfaces. The formation of metallic bonds between the surfaces to be joined in these types of welding occurs in the solid state of the metal as a result of mutual plastic deformation. Types of welding in the solid state differ in the methods by which plastic deformation is carried out, the magnitude of the plastic deformation and temperature regime.

These types of welding are divided by the degree of heating - with heating and without heating, by the degree of force action - with low-intensity and high-intensity action. Pressure welding with heating is performed, as a rule, with high-intensity force action. These include: diffusion, thermocompression welding, pressure welding without heating is performed with high-intensity force action. These types include explosion welding, cold, magnetic pulse, etc. Ultrasonic welding belongs to welding without heating with low-intensity external force action. The parameters of these types of welding (pressure, heating temperature, heating time, specific pressure, intensity of pressure and temperature) depend on the properties of the materials being joined, the condition of their surfaces, design features, etc.

Solid-state welding significantly expands the field of application of welding, allows you to connect not only homogeneous, but also dissimilar metals, welding by fusion of which would be impossible, to connect non-metallic materials with metals, etc.

The use of vacuum as protection in a number of special types of welding (electron beam, diffusion, etc.) makes it possible to protect the materials being welded and obtain high-quality welded joints.

Special types of welding allow you to carry out the so-called precision welding, that is, to obtain structures with specified design dimensions, to automate welding production using advanced welding equipment with software control.

7.2 Plasma welding

Plasma welding is fusion welding in which heating is carried out by a compressed arc.

A compressed arc is an arc whose column is compressed by a plasma torch nozzle or a gas flow (argon, nitrogen, etc.). Plasma is a gas consisting of positively and negatively charged particles, the total charge of which is zero.

Plasma is generated in the nozzle channel, compressed and stabilized by its water-cooled walls and cold plasma-forming gas. Compression and cooling of the outer surface of the arc column causes its concentration, which leads to a sharp increase in the number of collisions between plasma particles, an increase in the degree of ionization and a sharp increase in the temperature of the arc column (up to 10,000...20,000 K) and the kinetic energy of the plasma used for welding and cutting. A device for creating a directed plasma flow that moves at high speed and has a large energy reserve is called a plasma torch or plasma torch.

There are several schemes of devices for creating plasma arcs and jets:
 to obtain a plasma arc, when the nozzle and channel are combined, the plasma jet coincides with the arc column, one of the electrodes is the material being processed (Fig. 76, a);

with obtaining a plasma jet separated from the arc column with separate nozzles and channels (Fig. 76, b);

the same, but with a combined nozzle and channel (Fig. 76, c).

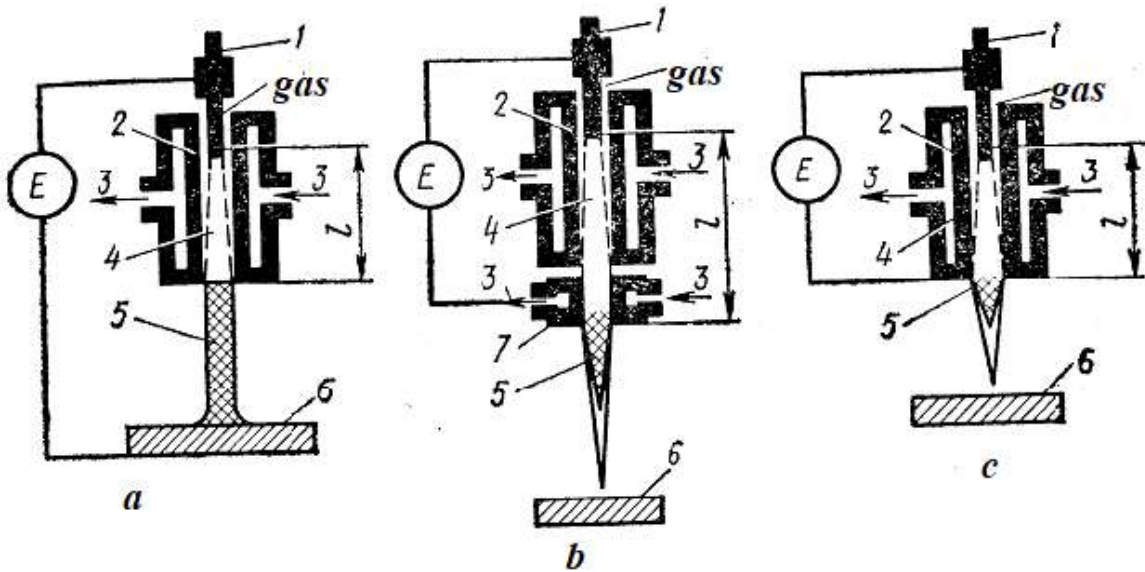


Figure 76 – Schemes of plasma arc welding (a) and plasma jet (b, c):
 1 – electrode; 2 – channel; 3 – cooling water; 4 – arc column; 5 – plasma jet;
 6 – product; 7 – nozzle;
 E – current source; 1 – length of the working part of the channel

The plasma jet is created by an arc discharge 4, which is excited between the electrode 1 and another electrode, which can be the product 6, the separate nozzle 7 or the walls of the channel 2.

The effective efficiency of plasma-arc heating is lower than the efficiency of the arc, which is explained by the large heat transfer to the nozzle walls and the surrounding space, and is $\eta_j = 0,3...0,8$.

Plasma arc welding is carried out by alternating or direct current of direct polarity. The arc is excited using an oscillator. To facilitate the excitation of the direct-action arc, a secondary arc is used, burning between the torch nozzle and the electrode. To power the plasma-forming arc, welding current power sources with an operating voltage of up to 120 V, and in some cases higher, are required.

A plasma (compressed) arc can be used to weld almost all metals in different spatial positions. Argon and helium are used as plasma-forming gases, which can also be protective. The advantages of plasma welding include high productivity, low sensitivity to arc length fluctuations, and elimination of tungsten inclusions in the weld metal. Without beveling the edges, it is possible to weld metal up to 15 mm thick with the formation of a specific mushroom-shaped penetration, which is explained by the formation of a through hole in the base metal, through which the plasma jet exits to the back side of the product. In essence, the process is cutting through the product with welding the cut site.

Butt and fillet welds are welded with a plasma jet. Butt joints on metal up to 2 mm thick can be welded with edge flanging; for thicknesses greater than 10 mm, it is recommended to bevel the edges. When necessary, additional metal is used. When welding sheets up to 25 mm thick, V- or U-shaped edge cleaning is required, and the depth and angle of cleaning are much smaller than for argon-arc welding. In plasma arc welding, the amount of filler metal is reduced by about 3 times. The filler metal is introduced into the plasma jet at the end of the weld pool.

Plasma arc welding gives the greatest advantages when joining sheets without filler metal. Multi-pass plasma arc welding of thick sheets should not be accompanied by through-penetration, therefore, when laying subsequent layers, the force action of the plasma jet is regulated by changing the flow rate of the plasma-forming gas so that the molten metal is not squeezed out of the weld pool.

Approximate modes of plasma arc welding of some metals with through-penetration are given in Table. 17 (aluminum welding was carried out in reverse polarity, welding of other metals in direct polarity).

A significant amount of welding work is made up of welding of metals and alloys of small thicknesses (0,05...1,5 mm). Among the known methods of joining metals of small thickness, gas welding, brazing and arc welding with a non-consumable electrode in continuous and pulsed modes have become widespread. However, the low heating rate, large heat-affected zone in gas welding, and in arc welding, low arc stability at low currents and a strong dependence of the seam parameters on the arc length complicate the welding process, and in some cases make it impossible. The use of other welding methods (contact, electron beam, laser, diffusion) is not always possible due to various design, technological and operational factors.

Table 17 – Approximate modes of plasma arc welding of butt joints without filler metal

Metal	Thickne ss, mm	I_w, A	U_w, B	$V_w,$ $M/x\epsilon$	Nozzle diameter, mm	Gas consumption, m^3/h	
						Plasma- forming	focusing and protective
Stainless Steel	2,5	160	30	0,9	-	0,14	1,0
	5,0	240	38	0,4	-	0,35	1,3
	6,4	240	38	0,3	-	0,5	1,4
	12,5	300	35	0,2	2,4	0,14	1,4
Titanum	3,0	180	22	0,5	-	0,23	0,85
	5,0	190	26	0,4	-	0,35	1,3
	12,5	280	38	0,25	2,4	0,12	0,85
Mild Steel	6,4	305	35	0,25	2,4	0,06	1,4
Aluminum	6,4	85	27	0,25	2,4	0,085+0,03	0,85

Work on plasma welding at high currents has shown that the compressed arc, which is formed by the plasma torch channel, has a much greater spatial stability than the one that burns freely, and the separate supply of plasma-forming and shielding gases allows the use of various gas mixtures during welding. The above-mentioned advantages of the compressed arc are also suitable for welding metals of small thickness (< 1 mm), which led to the emergence of an essentially new welding method - microplasma, i.e. welding of thin and especially thin materials with a compressed low-current arc. The compressed arc, which is used in this method as a concentrated source of heat, was called microplasma. Microplasma is formed by special burners - plasma torches, the schematic diagram of which corresponds to Fig. 76. The use of a secondary arc ensures the stability of the process even at very low currents, up to $I_{arc} \approx 0,1$ A, which allows welding of very thin metal ($\sim 0,01$ mm), which cannot be welded by argon arc welding. The vast majority of metals are welded in continuous or pulsed modes with a direct polarity arc burning between the tungsten electrode of the plasma torch and the product in a jet of plasma-forming inert gas (usually argon). To prevent the interaction of the molten pool of liquid metal and the surrounding area with the atmosphere, a shielding gas is

supplied along the periphery of the arc: Ar, He, N₂, CO₂, mixtures of Ar with N₂, Ar with He, Ar with N₂ and others, depending on the properties of the welded metal. Separate supply of plasma-forming and shielding gases determines a distinctive feature of microplasma: its near-cathode zone (on the electrode) exists in the plasma-forming gas environment, and the column and near-anode zone (on the product) - mainly in the shielding gas environment. This circumstance allows you to flexibly control the shape of the arc and its technological capabilities.

Table 18 shows the optimal modes of mechanized microplasma welding of low-carbon steel 08kp with a thickness of 0.5 mm.

Table 18 – Approximate modes of microplasma welding of steel 08kp

Conne ction	Welding mode	Welding speed, m/h	Arc current, A		Time, s		Gas consumption, l/min	
			next	working	pulse	pause	of the protective	plasma- forming
Butt	Pulse	25...30	2,5	20...22	0,065	0,03	1	0,5
End	Conti- nuous	25...20	2,5	26...28	-	-	1	0,5

When welding chemically active and refractory metals (Ti, Zr, Nb, Ta, Mo, W), it is necessary to use more effective means of protection with a minimum content of gases. For welding such metals, a method of plasma welding in a vacuum ($133 \cdot 10^{-1} \dots 5 \cdot 10^{-4}$) Pa has been developed, which provides good quality of metal joints with a thickness of more than 1 mm. This is achieved due to the contraction (compression) of the low-pressure arc, which is observed at currents above 80 A. Powering the arc with pulses allows you to reduce the average welding current while maintaining a high density during the pulse. By selecting the parameters of the pulse mode (current amplitude, duration, frequency of their passage), you can regulate the average current (2,5...50 A) and power (0,1...2,5 kW) of the low-pressure plasma arc in a wide range. At the same time, it is possible to weld metal of a fairly small thickness (0,1...0,2 mm).

Direct-action microplasma has found wide application for welding and cutting thin metals: carbon and stainless steels, non-ferrous metals and their alloys, chemically active metals.

For soldering, welding foil and thin meshes, and for processing thin non-metallic materials, side-action microplasma is used.

7.3 Beam welding types

Electron beam welding is fusion welding, in which the metal is heated by an electron beam. An electron beam is a stream of electrons emitted by a single source and moving along close trajectories in a certain direction. The essence of the electron beam welding process in a vacuum is to use the kinetic energy of electrons. When the metal surface is bombarded with electrons, the majority of their kinetic energy is converted into heat, which is used to melt the metal.

The electron beam is created in a special device—an electron gun (Fig. 77), with the help of which narrow electron beams with a high energy density are obtained. The gun has a cathode U, which can be heated to high temperatures. The cathode is placed inside the cathode electrode 2. At some distance from the cathode there is an accelerating electrode (anode) 3 with a hole. The electrons coming out of the cathode are focused by means of an electric field between the cathode and accelerating electrodes into a beam, the diameter of which is equal to the diameter of the hole in the anode 3. The positive potential of the accelerating electrode can reach several tens of thousands of volts, so the electrons emitted by the cathode acquire significant speed and energy on the way to the anode. The gun is powered by electric energy from a high-voltage direct current source 7.

To increase the energy density in the beam after the electrons leave the first anode, the electrons are focused by a magnetic field in a special magnetic lens 4. The flying electrons, focused into a dense beam, hit at high speed a small, sharply limited area (heating spot) on the product 6, while the kinetic energy of the electrons due to braking is converted into heat, heating the metal to very high temperatures. To move the beam along the welded product, a magnetic deflecting system 5 is placed in the path of the electrons, which allows the beam to be set exactly along the joint line. To ensure free movement of electrons from the cathode to the anode and further to the product, for thermal and chemical insulation of the cathode, and also in order to prevent the formation of an arc discharge between the electrodes in the welding installation, a deep vacuum of the order of $133 \cdot 10^{-4}$ Pa is created by a vacuum pump system.

The power of the electron beam can reach very high values, which makes it promising for welding large thicknesses (200...500 mm). The possibility of high energy concentration while using low power allows electron beam welding of microelectronic products.

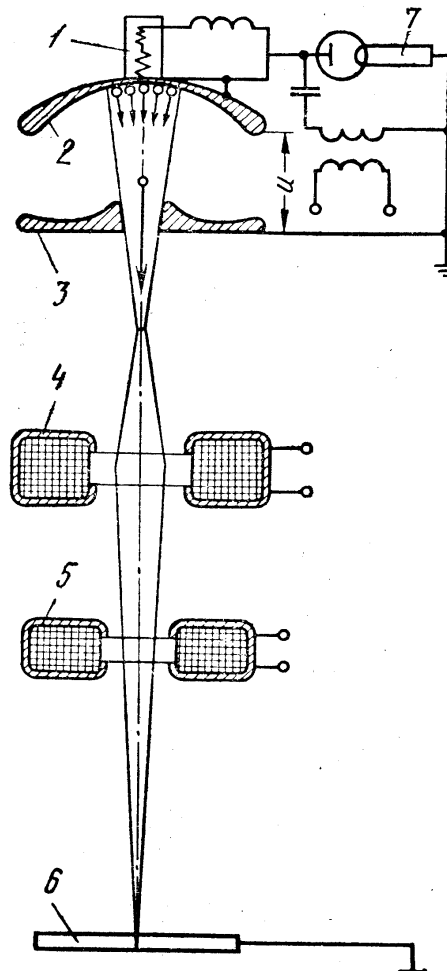


Figure 77 – Schematic diagram of an electron beam welding installation

The main parameters of the electron beam welding mode are current strength, electron beam voltage, welding speed. The accelerating voltage and beam current strength determine the power of the energy source. For example, the recommended modes of electron beam welding of titanium alloys with a thickness of 8...15 mm in the lower position and the technological substrate remaining: $U_w = 30$ kV; $I_w = 100...180$ mA; $v_w = 25...35$ m/h.

In the pulsed mode of electron beam welding, heat release is additionally regulated by the frequency and duration of welding pulses. The effective efficiency η_j of electron beam heating varies within 0,7...0,9.

Laser welding – fusion welding, in which the energy of a light beam obtained from an optical quantum generator is used for local melting of the parts to be joined. The essence of obtaining a laser beam is that due to the pumping of external energy (electric, light, thermal, chemical), the atoms of the active substance of the emitter pass into an excited state. After a certain period of time, the excited atom can emit the received energy in the form of a photon and return to the initial state. A photon is an elementary particle, a portion of light, which has zero rest mass and moves at a speed equal to the speed of light in a vacuum. Photons arise (are emitted) in the processes of transition of atoms, molecules, ions and atomic nuclei from excited states to more stable states with lower

energy. At a certain degree of excitation, an avalanche-like transition of the excited atoms of the active substance-emitter to a more stable state occurs. This creates coherent, i.e., excitation-related, light monochromatic radiation, which is amplified in the emitter by multiple reflection from its walls and is emitted in the form of a narrow directional beam. Monochromatic radiation is electromagnetic radiation of one specific frequency. Thus, a laser beam is created - a monochromatic directed stream of photons.

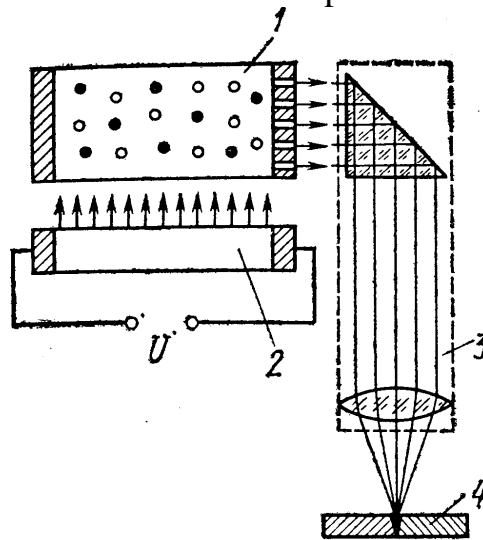


Figure 78 – General layout of the laser installation

By the type of active substance-radiator, lasers are divided into solid, gas, liquid and semiconductor, by the principle of laser beam generation - pulsed and continuous. Currently, solid-state and gas lasers are used for welding. In modern solid-state lasers, optical glass with an admixture of neodymium and other rare-earth elements is used as an active element. This allows you to increase the output power of radiation. Solid-state lasers operate in a pulsed mode. The general layout of a solid-state laser welding installation is shown in Fig. 78.

The installation consists of a working medium 1, a pump lamp 2, which provides light energy to excite the atoms of the active substance-radiator. The radiation obtained is focused and directed using an optical system 3 to the welded product 4. The power of solid-state lasers is small – 0,015...2 kW.

Gas lasers have a higher output power, operate in continuous and pulsed modes and, in terms of their technological capabilities, become competitive with electron beam welding.

The advantages of a laser beam are: the ability to transmit energy over long distances in a non-contact manner; welding through transparent shells, because transparent media are not an obstacle for light rays; obtaining high-quality joints on metals that are especially sensitive to prolonged exposure to heat; welding in air, in a protective atmosphere, and in vacuum. An important area of application of laser welding is the welding in microelectronics, radio electronics, and electronic engineering of microjoints both from homogeneous metals and from

different compositions (gold – germanium, gold – silicon, nickel – tantalum, copper – aluminum, etc.).

The use of continuous lasers on carbon dioxide makes it possible to obtain welded joints up to 15 mm thick or more. In the future, it is possible to increase the thickness of welded products and use the laser for heat treatment and metal cutting. The main disadvantages of the laser energy source are low efficiency values of the installations, high cost of equipment, and insufficient power of serial equipment.

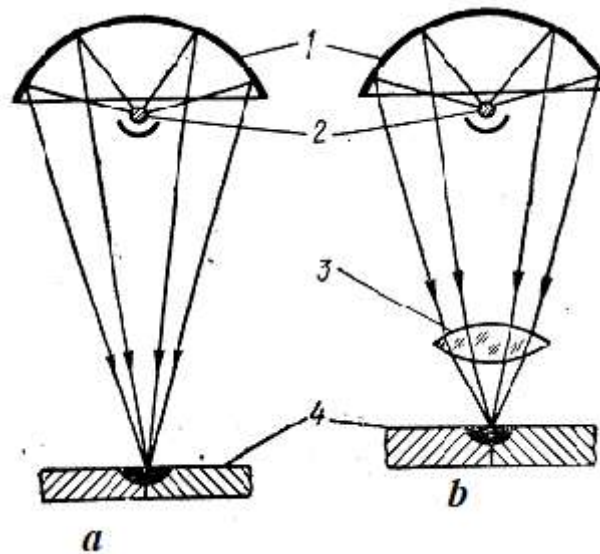


Figure 79 – Schemes of optical systems for welding and soldering:
a – without lens optics; *b* – with additional lens optics;
 1 – reflector; 2 – light source; 3 – optical lens; 4 – product

In installations for welding and soldering with a light beam, such radiation sources as the sun, a carbon arc, arc gas-discharge lamps and incandescent lamps can be used. For technological purposes, the most promising and convenient emitters are ultra-high-pressure arc xenon lamps. An arc xenon lamp is a spherical cylinder made of optically transparent quartz with two tungsten electrodes placed in it. The pressure of xenon in the lamp in the idle state reaches 1 MPa.

In systems used for welding with a light beam, the energy concentration in the heating spot reaches 10^3 W/cm^2 and can be increased by using special lenses and reflectors. The schematic diagram of optical systems for welding and soldering is shown in Fig. 79. The industry of rational application of the process is instrument making.

7.4 Special types of pressure welding

Cold welding – pressure welding with significant plastic deformation without external heating of the joined surfaces. The physical essence of the process is to approach the formation of metallic bonds between the welded surfaces due to plastic deformation and thus obtain a strong welded joint. A

distinctive feature of cold welding is the need for significant volumetric plastic deformation and a small degree of its localization in the contact zone of the joined materials. This is due to the need to destroy and remove oxide films from the contact zone mechanically, that is, due to intense combined deformation. A large compressive force ensures the rupture of oxide films, their grinding and the formation of clean surfaces capable of setting.

The weldability of metals during cold welding depends on their plasticity and the quality of surface preparation. The more plastic the metals, the smoother and cleaner their surfaces, the better they are welded. Plastic alloys of aluminum, copper, nickel, silver, gold and other similar metals and alloys in homogeneous and heterogeneous combinations are well welded. Cracks can form in insufficiently plastic metals with large deformations. High-strength metals and alloys are not welded by cold welding.

Cold welding has found its greatest application in the production of household products from aluminum and its alloys, in the electrical industry and transport for connecting copper and aluminum wires. Cold welding is used to make spot, seam, butt joints. Before welding, the surfaces to be welded are cleaned of contamination by degreasing, processing with a rotating wire brush, scraping. When butt welding the wires, only the ends are cut. For cold welding, standard press and rolling equipment is used, which is equipped with a special tool according to the parts to be welded, and specialized machines are also used.

Cold welding is used to join metals and alloys with a thickness of 0.2...15 mm. The main characteristics of the process are pressure and deformation. Depending on the composition and thickness of the welded metal, the pressure is 150...1000 MPa, the degree of relative deformation is 50...90%, which has the following values for different metals, %: Au - 35...40; Al - 55...60; Ti - 70...75; Pb and Ag - 80...85; Sn, Ni, Cu - 85...90; aluminum alloys - 75...80.

Sheets with a thickness of 0.2...15 mm are welded by indentation into the thickness of the metal from one or both sides of the punches. The connection is made in the form of individual points or a continuous seam. The width or diameter of the punch d_p is selected depending on the thickness S of the welded material, $d_p = (1...3)S$. A sealed seam connection can be obtained by pressing the punch along the entire length of the seam or by rolling the roller.

Rods, bars, profiles and wires are joined butt by compressing the welded elements. The pressure during cold butt welding is 700...800 MPa for Al, 2000...2500 for Cu, 1500...2000 MPa for Cu with Al. The magnitude of plastic deformation depends on the length of the ends of the welded rods released from the clamps, which are then completely squeezed out of the joint zone during the welding process. To ensure the strength of the connection, which depends on the amount of plastic deformation, the length of the rod extension is for Al -

$(1...1,2)d$, for Cu - $(1,25...1,5)d$, where d is the diameter of the rod. When welding Al with Cu, the extension of the copper rod should be 30...40% greater than that of the aluminum rod.

The degree of required deformation when welding dissimilar metals is determined by the properties of the metal being welded, for which less deformation is required. This is used when welding low-plastic metals, using gaskets made of plastic metals or layers applied electrolytically.

A type of pressure welding, close in physical essence to cold welding, is thermocompression welding, which differs from cold welding in that the joint is heated to a temperature below the temperature of formation of liquid phases, and then compressed. The main parameters of the process are the compression force, the heating temperature and the holding time.

Ultrasonic welding – pressure welding, which is carried out due to its ultrasonic vibrations. In this type of welding, an inseparable connection is formed as a result of the combined action on the parts to be welded of mechanical vibrations of high (ultrasonic) frequency and relatively small compressive forces. Welding occurs as a result of mutual friction of the welded surfaces, heating and pressure. Friction forces arise when mechanical vibrations of ultrasonic frequency (20...30 kHz) are applied to workpieces compressed by axial force. To obtain such a frequency, the magnetostrictive effect is used, which consists in changing the dimensions of some metals, alloys and ceramic materials under the influence of an alternating magnetic field. Ultrasonic welding machines consist of a power source, control equipment, a mechanical vibration system and a pressure drive. Fig. 80 shows the simplest scheme of ultrasonic welding. The workpieces to be welded 5 are placed on a support 6. The tip 3 is connected to the magnetostrictive transducer 1 through a transformer of elastic vibrations 2, which together with the working tool 4 constitute a waveguide (the figure shows how the amplitude of vibrations changes along the length of the waveguide). Ultrasound is emitted continuously during the welding process. The element of the oscillatory system that excites elastic oscillations is an electromechanical transducer 1, which uses the magnetostrictive effect. An alternating voltage creates a magnetizing current in the transducer winding, which excites an alternating magnetic field in the transducer material. When the magnetic field strength changes, a periodic change in the size of the material occurs, while the frequency of elastic oscillations is equal to twice the current frequency. The amplitude of oscillations at the end of the waveguide is ~20...40 μm at idle. Welding occurs under the action of friction, which is caused by microscopic reciprocating movement of particles on friction surfaces.

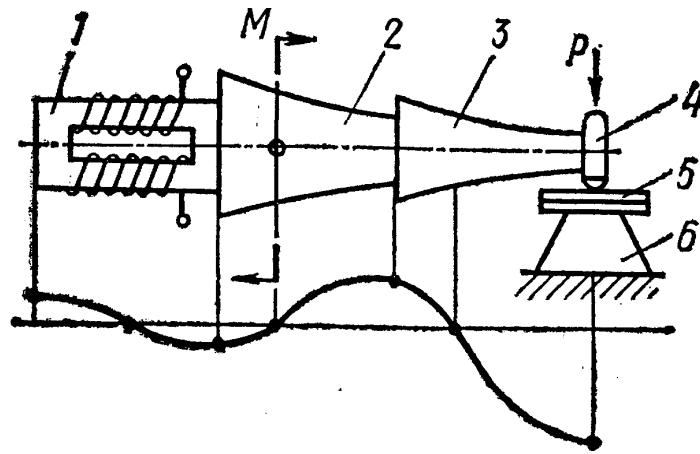


Figure 80 – Ultrasonic welding scheme

So, as a result of ultrasonic vibrations, "shear" deformations are created in thin layers of contacting surfaces, which destroy surface films. As the films are destroyed, setting nodes are formed, the surface layers of the metal heat up, soften slightly and plastically deform under the action of compressive force, the welded surfaces approach the distance of action of interatomic forces, and a strong welded joint is created.

A relatively small thermal effect on the welded metals ensures a minimal change in their structure and properties. For example, for Cu, the temperature in the contact zone does not exceed 600 °C, when welding Al - 200...300 °C.

The parameters of ultrasonic welding are the power of the oscillation generator, the amplitude of oscillations, pressure and welding time. Ultrasonic welding is used to obtain point and seam joints of metals and alloys of small thickness (usually less than 1 mm) and for welding plastics. Advantages of ultrasonic welding:

- solid-state welding without significant heating of the parts to be welded, which makes it possible to weld chemically active materials and alloys that form brittle joints;

- the possibility of welding and brazing thin and ultra-thin parts;

- the use of small compressive forces (0,1...2,5 kN), as a result of which the deformation at the joint is insignificant (dents 5...10%);

- low power of the welding equipment and the simplicity of its design.

The disadvantages of ultrasonic welding are the limited thickness of the parts to be welded (less than 1 mm), the significant cost of high-frequency generators, the effect of high frequency on the human body.

In the Ukraine, ultrasonic machines for welding various elements of microcircuits were developed and are being produced in series, which are equipped with automatic devices (automatic feeding of conductors, welding, cutting of conductors, etc.), as well as installations for welding polymeric materials, which allow to significantly increase productivity.

Diffusion welding is pressure welding, which is carried out due to the mutual diffusion of atoms of contacting parts under relatively long-term exposure to elevated temperature and with insignificant plastic deformation.

The main parameters of diffusion welding are heating temperature, pressure, heating time, environment in which welding is carried out.

The temperature for homogeneous metals, as a rule, should be 0,5...0,8 of the melting point of the metal or alloy, and when welding dissimilar metals – 0,5...0,7 of the temperature of the low-melting metal. Such a temperature accelerates the mutual diffusion of atoms of materials through the joint surface and facilitates the removal of surface irregularities and plastic deformation of the metal.

Heating is carried out mainly by induction currents, other sources of heating can also be used: conventional resistances, electric current passed through the parts themselves, an electron beam, etc.

The pressure in the contact of the joined parts, depending on the temperature and type of welded materials, can vary from 3...5 to 100 MPa. The deposition of parts is carried out mainly by pneumatic systems. The welding time is from several to tens of minutes. Removal of surface films and prevention of their formation during the welding process is achieved by using vacuum protection, thorough preliminary cleaning of the welded surfaces. Welding is performed under conditions of non-oxidizing heating, for which a vacuum of ($10^{-1} \dots 10^{-3}$) Pa is maintained in the welding chamber.

A special type of diffusion welding is welding in a controlled atmosphere, in which H_2 , Ar, He are used as protective gases.

The diffusion welding scheme and the process cycle are shown in Fig. 81. The diffusion welding installation consists of a vacuum chamber in which welding is performed, special pumps for creating a vacuum, a heating device with a power source and a device for transmitting pressure.

After the air is pumped out, the heating device is turned on, the part is heated to a given temperature, ensuring uniform heating of the parts over the entire cross-section. After the temperature is equalized, a compressive force is applied, which is maintained constant during the welding process. When the parts to be welded are cooled, the load is not removed immediately, but at temperatures of 100...400 °C to prevent the joint from breaking due to different coefficients of thermal shrinkage of the connected elements. Approximate welding mode parameters, for example, for titanium alloys: heating temperature $T = 800 \dots 1000$ °C, pressure $p = 5 \dots 10$ MPa, heating time $t = 5 \dots 10$ min; for nickel, respectively, $T = 1000 \dots 1170$ °C, $p = 15 \dots 20$ MPa, $t = 6 \dots 20$ min.

The advantages of diffusion welding are the possibility of welding dissimilar materials, obtaining uniform joints without a noticeable change in physical and chemical properties, the absence of filler materials, high quality of protection.

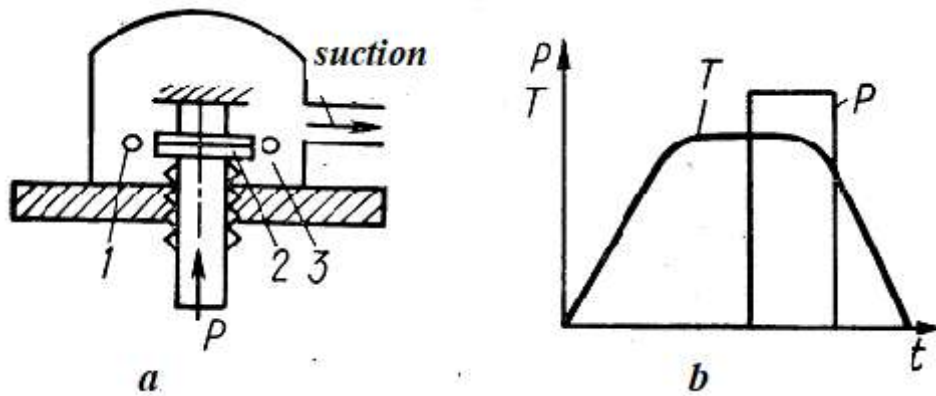


Figure 81 – Diffusion welding:

a – welding scheme; 1 – heater; 2 – workpieces; 3 – chamber;
b – welding cycle; *P* – force, compression; *T* – temperature; *t* – time

Diffusion welding allows you to create strong joints not only of homogeneous, but also of dissimilar metals and alloys, including those that differ sharply in their properties: low-plasticity, refractory, those that do not dissolve in each other or form brittle joints between themselves. With the help of diffusion welding, joints of such pairs of metals and alloys are obtained, which are very difficult to connect directly by other types of welding (for example, titanium with corrosion-resistant steel, titanium with aluminum, steel with cast iron, copper with molybdenum, tungsten with niobium, etc.).

In the case of insufficiently intensive diffusion between the materials being joined with sharply different coefficients of linear expansion or with the possibility of brittle joints between them, it is advisable to use an intermediate gasket or layer in the form of foil, powder, etc. The welding mode parameters are selected depending on the presence and properties of the intermediate gasket. In this way, not only metallic (for example, heat-resistant alloys) but also non-metallic materials (for example, quartz joints through a copper layer) are joined.

Friction welding is pressure welding in which heating is carried out by friction, which is caused by the relative movement of the welded surfaces. Distinctive features of the process:

Heating of compressed parts is carried out as a result of friction of the joined surfaces during their rotation or reciprocating movement of one relative to the other, while mechanical energy is directly converted into thermal energy at the point of contact;

strictly localized heat generation in the near-surface layers of the welded parts;

welding occurs in a solid state without melting the metal of the welded parts;

the welded joint is formed as a result of combined plastic deformation during heating and compression due to the emergence of metallic bonds between the clean contacting surfaces of the welded parts; oxide films present on the

metal surfaces at the joint are destroyed as a result of friction and are removed due to plastic deformation in the radial direction.

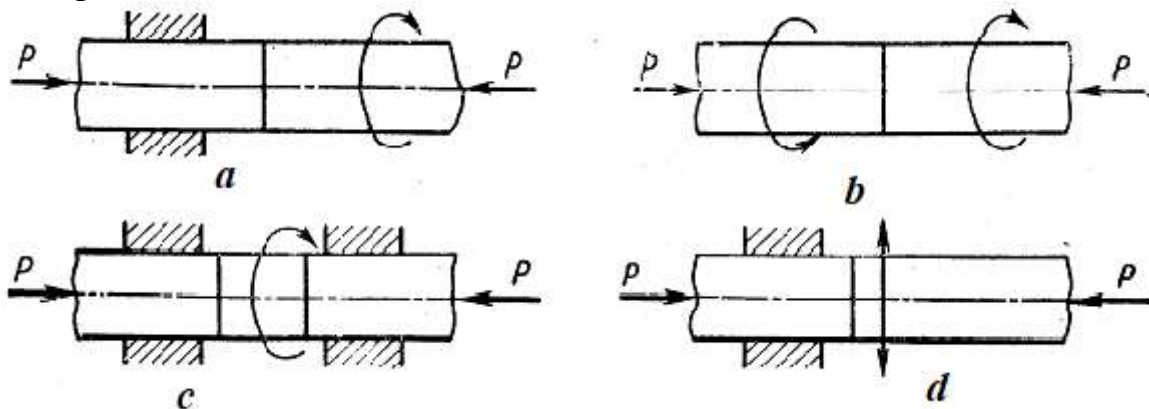


Figure 82 – Friction welding scheme:

- a* – with rotation of one part; *b* – with rotation of both parts;
c – with fixed parts with a rotating insert; *d* – with reciprocating motion of one part

The schematic diagrams of friction welding are shown in Fig. 82. The simplest and most common process diagram is shown in Fig. 82, a. Two parts to be welded are mounted coaxially in the machine clamps; one of them is stationary, the other is rotated around their common axis. Friction forces arise on the mating end surfaces of the parts, pressed against each other by axial forces P . The work spent during rotation to overcome these friction forces is converted into heat, which is released on the friction surfaces and heats the thin layers of metal adjacent to them to the temperatures required to form a welded joint (1000... 1300 °C - when welding ferrous metals). Heating ends when the relative rotation stops quickly (almost instantly). The metal prepared in this way for welding is subjected to strong compression - forging, as a result a strong welded joint is formed.

The main parameters of the friction welding process are the speed of rotation of the welded parts, the magnitude of the axial force during heating and forging, the magnitude of the shrinkage during heating, the duration of the forging force application. An approximate mode for welding carbon steel blanks with a diameter of 50 mm: rotation speed 400 rpm, axial force during heating 100 kN, axial force during forging 200 kN, heating time 20 s, forging time 2.0 s, power consumption 25 kW, machine process time - 22 s. The advantages of friction welding are high process productivity, low energy consumption (5...10 times less than in butt contact welding), high quality of welded joints, the possibility of welding metals and alloys in various combinations, simplicity of mechanization and automation.

The disadvantages of friction welding are the non-universal nature of the process (it can be used to weld such pairs of parts, of which at least one must be a body of rotation), the bulkiness of the equipment, the presence of burrs after welding.

Friction welding is used to connect parts butt-jointed (rods, pipes) and to form T-shaped joints. In industrial production, friction welding is used to connect parts with a cross section of 50...10,000 mm² from the same and a number of different structural materials. Universal specialized machines are used for welding, which have clamps for the parts to be welded, a compression mechanism and a rotation drive; They produce serial machines of the MST type - MST-23, MST-35, MST-41, etc.

Explosion welding is a welding process in which a joint is formed by mutual plastic deformation as a result of the explosion-induced collision of fast-moving parts. The kinetic energy of the collision of the joined parts is spent on the work of mutual plastic deformation of the contacting metal layers, which leads to the formation of a welded joint. In this case, part of the work of plastic deformation is converted into heat, which can heat the metal in the joint zone to high temperatures, up to melting of local volumes. Most types of explosion welding are based on the use of a directional (cumulative) explosion (Fig. 83). The joined surfaces of two workpieces 3 and 4 (in the simplest case, plates), one of which (4) is stationary and is the base, are placed parallel to or at an angle α to each other at a distance h_0 . On the moving (throwing) workpiece 3, a BP (explosive) 2 with a thickness of H is placed, and a detonator 1 is installed on the side above the vertex of the corner. When the BP charge is excited by a detonator, a detonation wave front spreads along it with a detonation velocity $D = 2000...8000$ m/s (detonation is the process of decomposition of an explosive with the release of gases and heat). The gaseous explosion products formed behind the detonation front initially create a pressure of 100...200 GPa, retaining the previous BP volume for a short time by inertia, and then expand at a speed of $0.5...0.75D$, giving the metal section located under them an impulse of motion. Under the action of this impulse, the volumes of the workpiece are sequentially involved in accelerated motion towards the surface of the stationary part of the metal and collide with it at high speed. In the established process, the moving plate bends twice at a certain length, its inclined section at an angle \square moves with a speed D behind the detonation wave front. When colliding with the apex of the angle, thin surface layers, oxides and contaminants are removed. High-speed colliding of the moving part of the metal with the fixed plate causes metal flow in their surface layers. The surfaces approach the distance of action of interatomic adhesion forces and bonding occurs over the entire area of the joint with a characteristic wave-shaped boundary of the parts to be joined. The duration of explosion welding does not exceed several microseconds.

The strength of joints made by explosion welding is higher than the strength of the materials being joined. This is explained by the strengthening of thin layers of metal adjacent to the surfaces being joined during their plastic deformation.

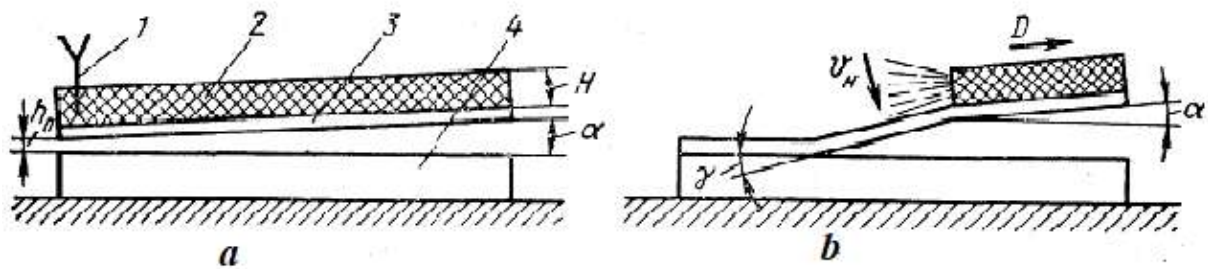


Figure 83 – Schematic diagram of welding: explosion:
a – before welding; *b* – during welding

Explosion welding is used in the manufacture of bimetal blanks, for cladding the surfaces of structural steels with metals and alloys with special physical and chemical properties, and for welding blanks made of dissimilar materials.

A type of explosion welding is magnetic pulse welding. In magnetic pulse welding, the impact of the welded parts is provided by a pulsed magnetic field from the discharge of capacitor banks. The pulse duration and impact speed in this method are close to those of explosion welding. The advantage of magnetic pulse welding over explosion welding is only the control of the process parameters.

Control questions

1. What types of welding are special? Their field of application.
2. What is the essence of plasma and microplasma welding? and
3. What is the essence of electron beam welding?
4. How does laser beam welding work?
5. How is cold welding done?
6. What is the essence of ultrasonic welding?
7. What is the essence of diffusion welding?
8. How does friction welding work?
9. How is a joint formed in explosion welding?

8 MECHANIZATION AND AUTOMATION OF WELDING PRODUCTION

8.1 General information

One of the main technical and social tasks in welding production is to replace manual labor of welders with mechanized and automated welding. This task is solved by replacing manual welding with mechanized for structures where it is difficult to use automatic welding (short seams, complex spatial position), the widespread use of robotics, the use of mechanized and automated welding installations using improved and new welding processes.

At the same time, the labor intensity of welding is approximately one third of the total labor intensity of manufacturing a welded structure. Therefore, further reduction of the time for manufacturing welded structures, along with mechanization and automation of welding, is envisaged due to the comprehensive mechanization and automation of welding production, i.e. mechanization and automation of all production processes that make up the technological cycle of manufacturing a welded structure (preparation, processing, assembly and welding, finishing, control).

The effectiveness of mechanization and automation of technological processes depends on the serial production of structurally and technologically similar welded structures at a particular enterprise.

In mechanical engineering, including welding production, the following types of production are distinguished:

small-scale, characterized by a wide range of manufactured products and a small volume of product output;

serial, characterized by a limited range of products manufactured in batches that are periodically repeated, and a relatively large volume of output;

large-scale production, characterized by a stable range of products that are produced in large quantities throughout the year. There are no strict boundaries between the types of production. Approximate signs of seriality of welding production depending on the mass of welded assemblies and their annual output are given in Table. 19.

Each type of production has its own optimal technological processes, equipment and production organization. With an increase in the seriality of welded structures, the degree of mechanization and automation of technological processes and operations used in their manufacture increases.

Table 19 – Approximate characteristics of serial welding production

Weight of welded joints for the product, kg	Annual output of components (parts), thousand pcs., from production		
	small-batch and single-unit	serial	large-scale production
До 25	До 5	5...200	200...400
25...100	2...8	2...100	100...800
100...500	0,5...2,5	0,5...150	30...350
500...1000	0,3...0,6	0,3...10	5...100
1 000...5 000	0,2... 1,0	0,2...17,5	3,5...125
5 000...25 000	0,1...0,5	0,1...10	2,0...2,5
25 000... 100 000	0,05...0,2	0,05...4	1,0...10
Above 100 000	До 0,01	Above 0,01	—

8.2 Assembly work and its mechanization

Assembly for welding is a technological operation that ensures the necessary mutual placement of parts to be welded, with their fixation with special devices or tacks.

Assembly is performed on a plate, rack, stand or in a special device designed to place and fix the product being assembled and welded.

An assembly and welding plate is a support device in the form of a horizontal metal plate with grooves; a rack is the simplest support device with a flat horizontal surface for placing large-sized products in the workshop. Assembly and welding stands are more complex devices for placing parts of large-sized products that are assembled and welded, and fixing them in the desired position. Examples of assembly and welding stands can be electromagnetic stands in the manufacture of planar sections of ship hulls, tanks, wagons and other sheet metal structures.

In the conditions of unit production, the placement of parts in the welded assembly is set by marking, and clamps, strips, brackets with wedges and other simple universal devices are used to secure them.

The use of special assembly devices-conductors allows you to increase labor productivity and assembly quality. A welding conductor is a device for assembling and securing the welded parts relative to each other in a certain position. The basis of the assembly device is a rigid frame that carries stops, clamps and clamps (Fig. 84).

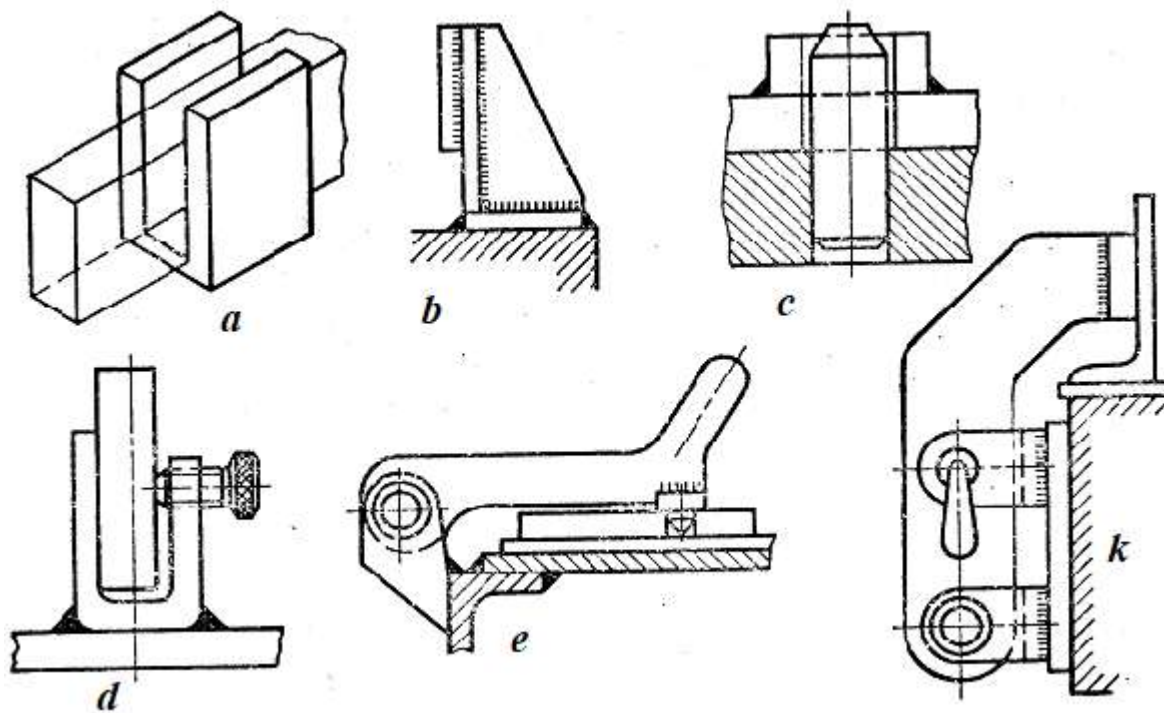


Figure 84 – Elements of assembly devices:
a – pocket; *b* – stop; *c* – rigid finger; *d* – clamp; *e* – folding finger;
k – folding stop

When assembling, the parts are inserted into the device, placed on the stops and clamps and secured with clamps. Manually and mechanically driven tension and expansion clamps are used. Manually driven clamps (screw, lever, eccentric) are simple, but require direct manual labor by the assembler (Fig. 85). The use of pneumatic, hydraulic, electromagnetic and vacuum clamps significantly reduces auxiliary time, especially when it is necessary to clamp the product in several places.

The fixation of assembled parts to provide the necessary rigidity to the assembled unit is most often carried out on a tack. The tacks must have a limited cross-section and be placed in places that ensure their complete digestion when laying the main seam.

The sequence of assembly and welding operations may be different:

Welding is performed after the assembly is completely completed;

Assembly and welding are performed alternately, for example, when manufacturing a structure by building up individual elements;

General assembly and welding are preceded by assembly and welding of components.

For the convenience of performing certain seams, the product must be installed in different positions. This is done using devices - positioners, rotators, tilters, roller stands, manipulators. Such devices can be both installation devices, designed only to rotate the product into a position convenient for welding a particular seam, and welding devices, which provide, in addition to installing the product, its rotation (movement) at a given speed equal to the welding speed.

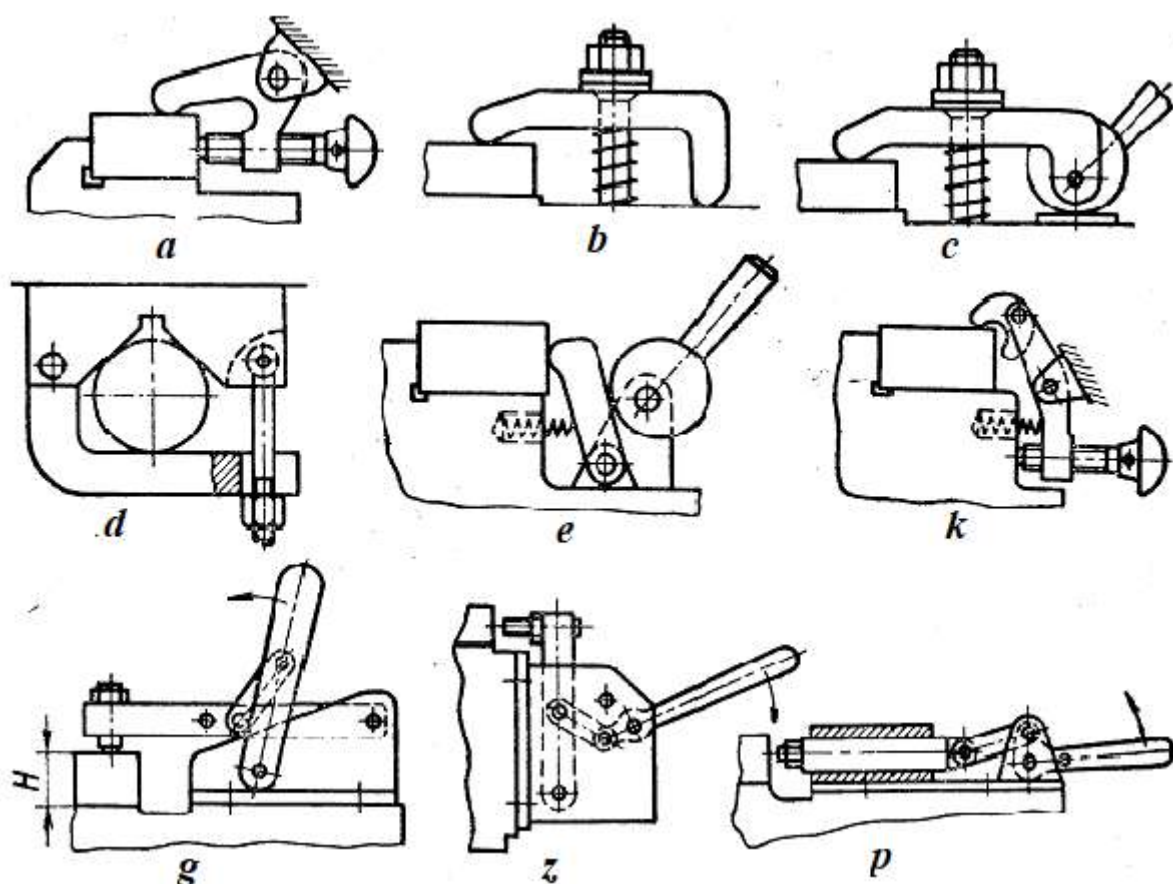


Figure 85 – Schemes of mechanical clamping devices:
a, b, d, k – screw; *c, e* – eccentric; *g, z, p* – lever

Positioner - a device designed to install the product in a spatial position convenient for assembly and welding. Unlike manipulators, the positioner does not rotate the product at the welding speed, but only holds it in the desired position.

Rotator - a device for rotating the product during welding around a constant axis at the welding speed.

Tilter - a device for rotating heavy non-cylindrical products around one or more fixed axes of rotation. The tilter allows you to install the product in a position convenient for work. Roller-type, pin-type and chain tilters are used.

A manipulator is a carousel-type device for rotating workpieces during assembly and welding with different angles of inclination of the axis of rotation.

Universal roller supports are widely used, in which the bearings of the axis of one of the rollers can move perpendicularly to the axis of the stand, which makes it possible to set the desired distance between both rollers, which corresponds to the diameter of the product being assembled or welded.

Universal general-purpose devices (assembly plates, racks, manipulators, tilters, roller stands) are used for assembly and welding of products of a wide range and different sizes.

For products of a certain type, but different sizes, universal special-purpose devices are used, which are designed individually. Universal devices are used in single and small-scale production. In addition to universal and special devices, in small-scale and single-unit production, universal assembly devices are used, which are a set of various structural elements - universal plates with longitudinal and transverse grooves, typical interchangeable stops, clamps, pins, clamps, strips, fasteners, etc.

In conditions of large-scale and mass production, special single-purpose devices are used to perform certain operations in the manufacture of a particular product.

A number of measures are used to reduce welding deformations and stresses during assembly. An effective measure to reduce residual deformations is rigid fixation of welded parts in special devices - conductors. Additional deformation of workpieces is often used, which should be opposed to the expected welding deformation. The method of preliminary bending of welded parts is used to combat angular deformations when welding butt and lap joints. When welding sheets of small width with V-shaped edge clearing, they are placed with a preliminary bend in the direction opposite to the expected deformation. Sheets of large width can be inserted with a preliminary bend of the welded edges. To prevent deformations when welding T-beams and I-beams, devices are used that bend the beam in the direction opposite to the expected deformation. An effective measure to prevent the bending of the riser in I-beams caused by welding of belt seams is assembly with a preliminary tension of the wall. Assembly stands with jacking devices are used to tension the wall.

8.3 Flow-through mechanized and automated lines

A flow-through line is a set of equipment that is interconnected and operates in accordance with a certain given rhythm according to a single technological process. Assembly-welding mechanized flow-through lines include equipment for assembly, welding, and sometimes metal preparation operations, cutting, inspection of finished products, etc.

Several types of flow-through lines are distinguished based on mechanization and automation:

with partial mechanization, in which manual and semi-automatic welding are used, and the remaining processes of the production cycle - metal cutting, cutting, assembly, painting, etc. - are performed manually;

with complex mechanization, when several operations are mechanized, for example, mechanized cutting and semi-automatic welding are used;

with partial automation, in which the main processes (cutting, welding) are automated, and the remaining work (assembly, quality control, painting) is performed using mechanized tools and devices; with comprehensive automation - automatic lines.

Automatic lines are a set of machines that perform the entire cycle of operations for manufacturing a product in a given technological sequence, with

control mechanisms common to the entire line and automatic transport devices that move the processing object from one machine to another. An example of such a line can be assembly-welding automatic lines for the manufacture of large-diameter pipes with a spiral seam, on which all operations for the manufacture of pipes from steel strip are carried out using automatic machines under the supervision of a small number of operators.

In welding production, assembly and welding lines with varying degrees of mechanization and automation of equipment and equipment used are used, taking into account the mass, seriality and individuality of production for many types of welded products - when assembling and welding panels, manufacturing shells, pipes, vessels, beams, lattice and complex structures, welded blanks for machine parts.

Small-scale (single) production of welded structures is most common in industry and construction.. The efficiency of small-scale production of welded structures is increased due to:

1. Concentration of welded structures of the same type (plane, beam, cylindrical, lattice, frame, body, spherical, conical, etc.) and the creation of typical sections for their manufacture. This brings small-scale production closer to serial production and creates conditions for the use of mechanization and automation.

2. Replacement of manual welding with mechanized and automated. Currently, about 70% of welded structures are short and angular seams, so the main way to mechanize the welding of such seams is semi-automatic welding in a protective gas environment. In cases where automatic welding is advisable, light portable tractors weighing up to 12-14 kg and self-propelled trolleys for semi-automatic machines should be used in addition to conventional welding heads and tractors to move the torch during welding. Such areas and workshops have been created at shipbuilding plants (for assembling and welding panels and welding a set, manufacturing T-profiles), at machine-building plants and metal construction plants (for assembling and welding beams and panels).

3. Mechanization of procurement operations. Semi-automatic lines for the manufacture of sheet metal parts using gas and plasma cutting have been created at almost all shipbuilding plants. Lines and sections for cold processing of sheet metal, rolled angles, channels, I-beams and pipes have been created at many machine-building plants and enterprises that manufacture metal building structures.

4. Use in cutting and pre-fabrication departments of plants of automated assembly sections, in which accounting and issuing of incoming parts, as well as control of stackers and lifting and transport devices is carried out using a computer. Such automated sections allow not only to reduce the number of service personnel engaged in assembly, but also to ensure timely receipt of parts to assembly and welding departments. In this case, parts are stored and submitted for assembly in containers and pallets (depending on the size of the parts), which are the general equipment of cutting and pre-fabrication and assembly and welding departments.

5. Expansion of mechanization of auxiliary operations. In the cutting-preparing and assembly-welding departments, along with bridge cranes, autonomous lifting equipment (cantilever and semi-gantry cranes, crane beams, rotating consoles with hoists, etc.) is used, equipped with high-speed grippers and remote controls, which are operated not by crane operators and slingers, but by workers in the main production.

In the serial production of welded structures, assembly and welding operations are usually performed on specialized flow lines with separately located workplaces, and if necessary, connected to each other by a single transport system. The rhythmic operation of such lines is ensured by the location of accumulators and intermediate warehouses between workplaces and lines. A special place in serial production is occupied by highly mechanized and automated reconfigurable lines designed to manufacture certain, but slightly different in shape and size, welded structures. In such lines, assembly and welding installations are reconfigured by changing the position of the main units on the frames of these installations during the period of preparation of the line for the manufacture of a new welded structure. The equipment of the reconfigurable lines does not change structurally, therefore the main components of the assembly (bases, clamps, clamps, etc.) and welding (automatic machines, their rail tracks, etc.) installations, as well as auxiliary equipment for performing lifting and transport operations and automation systems of these lines can be highly productive and perform technological operations with a high level of mechanization and automation. Reconfigurable lines are available in crane construction, the manufacture of electric motor housings, the production of panels in shipbuilding, welded I-beams in construction, but there are still not enough such lines, and therefore, even in serial production, many structures are manufactured using methods typical of small-scale production.

Large-scale production of welded structures is specialized and is intended for the manufacture of a certain structure and its components (for example, welded bodies of cars of various brands, mainline gondolas, mine trolleys, etc.). In this case, automatic lines or units for the manufacture of welded semi-assemblies are connected by intra-shop transport to the line for the manufacture of assemblies on them and further to the lines of general assembly and welding of the structure being produced, and the welded structures themselves are manufactured by machines controlled by an operator. Such lines are available at many automobile, tractor and other factories with large-scale production. A distinctive feature of fully automatic assembly and welding lines is that the workplaces of these lines are interconnected by a transport system, which in its design and operation is connected with the main and auxiliary equipment of the workplaces. The connection between the workplaces of automatic lines can be rigid and flexible. Flexible communication on the lines is provided by the use of inter-operational accumulators of parts and assemblies, which creates uninterrupted operation of the line in the event of failure of any element. In large-scale production, welding operations of seams located in all spatial positions should be performed by automatic machines. These can be automatic

arc welding machines, machines for contact and spot arc welding, industrial robots, as well as various welding devices in which the product is moved by mechanical equipment of the line. Depending on the required productivity, several automatically operating welding machines are installed at one workplace of the line instead of one, which simultaneously weld certain seams or sections of these seams. Due to the great capabilities of industrial robots (see section 8.3), they can be effectively used as a single universal equipment, which is adjusted according to a certain program and is designed for automatic welding of seams of various shapes and sizes. Automated lines with welding robots are widespread in automobile factories.

Automatic lines Can be created under the condition of automation of product assembly. This is achieved by dismembering assembly operations, that is, assembly is performed not at one workplace, but at several, as a rule, with welding of the installed part. In this case, welded structures are manufactured by the method of gradual build-up, and assembly turns into a simple and relatively easy-to-perform operation.

In the mass production of welded structures, it is most expedient to use suspended pusher conveyors to service automatic lines and units and in the preparation, assembly-welding and finishing departments. The use of suspended conveyors and automatic lines and units in combination with their control by means of a computer will allow welding production to move to the creation of complex automated enterprises and automatic factories.

An example of complex mechanization and automation of welding production in large-scale production can be the manufacture of passenger car components on a scale. Assembly and welding of car components are carried out on complex mechanized and automated lines. Large parts are fed to the lines by a system of conveyors, small ones - in containers by forklifts. Components are transferred from one position to another by automatic conveyors. At the end of each automatic line there are reloading stations, from which, using an overhead conveyor, the component is transferred to the next automatic line or to the place of storage of inter-operational parts. High productivity of work on the scale is achieved through the use of high-speed machines and mechanisms, trouble-free operation of all equipment and a clear organization of maintenance. Welding machines have a high-speed connector for supplying them with electricity, compressed air, water. Reconfiguration, repair, replacement of equipment are carried out during non-working hours or with minimal loss of working time. Almost 40% of the total number of welded points of the car at this plant is performed on multi-electrode machines. Assembly and welding of the main body components (roof, side, floor, front wings and doors) are carried out on complex mechanized and automated lines consisting of multi-electrode machines.

The main type of multi-electrode machines is a press with removable welding dies. Welding dies for some of the reconfigurable machines are placed on the spare position of the loading guides and can be set to the working

position in a few minutes. Universal welding machines are equipped with quick-release, easily accessible devices.

75% of all seams are performed by semi-automatic and automatic arc welding on a scale. The design of automatic arc welding machines also provides for quick change of individual parts.

8.4 Application of industrial robots in welding production

An industrial robot is an automatic manipulator with program control that can be quickly reconfigured to perform various operations usually performed manually. The main difference of this new type of automatic machine from other automatic machines is the application of the principles of manual labor and versatility, which makes its use advantageous in large-scale production and especially in conditions of frequent change of types of products, that is, in serial and small-series production. An industrial robot has a mechanical "hand" and "brush", which provide several independent movements of the tool (longitudinal, transverse, rotational, angular) to any point in space within its working area at the command of a built-in control system containing a memory device for storing a given program.

Currently, first-generation robots with a rigid action program and no feedback with the environment are mainly used in industry. The second generation are robots with a non-rigid program and feedback sensors. The third generation of robots is robots with artificial intelligence, capable of completely replacing a person in the field of skilled labor.

A robot can replace a worker, especially in monotonous operations, it does not get tired, does not make mistakes, is able to develop great efforts, can work in harmful conditions. The use of robots increases the uniformity of product quality, makes it possible to transition production to continuous 24-hour operation.

In welding production, robots have found preferential use in contact spot welding in the following cases:

unloading and loading a specialized welding machine designed for a certain type of product. Here, the robot installs the workpiece in the machine, and after welding, removes it and replaces it with the next one;

servicing a stationary welding machine, which consists in the robot feeding the next part, installing it, turning on the machine, moving the part and removing it;

welding using automatically operating pliers attached to the end of the robot's arm.

In the first case, a conventional positional transport robot is used, in the second and third cases, a special welding robot.

The robot shown in Fig. 86 is used as a carrier of welding tongs for contact welding in the automotive industry. Before work, the robot's memory device is entered with its action program. To do this, an experienced welder at the first node sequentially moves the tool from one working position to another, entering the coordinates of each of these points into the memory device by pressing the

"Memory" button. If an obstacle is detected on the path between adjacent welding points, for example, elements of a clamping device, then the coordinates of additional points are entered into the robot's memory, which determine the trajectory of the tool's movement around the obstacle. The program execution begins after the assembly being stored or welded takes the desired initial position and a signal about this is received in the memory device, after which the robot performs the necessary actions according to the set program.

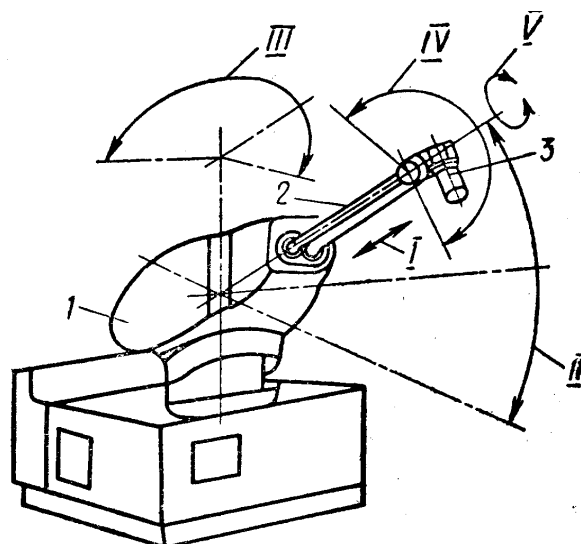


Figure 86 – Scheme of the robot's actuators:
 1 – body; 2 – arm; 3 – wrist; I – extension-retraction;
 II – raising-lowering; III – turning; IV – bending; V – rotation

Unlike spot welding, where an industrial robot takes on the purely physical work of moving welding cycles, in arc welding its movements are determined by the welding process itself. Robots designed for arc welding must perform continuous movement of the electrode at adjustable displacement values. This complicates the design and requires a much larger memory capacity of programming devices.

A significant disadvantage of first-generation robots is the requirement for high accuracy in assembling the parts to be welded and their placement in the robot's workspace. Second-generation welding robots are currently being created, with the help of which the work program and robot manipulations will be automatically adjusted when the position of the product or its individual elements changes. Such robots, equipped with special sensors, will be able, for example, to automatically bypass elements of clamping devices that occur on the way. Along with the improvement of conventional industrial robots, robots are being created that operate in extreme (complex, hard-to-reach, dangerous for humans) conditions - in aggressive environments, under water, in space, under the influence of radiation.

The main perspective of modern production is the full automation of technological processes with the possibility of frequent changes in the nomenclature of manufactured products. For welding processes, these

requirements are met by welding robotic complexes. The robotic complex has hardware - sensors that provide the necessary information, and systems for entering their signals into a computer, software - algorithms and programs that implement them, which allow calculating the required trajectory of the welding torch and the welding mode.

As a computer for robotic complexes, it is advisable to use microprocessor systems. Such systems, having a low cost, allow welding products of various sizes and configurations from different materials, and automatically select the modes that are best for the real parameters of the welded joint.

Microprocessor systems or microcomputers are built from microprocessors. A microprocessor is a universal programming element that is a large integrated circuit containing several thousand transistors, with a structure similar to that of a computer. Due to their small size and cost, microprocessor systems can be built directly into equipment, which dramatically increases its capabilities.

A microprocessor with auxiliary circuits forms a processor module, to which peripheral modules are connected using system buses. System buses are a set of connecting conductors-lines that combine the outputs of all peripheral modules.

System buses are divided into three groups: data bus, address bus, and control bus. Peripheral modules can be storage devices, displays, sensors, and actuators.

The work of a microprocessor consists in processing output data according to a given algorithm. Algorithm - a set of sequentially executed commands for processing output data in order to obtain the desired result.

Each microprocessor is characterized by a certain command system. A command system is a complete list of elementary actions that a microprocessor is capable of performing.

By composing a program from such commands, you can program the execution of an algorithm of any complexity when performing welding and other work.

Control questions

1. What are the main operations included in the technological process of manufacturing a welded structure?
2. What does comprehensive mechanization and automation of welding production involve?
3. What assembly and welding devices are used in the manufacture of welded structures?
4. What is a production line, classification of production lines?
5. What are the features of mechanization and automation depending on the seriality of welding production?
6. What is a welding industrial robot? How are robots used in welding production?

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Електронне навчальне видання

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Study guide

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