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Analysis of the Effects of Welding Conditions on the Microhardness of Low-Carbon Low-Alloy Steels

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Abstract. Achieving dependable connections in open construction settings presents challenges or renders the use of stationary machines and equipment complicated, if not impossible. Therefore, there is a particular focus on the requirements for welding processes. Of particular interest is ensuring the strength and reliability of welded joints, especially through processes developed subsequent to the solidification of the weld at the weld zone. The extent of the thermal influence zone is contingent upon the welding conditions and the properties of the metal being welded. Hence, research into the impact of welding conditions on the formation of the structure of the welded zone and the thermal influence zone remains pertinent.

1 Introduction

The development of the construction industry is inextricably linked with the development and implementation of advanced technological processes based on the latest achievements of mankind. Scientists are tasked with improving the properties and characteristics of metal, creating new structural materials that increase the rationality of their use in all spheres of life and become the basis for creating competitive products [6].

Welding allows you to combine structures of different shapes and configurations. The use of welded constructions instead of riveted, cast, and forged ones helps to save metal, reduce labour costs and shortens the production period. Less weight (by 20-25%) compared to other connection methods is one of the biggest advantages. The tightness of seams ensures the reliability and tightness of such structures as boilers, tanks, and pipelines etc. Automation and mechanization of production processes are expanding.

The requirements for welding processes are becoming more and more specific every year and are gaining special importance. As a result, the most important point in ensuring reliability and strength of welding are the ones that are formed during the hardening of the seam. Their technological properties directly depend on the configuration, welding method and mode.

2 Organization of the Text

Low-carbon, low-alloy steel 10KhSND, which are often used in metallurgy, oil and gas production and other industries, was chosen as the material for research.

10KhSND is a low-alloy structural steel used in high-strength, corrosion-resistant welded metal structures. It conforms to the DSTU 8817, GOST 6713, DSTU 8541, and GOST 19281 standards [1].

Classification: Low-alloy structural steel for weld-fabricated structures.

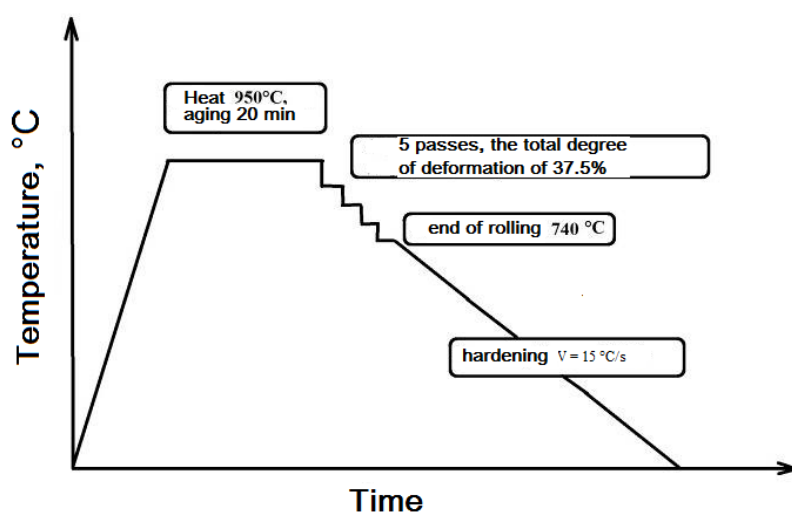
Product: Thick-plate, wide-strip, flat, rolled and shaped products.

The chemical composition of 10KhSND steel is given in table. 1

Table 1. Chemical composition of 10KhSND steel, [%]

C	Si	Mn	S	P	Cr	Ni	Cu	V	Nb	N	As
≤ 0.12	0.8-1.1	0.5-0.8	≤ 0.04	≤ 0.035	06-0.9	0.5-0.8	0.4-0.6	-	-	≤ 0.008	≤ 0.008

Rolling was performed by the technology of continuous controlled rolling developed the works [2-4]. Proposed scheme includes: austenisation at the temperature 950°C during 20 minutes; hot deformation in intercritical interval of temperatures for 5 passes with total sum of deformation 37.5%. Temperature of the beginning of deformation was 950...930°C, the end of deformation was 730...740°C respectively; 3) after rolling ending cooling was with the velocity of $\approx 15^\circ\text{C}/\text{s}$ (Fig. 1)/

**Fig. 1.** The scheme of continuous controlled rolling of 10KhSND steel [5]

The structure of 10KhSND steel after continuous controlled rolling is presented in Fig. 2. The analysis of the given data shows that the structure of the studied steel is a ferrite-pearlite-bainite conglomerate. At the same time, it should be noted that the use of continuous controlled rolling leads to the production of dispersed ferrite grains. The size reduction of the ferrite component occurs due to a decrease in the temperature at the end of the hot deformation to the lower limit of the intercritical temperature interval. This regime leads to the nucleation of numerous grains of pre-eutectoid ferrite not only at large-angle, but also at subgrain boundaries of austenite. Continuous deformation of the metal in the intercritical temperature interval allows recrystallization processes in austenite to be suppressed, and additional small-angle subgrain boundaries to form in the formed small ferrite grains, which leads to additional grinding of the structural component steels.

Quantitative analysis of the percentage content of structural components is given in the table. 2

Table 2. The dimensions of the structural components of steel 10KhSND

The dimensions of the structural components		
Ferrite (μm)	Pearlite (μm)	Bainite (μm)
75	17	8

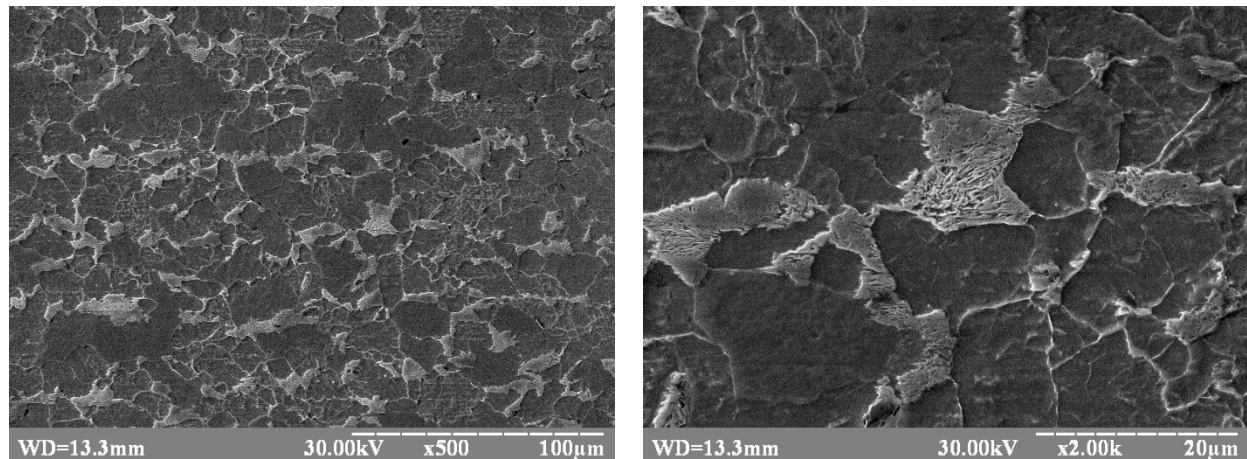


Fig. 2. The structure of 10KHhSND steel after continuous controlled rolling

Electron beam welding (EBW) of steel plates was carried out in one pass with through penetration on the UL-144 installation in the lower position of the plates. EBW was performed in the UL-144 installation, equipped with an ELA-60/60 power source, a CF-4 welding gun and a SU-220 beam control device. Welding was carried out according to the regime: accelerating voltage - 60 kV; beam current – 70 mA; the diameter of the circular sweep on the surface at 100 mm from the welded product is 2 mm; welding speed 5.5 mm/s (20 m/h). In all cases, the welding modes ensured the execution of seams in one pass without edge processing and without the use of filler wire. The driving energy at ELS was 3.11 kJ/cm.

Welding in an environment of shielding gases was carried out by a mechanized method in a gas mixture of 80% Ar+20% CO₂ with a Sv-08G2S wire with a diameter of 1.2 mm. Welding mode:

- root roller: Izv=120...140 A, Ud=20...22B, Vz=8...8.5 m/h;
- fills the layer: Izv=160...180 A; Ud=24...26B, Vz=12...14 m/h.

During **laser welding**, butt joints of plates measuring 290×140×18 mm were welded using a DY 044 model Nd:YAG laser (Rofin Sinar, Germany) with a power of up to 4.4 kW, and the lens included in the welding head with a focal length of $F = 300$ mm. Radiation from the laser to the lens was transmitted through an optical fiber with a diameter of 600 μm. During the welding process, the welding head with the protection system moved. In all cases, the lower (root) part of the weld was protected by Ar+ CO₂, the flow rate of which was 7 l/min. It was fed through a tube located in a clamping device. The upper part of the seam was protected by the nozzle of the welding head. The welding speed was 1.5 m/min.

Automatic arc welding was performed:

Under the ANKS-28 flux;

Wire Sv-10G1NMA1.

Seam on modes:

1 seam (narrow) – 600A-28B-19 m/h;

2 seam (wide) - 750A-33B-19 m/h.

The microstructure of the weld of 10KHSND steel after different welding modes is shown in Fig. 3.

Analysis of the data shown in fig. 3 a, shows that crystallization occurs in non-equilibrium conditions. As a result, a columnar zone with preferred orientation is formed due to dendritic growth. Boundaries between crystallites, which are formed as the crystal lattice of the solid phase moves into the melt, are usually also elongated in the direction of growth. In contrast to ingots in welded joints, crystallite growth axes are generally spatial curves due to the change in the shape of the weld pool in planes parallel to the area of the weld plate and the movement of the thermal field in the direction of welding.

The small volume of the weld pool and the large curvature of the melting surface are the reason that the columnar crystallites in the welded joint are more disorientated than in the ingots. Thus, the misorientation angles between columnar crystallites in welded joints are 5-20°.

The intracrystalline structure of the metal of welded joints is characterized by three types of structures - cellular, dendritic and mixed, which differ from each other in the degree of development of liquation of alloying elements and the dispersion of their distribution.

In the process of crystallization of alloys adjacent to the solid metal, the layers of the liquid phase are enriched with soluble elements that have a lower melting point. If, as a result of diffusion processes or the influence of convection currents of liquid, the dissolved element will be removed from the interface into the liquid phase, then as a result of the system's desire for equilibrium, part of the atoms of the liquid phase will move to the solid phase, restoring the boundary concentrations and ensuring the growth of solid solution crystals.

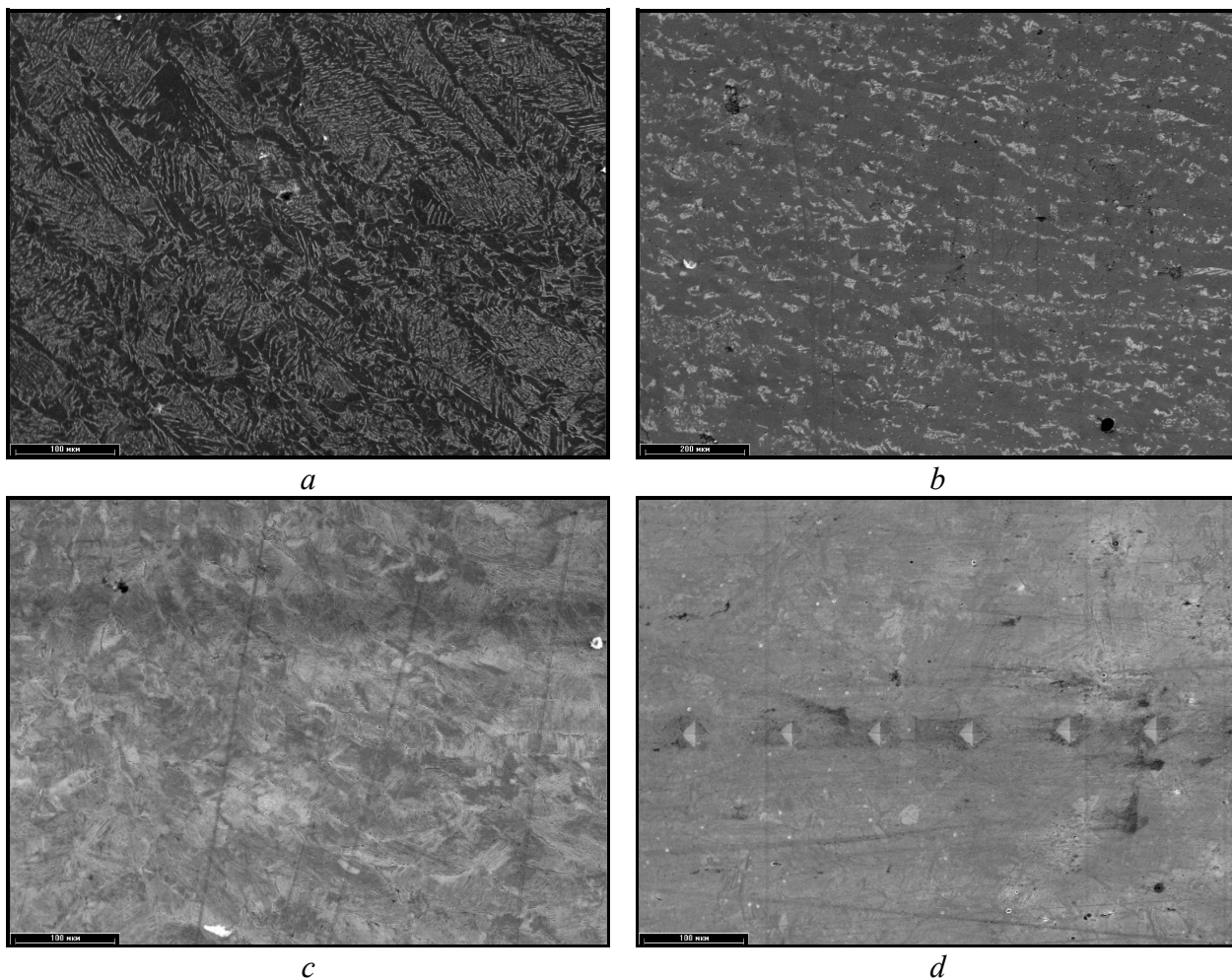


Fig. 3. The structure of the weld after welding in different modes: a – welding in an environment of protective gases; b – flux welding; c – laser welding; d – electric beam welding

Welding under the flux (Fig. 3,b) leads to the enrichment of the metal with manganese and silicon with the formation of slag. As the current increases, the proportion of molten weld metal increases and the transition of silicon and manganese into the metal decreases. An increase in voltage leads to an increase in the amount of molten flux, while the transition of silicon and manganese into the seam increases. With the growth of the welding current, the depth of penetration of the base metal increases due to the increase in the pressure of the arc on the surface of the welding bath, the conditions of heat transfer from the arc to the base metal improve, and the linear energy increases.

The presence of slag on the weld surface reduces the rate of crystallization of the weld pool metal and the rate of cooling of the weld metal. As a result, the weld metal has no pores and contains a reduced number of non-metallic inclusions. Improving the shape of the seam and the stability of its dimensions, especially the penetration depth, ensure a constant chemical composition and other properties along the entire length of the seam.

The height of the seam reinforcement increases with the increase in the volume of the molten electrode metal. The growth rate of crystals in different parts of the bath is different. At the same time, the growing columnar or dendritic crystals are drawn in the direction of the movement of the arc. As a result of the selectivity of the crystallization process, impurities accumulate in front of the front and the central parts of the seam are enriched with them.

During laser welding (Fig. 3,c), high cooling rates affect the primary and secondary structure of the seam.

Due to the lagging of the rate of solidification from the rate of increase of the temperature gradient at the crystallization front, the primary structure is dendritic-columnar.

During electron beam welding (Fig. 3,d), the process of crystallization of the weld pool occurs unevenly in height. Crystallization is faster in the lower zone. Due to this, conditions are created when the crystallization of the lower part of the seam occurs under the liquid metal layer of the upper part of the weld pool. At the same time, due to the diffusion mechanisms of the formation of the ferrite phase, carbon atoms are pushed out with the simultaneous formation of the corresponding regions enriched and depleted in carbon. The subsequent cooling (forced removal of welding heat during the hardening of the contact point) leads to the disintegration of austenite by the bainite mechanism. The ferrite component is vidmanštetov ferrite, which is also formed as a result of relatively high cooling rates.

The cast zone of the welded joint is metal solidified on the substrate, which is the fused edges of the base metal. According to the theory of crystal growth, solidification of liquid metal occurs through the formation of new atomic layers of the solid phase. These layers preserve the crystallographic orientation of the substrate. The first crystallites, which grow from the fusion line to the depth of the bath, have the orientation of the melted recrystallized grains of the near-seam zone, that is, they are strongly disoriented.

3 Investigation of the Microstructure of the Heat-Affected Zone and the Base Metal

During fusion welding of alloys of polymorphic metals, the processes of phase recrystallization during heating, grain growth and homogenization of the high-temperature phase and its subsequent transformations during cooling occur sequentially in the near-seam zone. The results of metallographic studies of the thermally affected zone are shown in Fig. 4.

The analysis of the given data shows that as the heating rate increases, the phase recrystallization temperatures of steel (Ac_1 and Ac_3) gradually increase, and the interval Ac_1 - Ac_3 expands. The higher the temperature of the end of transformation of pearlite Ac_{1k} and ferrite Ac_{3k} into austenite, the finer the initial grain of austenite and the higher the temperature of the beginning of intensive grain growth. In steel alloyed with carbide-forming elements, the Ac_3 temperature rises to a greater extent, and grain growth begins at higher temperatures than in steel with a small amount of these elements.

The most intensive growth of the austenite grain in the near-seam zone occurs during the heating period at temperatures close to T_{max} of the welding cycle. When heated, grain growth does not end; it continues with cooling, but with less intensity.

Thus, it is possible to conclude that the zone of thermal influence consists of several structurally different areas. The area of overheating: the area of the base metal, heated to 1100...1450 °C, has a coarse-grained structure. Overheating reduces the mechanical properties of the metal, mainly plasticity and viscosity. The destruction of the welded joint usually occurs in this area, the width of which reaches 3...4 mm. Normalization area: the area of the base metal heated to 900...1100 °C. Due to the fine-grained structure, the mechanical properties of the metal in this area are higher compared to the base metal. The area of incomplete recrystallization: the area of the base metal

heated to 725...900 °C; consists of small and large grains. The uneven crystal structure leads to a decrease in mechanical properties. The recrystallization area: the area of the base metal heated to 450...725 °C. At these temperatures, the shape of grains deformed after previous mechanical impact (during rolling, stamping, etc.) is restored. The width of the zone of thermal influence depends on the specific energy introduced into the workpiece and the type of welding.

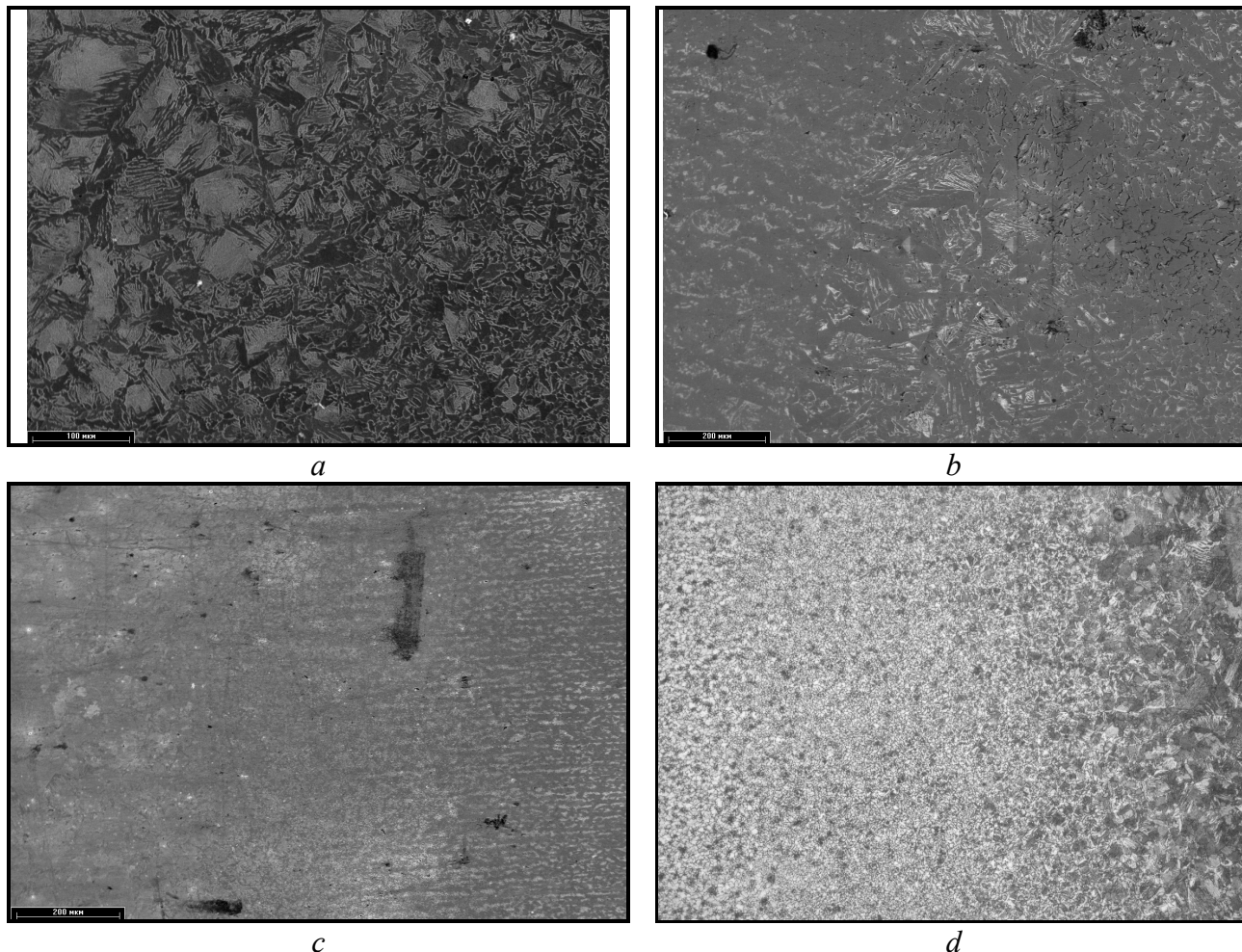


Fig. 4. Structure of heat-affected zone: *a* – welding in an environment of protective gases; *b* – flux welding; *c* – laser welding; *d* – electric beam welding

The microstructure of the base metal is shown in Fig. 5. Analysis of the given data shows that the base metal has a ferrite-pearlite structure. During welding and, accordingly, the temperature rises to the critical point A_{c1} , processes of diffusion redistribution take place, after which the formation of pearlite colonies occurs when the carbon concentration is less than 0.8%. The resulting pearlite component has a finer structure and is called a quasi-eutectoid.

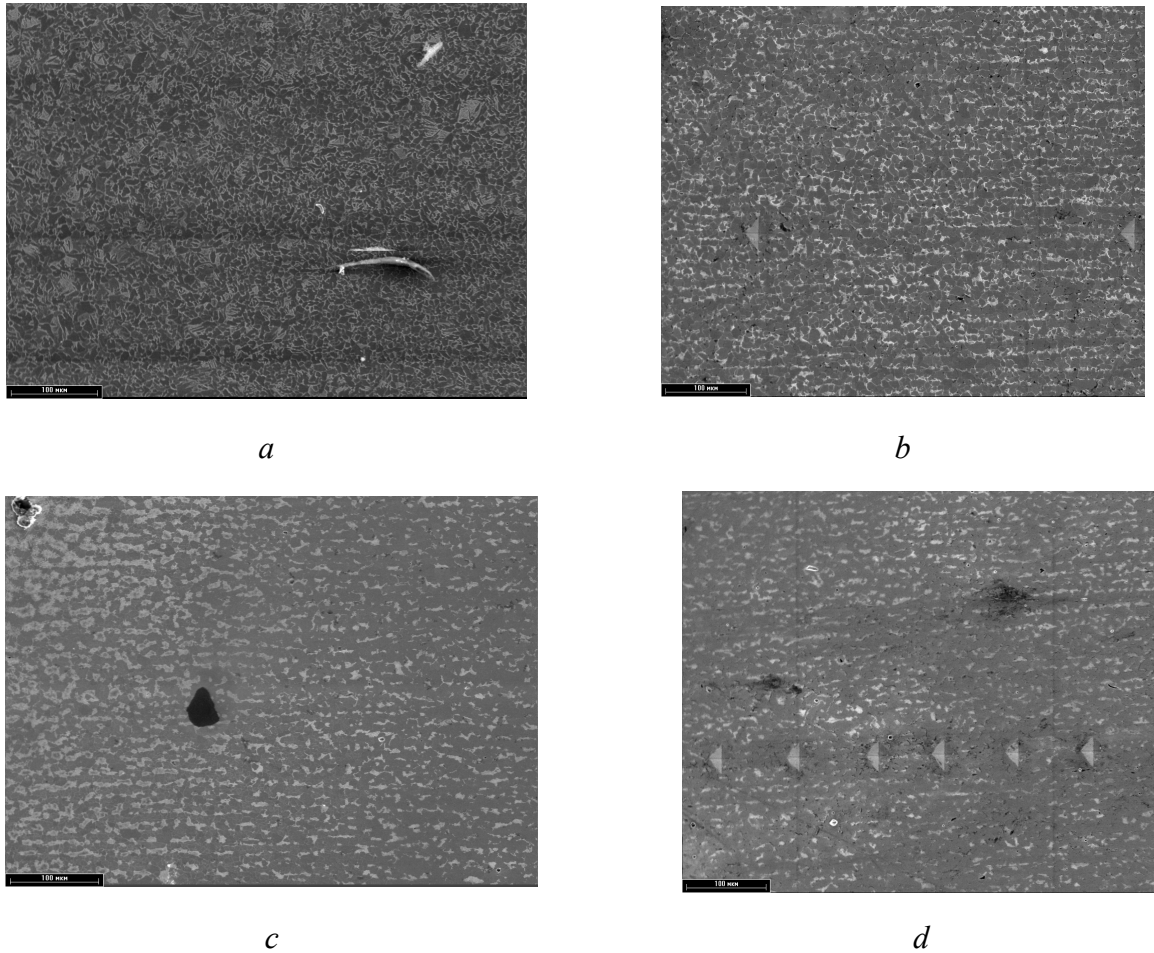


Fig. 5. The microstructure of the base metal: a – welding in an environment of protective gases; b – flux welding; c – laser welding; d – electric beam welding

4 Microhardness Research of Welded Joints

When the metal structure changes, the size and relative location of its grains (crystals) change too. This process is accompanied by a change in the volume of the metal, which causes the formation of internal stresses. Stresses arising after changes in the structure of the metal can be of practical importance only when welding alloyed and high-carbon steels that have a tendency to quench.

The strength of a welded joint is characterized by the number of stresses that arise in it under the influence of applied forces. For the connection to be strong, the actual stresses in it during operation should be several times lower than those at which the metal of the seam is destroyed.

To study the distribution of the strain-stress state in the zones of the welded joint and approximate the strength of the welded joint, a study of the microhardness in the zones was carried out (see Fig. 6). The obtained results are summarized and shown in the table. 3. In the table 4 shows the set of mechanical properties of 10KhSND steel after continuous controlled rolling.

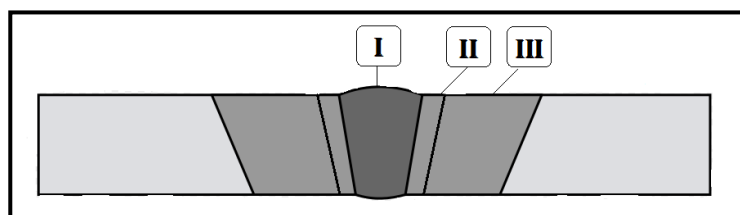


Fig. 6. Schematic representation of microhardness control zones: I - weld zone; II - fusion zone; III - zone of thermal influence

Table 3. The value of microhardness in the zones of the welded joint

The material zone according to fig. 6	Welding in an environment of protective gases	Flux welding	Laser welding	Electric beam welding
I	160.	129.5	341.2	198.2
II	149.0	119.0	336.0	167.5
II	130.7	125.0	162.3	147.8

Table 4. The complex of mechanical properties of 10KhSND steel after continuous controlled rolling

Steel	Mechanical Properties			
	δ , [%]	ψ , [%]	YS, [MPa]	US, [MPa]
10KhSND	23.4	71.5	505.5	680.6

The analysis of the obtained data shows that the maximum values of microhardness (as a result, the maximum stress level) appear in the peri-seam zone. At the same time, in this zone, the stress level reaches values that are almost equal to the yield strength. the border of zones 2 and 3 (see Fig. 6), the stress level is 0.5...0.8 YS, while higher values are observed when the source power and welding speed increase.

Residual tensile stresses form a reserve of energy in the metal, which can contribute to the destruction of the metal. They also contribute to the acceleration of corrosion processes. The plastic deformations associated with them lead to a decrease in the plasticity of the joint. Composed of working stresses, residual stresses impair the work capacity of the structure: in elements working under variable loads, it reduces the limit of endurance; in elements that work for bending, the stiffness of the section decreases due to the transition of part of the section to a plastic state. Residual stresses significantly affect the accuracy and dimensional stability of welded joints. During mechanical processing, due to the redistribution of residual stresses, the shape and size of the part changes. Creep deformations occur under the action of residual stresses, especially at elevated temperatures. At the first application of the working load, the working stresses, combined with the residual stresses, may in some places exceed the yield strength and cause plastic deformation.

6 Conclusions

1) Analysis of the weld microstructure shows that crystallization occurs in non-equilibrium conditions. As a result, a columnar zone with a directional orientation is formed due to dendritic growth. Boundaries between crystallites, which are formed as the crystallization front moves into the melt, are usually also elongated in the direction of growth. At the same time, the axes of crystallite growth in the general case are spatial curves due to the change in the shape of the welding bath in planes parallel to the area of the welded sheet and the movement of the thermal field in the direction of welding.

2) The zone of thermal influence consists of several structurally different areas. The area of overheating: the area of the base metal, heated to 1100...1450°C, has a coarse-grained structure. Overheating reduces the mechanical properties of the metal, mainly plasticity and viscosity. The destruction of the welded joint usually occurs in this area, the width of which reaches 3 ... 4 mm. Area of normalization: the area of the base metal heated to 900 ... 1100 ° C. Area of incomplete recrystallization: area of the base metal heated to 725 ... 900 ° C; consists of small and large grains. The uneven crystal structure leads to a decrease in mechanical properties. The recrystallization area: the area of the base metal heated to 450 ... 725°C. At these temperatures, the shape of grains deformed after previous mechanical impact is restored. The width of the zone of thermal influence depends on the specific energy introduced into the workpiece and the type of welding.

3) Analysis of the given data shows that the base metal has a ferrite-pearlite structure. During welding and, accordingly, the temperature rises to the critical point A_{c1} , processes of diffusion redistribution take place, after which the formation of pearlite colonies occurs when the carbon concentration is less than 0.8%. The resulting pearlite component has a finer structure and is called a quasi-eutectoid.

4) Data analysis shows that the maximum values of microhardness (as a result, the maximum stress level) appear in the peri-seam zone. At the same time, in this zone, the stress level reaches values that are almost equal to the yield strength.

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