EFFECT OF STRESS-STRAIN STATE ON STRUCTURE AND PROPERTIES OF JOINTS IN DIFFUSION WELDING OF DISSIMILAR METALS

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Computer modelling of stress-strain state (SSS) considering change of physical-mechanical properties, structural transformations and creep strains determined that distribution of plastic strains along the joint butt in diffusion welding (DW) of dissimilar materials is non-uniform. The results of mechanical tests of welded joints provide estimation not for different zones of joint but welded joint integral estimation. Aim of the work is determination of effect of SSS on structure and properties of joints in different zones of joint butt at constant temperature of DW and using temperature cycling. Welding of steel 12Kh18N10T and electric steel 10864 (armco-iron) was carried out at constant temperature 1050 °C and two temperature cycles 700–1000 °C. Welded joints were subjected to microstructural and local X-ray microanalysis. Hardness distribution was studied. Significant attention was made to study of fine structure of metal in joint zone and estimation of specific contribution of different structural constituents in total value of yield strength of the welded joints, considering dependence of dislocation density on value and intensity of plastic strain. Carried investigations confirm the results of SSS computer modelling and presence of significant zone of deformation stagnation in DW with constant temperature. It is determined that DW with temperature cycling allows controlling SSS, intensifying processes of volume interaction and providing full strength of 10864 steel joints. 12 Ref., 6 Figures.

Keywords: *diffusion welding, SSS modeling, temperature cycling, structure, plastic strain, mechanical properties, diffusion*

Development of technologies in different branches of industry requires application of dissimilar materials in manufacture of parts and assemblies for rising of their operation efficiency. Diffusion welding (DW) in vacuum [1, 2] is one of the perspective methods for joining of these materials. Joints from more than 800 types of pairs of different materials have been made up to present time [3]. The main problem of DW is instability of joint formation along the butt area and in change of geometry of welded assemblies, that is explained by scale factor. Uniform distribution of compression force over the butt area is usually taken as a basis in development of welding mode and estimation of plastic strains, being the main factor of joint formation. In fact, Yu.L. Krasulin in works [4, 5] showed already that the strains have non-uniform distribution along the joint butt and form central zone without traces of interaction. Nature of fracture during testing in welding of cylinder specimens of heat-resistant alloys EI607A and EI896, taken from thesis of V.N. Stolyarov (I.I. Polzunov CRI DCBT), showed that the weakest zones of the joint appear in central zone close to the axis. Such zones were not observed in welding of large diameter billets and testing of specimen.

Investigation of dependencies of formation of joints in different zones of the joint butt in works [5, 6] were carried out using analytical methods of modelling applied in theory of pressure treatment of metals [7, 8], which do not allow taking into account the effect of number of alternating factors on stress-strain state (SSS) in the joint butt, including change of physical-mechanical properties, structural transformations, creep strains and other factors, which can be considered by computer modelling. Investigations [9, 10], carried out under the leadership of Prof. V.I. Makhnenko, allowed determining the dependencies of SSS formation under conditions of elasticity, instantaneous ductility and creep during DW of dissimilar materials considering their changing physical-mechanical properties, geometry and structural factors as well as possibility of SSS control in the joint butt in DW with changing temperature (with temperature cycling) in contrast to DW with constant temperature on classical scheme.

Efficiency of DW with temperature cycling is confirmed by results of mechanical tests of welded joints, providing for integral estimation rather than on different zones of the joint butt. It shows the relevance of performance of these investigations.

Aim of present work is determination of SSS effect on structure and properties of the joints in different zones of joint butt in DW with temperature cycling and constant temperature. The idea of performance of the investigations, described below, belonged to Prof. V.I. Makhnenko.

Welding of steels 12Kh18N10T and 10864 in 10^{-2} Pa vacuum on DW classical scheme at constant temperature 1050 °C and pressure 15 MPa with 12 min holding, and using two temperature cycles of 750–1000 °C interval with 2 min holding at 1000 °C was studied in the work. After second cycle, heating was continued to 1050 °C for 6 min and further cooling as in the first case. Cylinder specimens of 12 mm diameter were used. 12Kh18N10T steel refers to nonmagnetic corrosion-resistant heat-resistant steels of austenite class and contains not more than 0.08–0.12 % C, 17–19 % Cr, 9–11 % Ni and up to 0.8 % Ti. Conventional yield strength at room temperature makes not less than 200 MPa, ultimate tensile strength is not less than 500 MPa, relative elongation and reduction in area not less than 40–55 %. Steel 10864 refers to magnetic steels of ferrite class, which is used in manufacture of electromagnet cases, and contains to 0.035 % C, ≈0.3 % Si and Mn, up to 0.1 % Ni and 0.03 % Cr. The yield strength makes not less than 215 MPa, ultimate strength and relative elongation are not less than 320 MPa and 33 %, respectively.

After welding the specimens were cut along the diameter and studied along the lines parallel to the axis and passing through 0, *A* and *B* zones, i.e. along the axis, middle of the radius and close to the side surface of specimen, respectively, as shown in Figure 1.

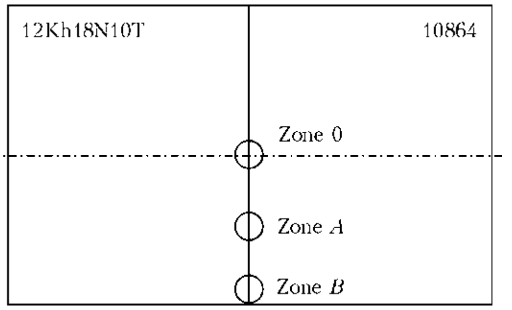


Figure 1. Scheme of welded cylinder specimen from steels 12Kh18N10T and 10864

Welded joints were subjected to microstructural and local X-ray microanalysis as well as study of microhardness distribution.

DW is characterized by low intensities and values of plastic strains. Deformation takes place at 10^{-4}–10^{-3} s^{-1} rates on dislocation mechanism, plastic strain is considered as a process of formation of new dislocations and their movement along the crystal [11]. Emergence of dislocations on the surfaces being joined and their accumulation is accompanied by delivery of atoms with unlinked binding forces, forming active center of the joint. Breaking of old bonds with oxygen of oxide film and formation of new ones between subsurface atoms of parts being joined take place within the active centers. Thus, deformation activation of the surfaces and their setting (establishing of interatomic bonds) take place. Frequency of dislocations emergence is determined by intensity of plastic strain [11]. It is no change of dislocation density at the first stage of light slipping and it makes around 10^8 cm^{-2}. Irregular dislocation mesh emerge at the second stage. Average density of dislocation at the beginning of the first stage rises to 10^9, and at the end makes 10^{10} cm^{-2}. Local dislocation density achieves 10^{11} cm^{-2}. Appearance of wide slip bands is observed at the third stage, that is promoted by transverse sliding of screw dislocation components, gaps between which are filled by fine, short slip lines.

Specific attention in the work is made to examination of metal fine structure in zone of the joint butt considering the clear dependence of dislocation density on value and intensity of plastic strain. Optical metallography, analytical scanning (the Philips SEM-515) and microdiffraction transmission electron microscopy using the JEOL JEM-515 assembly with energy dispersive and wave spectrometers, as well as Comebax assembly of SX-50 type were used at that. The method of transmission electron microscopy allows also detecting segregation processes, related with diffusion.

Works [9, 10] indicated presence of a zone with minimum plastic strains, where tangential stresses equal zero, in central part of the cylinder specimen at constant temperature as well as in welding of bush-to-bush assembly at some distance from the internal surface (between internal surface and average thickness of bushing). This zone is called the zone of deformation stagnation.

Figure 2 shows the fields of equivalent plastic strains considering creep deformations during

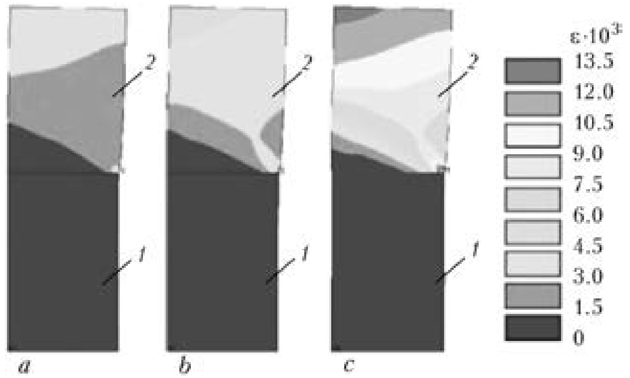


Figure 2. Change of equivalent plastic strains in section of axially symmetric part of the specimen during DW of steels 12Kh18N10T (*1*) and 10864 (*2*) using classical scheme at time of welding 90 (*a*), 120 (*b*) and 300 (*c*) s

compression of specimens by 15 MPa pressure at constant temperature. The fields of shear plastic strains are not shown due to their low level.

It can be seen in Figure 2 that plastic strains at constant temperature of welding start to develop from steel 10864 cylinder surface, slowly propagating its area to the center of specimen and intensively develop at a distance from the joint butt. Such SSS results in development of welded assembly deformations behind the zone of joint butt and are unfavorable for formation of the joint. Modelling results show that DW

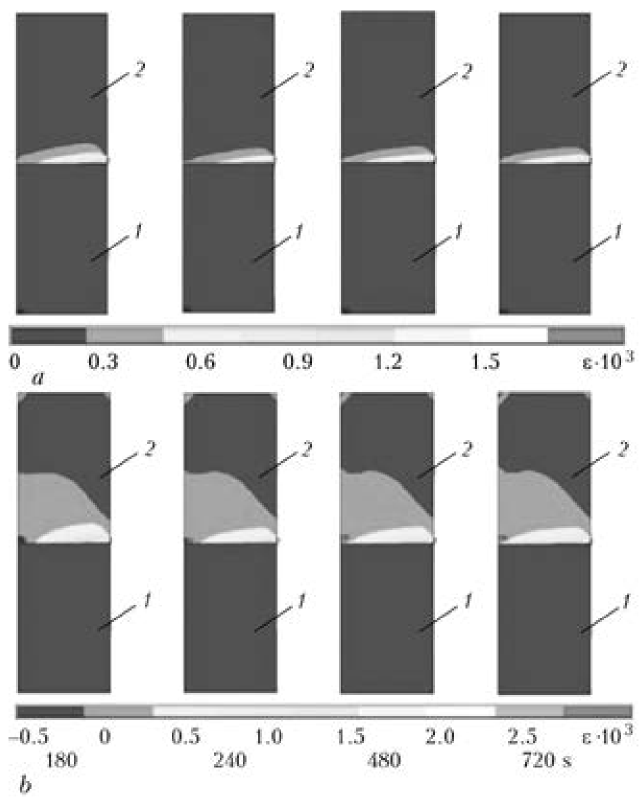


Figure 3. Change of fields of equivalent (*a*) and shear (*b*) plastic strains in section of axially symmetric part of the specimen during DW with temperature cycling of steels 12Kh18N10T (*1*) and 10864 (*2*) during of first cycle (180, 240 s), after second (480 s) and third (720 s) cycle

with temperature cycling promotes formation of SSS being favorable for surface activation and formation of joints along the whole area of joint butt (Figure 3).

Analysis of fields of plastic strains (see Figure 3) show that equivalent and shear strains at thermal loading localize in zone of the joint butt. It is close to ideal variant for providing of deformation mechanism of activation of surfaces being joined. The fields of plastic strain distribution in zone of the joint butt show small changes at the end of each cycle, but position of zone of deformation stagnation is somewhat changed in process of heating, that promotes more uniform distribution of deformations over the joint butt. It is also promoted by surface slipping at the first stage of joint formation.

Figure 4 shows the results of investigation of fine structure of 12Kh18N10T and 10864 steel joints at constant DW temperature and welding with temperature cycling. Study of structure of joint metal in zone 0 using electron microscope with magnification (×15,000–50,000) showed formation of elongated 1.8–2.7 μm width band of surface layers collapsing from side of 10864 steel and preserving from side of 12Kh18N10T steel. Inactivity of contacting surface from the side of austenite steel is confirmed by stability of interface and presence in this interface of surface oxides (Figure 4, *a*), which are barriers for establishing the bonds between subsurface atoms of metals being joined and resolidification. Removal of these barriers is possible by means of their diffusion dissolving, however, this requires long time even at DW of nickel [11]. Plastic strain of metal in the joint butt promotes for removal of oxides on the mechanical failure–dispersion–diffusion dissolving of oxides scheme, that intensifies interaction (binding) of materials being joined. At that, areas of brittle cleavage, observed at the initial stage in the zone of oxide plate location, are replaced by areas of tough fracture.

Deformation along the interface in zone 0 is noted only from the side of steel 10864 with maximum depth of deformed layer 2.8 μm. Small rise of dislocation density, typical for initial stage of formation of block structures, is found from the side of austenite steel directly in 0–2 μm contact zone. And only single, randomly located dislocations of the same density as at a distance from the joint butt are detected at increase of distance from the joint butt to 10–80 μm. Separate twins typical for austenite steel are found there on the background of uniform distribution of dislocations at their minimum density 10^8 cm^{-2}, that

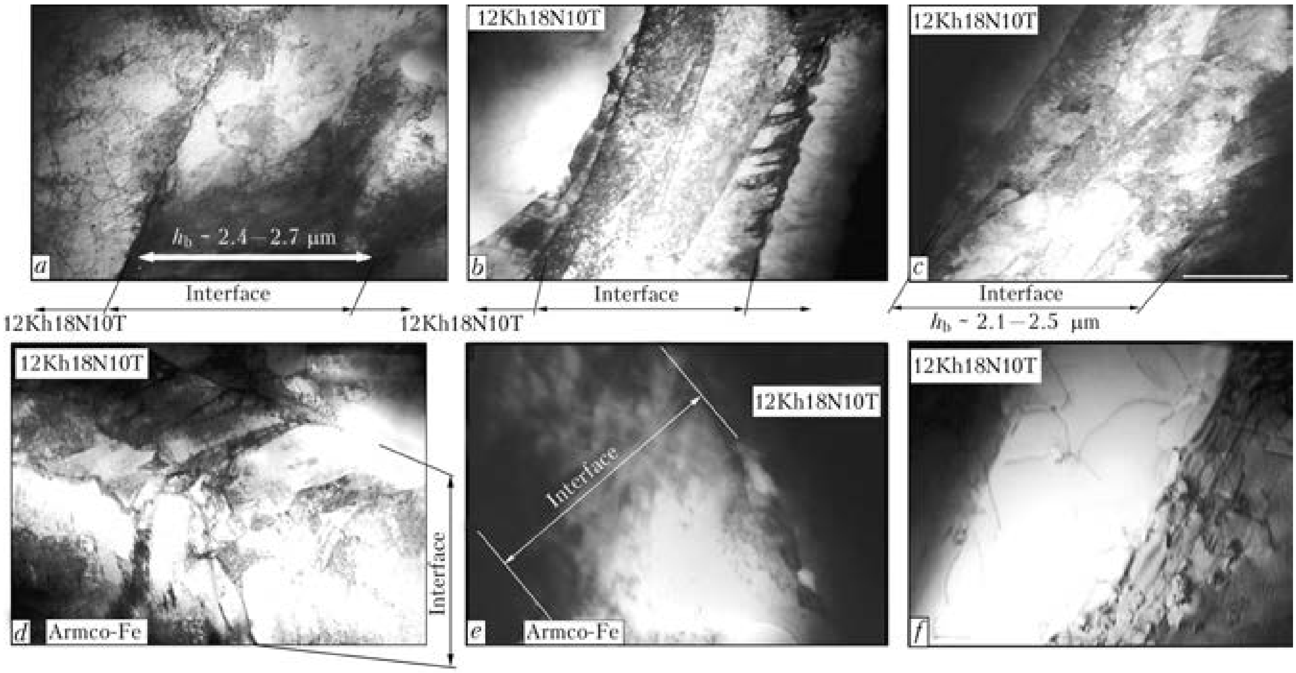


Figure 4. Fine structure of welded joint of steels 12Kh18N10T and 10864, produced at constant temperature of DW in zone of joint butt 0 (*a*), *A* (*b*), *B* (*c*) and in DW with temperature cycling in zone of joint butt 0 (*d*), *A* (*e*) and *B* (*f*) (*a*, *c*, *d* — ×20000; *b*, *e*, *f* — ×30000)

indicates insignificant deformation on the surface of steel 12Kh18N10T.

Elongated band structures with rapidly rising dislocation density, indicating high deformation intensity, are observed in zone *A* of the joint butt (Figure 4, *b*). It is important that subsurface activation of deformation processes from the side of austenite steel takes place in indicated zone. Intergrain density dislocation rise to 10^{11} cm^{-2}, number of slip systems increases as well as processes of phase formation are observed. Formation of high-dispersion phases of d_{ph} = 0.03–0.05 μm diameter is noted in the zone of dislocation accumulation and development of slip systems. Structural changes in austenite steel are observed in layer of to 100 μm depth from the joint butt.

Cell and subgrain structure of d_s = 0.13–0.30 μm size are formed in zone *A* from the side of steel 10864. Intensification of deformation activation of metal is observed in near-contact zone, that is indicated by rise of total dislocation density and formation of elongated dispersion band structures with clear intergrain boundaries.

Nature of metal structures indicates accumulation of energy in zone *A*, but relaxation processes are at initial stage.

Metal structure in zone *B* (Figure 4, *c*) of the joint butt indicates that active processes of plastic strain move to the stage of relaxation development, namely redistribution of general dislocation density is observed with rise of sizes and equiaxial nature of the structure (grain and subgrain), formation of more uniform equilibrium high-angle boundaries and areas with common grains, i.e. with set intercrystalline interatomic bonds of metals being joined.

Processes of relaxation (redistribution of dislocations, rise of sizes of grain and subgrain structure) and redistribution of defects of crystalline structure (reduction of dislocation density in grain body and improvement of grains) actively take place. Intensity of relaxation processes from the side of steel 12Kh18N10T is traced at up to 150 μm distance from the joint butt. Increase of sizes of forming phases with diametar to 0.3 μm takes place in this zone, that also confirms activating role of thermo-deformation processes in zone *B* of the welded joints.

Figure 4, *d*–*f* gives the results of study of structure of joints from 12Kh18N10T and 10864 steels at DW with temperature cycling.

Area of interaction of steels in zone 0 has around 2.1 μm width with clearly observed block structure of elongated shape and sizes of blocks approximately 0.25 × 2 μm (Figure 4, *d*). Elongation and shape of blocks, as well as lamellar nature of their distribution in zone of the joint butt, are the evidence of orientation and high intensity of local plastic deformation under effect of external compression and thermal loading, caused by different physical-chemical properties of materials being joined.

Dispersion of structure, high dislocation density with maximum value to 10^{11} cm^{-2}, block morphology with clear interblock interface confirm high level of deformation.

Areas of segregation of high-dispersion accumulations having 0.05–0.12 μm size particles are observed in some zones of the joint butt that is the evidence of active processes of mass-transfer.

Processes of intensive dislocation redistribution with multiple slip traces as well as decoration of dislocations by alloying elements and development of phase formations of d_{ph} = 0.10–0.15 μm size are observed directly near the joint butt from the side of austenite steel in area of to 70 μm depth. State of equilibrium of metal structure is indicated at a distance around 300 μm from the joint butt.

Dislocation density of 10^9–10^{10} cm^{-2} with formation of dislocation accumulations, cells and dispersion blocks is observed from the side of 10864 steel in area of contact interaction. At a distance from the joint butt the dislocation density drops to 10^8 cm^{-2} that indicates activation of relaxation processes. Formation of fine as well as coarser phase precipitates takes place directly in contact zone and at some distance from the joint butt in addition to segregations on separate dislocations. New phases are in particular actively formed along the intergrain boundaries.

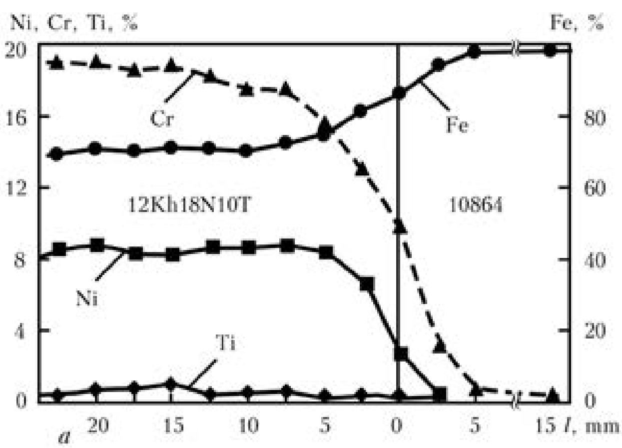
New disperse more equiaxial structures of relaxation nature are formed in zone *A* (Figure 4, *e*). Traces of active plastic strain are typical for structure from the side of steel 12Kh18N10T at 5–10 μm distance from the joint butt at significant level of dislocation density with clear twinning of grain microvolumes. The processes, related with segregation of elements and additives (diffusion) as well as nucleation of new phases on dislocations accumulations at initial stage, and phases having clear morphology and size, are also observed.

The traces of slipping, formation of segregation and new dispersion phases are found along the whole width of band of plastic strain of steel in zone of the joint butt.

Metal structure in zone *B* of the joint butt is characterized by indistinct equiaxial grains of d_s ~ 1.3–3.0 μm with sub- and intergrain boundaries (Figure 4, *f*). Active phase formation, dispersion of which makes d_{ph} = 0.01–0.04 μm, and accumulation of dislocations in body as well as along the boundaries of structural elements are typical for this zone. The structure in microvolumes of austenite steel at 5–10 μm distance from the joint butt is similar to one that is formed directly near the joint butt on appearance, distribution and size of phase precipitations (d_{ph} = = 0.03–0.08 μm). Dislocation density makes around 10^{10} cm^{-2}. However, rapid increase of grain structure and drop of dislocation density to $6\cdot10^8$ cm^{-2} take place already at around 20 μm distance from the joint butt. The phase precipitates became coarser approximately by order (d_{ph} = 0.3–0.7 μm) and their quantity reduces. Structure of steel 12Kh18N10T shows no difference from structure of the base metal at increase of distance from the joint butt to 250–400 μm.

Steel structures in zones *B* and *A* in DW with temperature cycling and *B* at constant welding temperature are similar, that indicate intensive development of relaxation processes. It is also confirmed by steel microhardness. Microhardness of both steels in section along the zone *B* is lower than in zones *A* and 0, where relaxation processes do not develop at constant DW temperature.

Depth of mutual diffusion in zones *A* and *B* of steels being joined makes 8–14 μm on different elements. Width of diffusion zone (Figure 5, *a*) significantly exceeds accepted in literature criterion of strength on width of diffusion zone 3–5 μm [1] in DW with temperature cycling even in zone 0. Formation of transition layer between



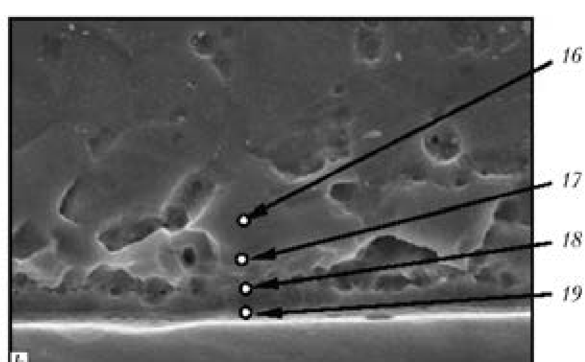


Figure 5. Distribution of elements (*a*), and microstructure (*b* — ×4020) of metal in zone of joint butt of steels 12Kh18N10T and 10864 (chemical composition, wt.%, in points *16* — 78.7Fe, 5.36Ni, 14.3Cr, 0.56Ti; *17* — 79.9Fe, 5.36Ni, 12.27Cr, 0.53Ti; *18* — 86.4Fe, 3.2Ni, 9.8Cr; *19* — 92.47Fe, 1.3Ni, 6.2Cr)

steels 12Kh18N10T and 10864 is shown in Figure 5, *b*.

Analysis of received results of study of fine structure and chemical composition of metal in zone of the joint butt shows that DW with temperature cycling provides for formation of joints without defects and brittle phases along the whole area of the joint butt. Diffusion porosity in the diffusion zone is absent. Mechanical tests showed that fracture of welded joints has brittle nature and occurs in steel 10864 out of the joint zone.

Results of study of fine structure and formation of joints verify the results of computer modelling of SSS in DW of steels 12Kh18N10T and 10864, received in work [6] as well as given in Figures 2 and 3. Plastic strains take place along the whole area of the joint butt in DW with temperature cycling in contrast to DW at constant temperature that guarantees welded joint quality.

Performed complex of experimental investigations of structural constituents (sizes of grains and sub-grains, dislocation density, size and distribution of phase precipitates), formed in metal under different thermal-deformation conditions, allows carrying out analytical estimations of specific contribution of different structural constituents in total value of mechanical characteristic of the welded joints of steels 12Kh18N10T and 10864 in different zones of the joint butt at constant DW temperature (traditional scheme) and in DW with temperature cycling. Yield strength of metal in joining zone is taken as such a characteristic [12]. At that, it was accepted that $\sigma_{0.2}$ value, according to Archard equation, including known Hall–Petch, Orowan, Ashby, Armstrong, Peierls–Nabarro and Conrad dependencies is written by formula

$$\Sigma\sigma_{0.2} = \Delta\sigma_0 + \Delta\sigma_{s.s} + \Delta\sigma_g + \Delta\sigma_s + \Delta\sigma_d + \Delta\sigma_{d.s},$$

where $\Delta\sigma_0$ is the resistance of metal lattice to movement of free dislocations (stress of lattice friction or Peierls–Nabarro stress); $\Delta\sigma_{s.s}$ is the strengthening of solid solution with alloying elements and additives (solid solution strengthening); $\Delta\sigma_g$, $\Delta\sigma_s$ are the strengthening due to change of value of grain and subgrain (Hall–Petch dependencies, grain and substructural strengthening); $\Delta\sigma_d$ is the dislocation strengthening caused by interaction between dislocations; $\Delta\sigma_{d.s}$ is the strengthening due to dispersion particles by Orowan (dispersion strengthening).

Results obtained during study of metal fine structure in zone of the joint butt were used for quantitative estimation of effect of different structural factors on yield strength of metal in zones 0, *A*, *B* using traditional scheme of DW and DW with temperature cycling. Constituents of stresses in Archard equation were determined according to work [12]. Figure 6 shows the calculation results.

Analytical estimations of specific (differential) contribution of different structural-phase parameters in change of strength characteristics ($\Sigma\sigma_{0.2}$) showed that the most significant increase of total (integral) value of yield strength $\Sigma\sigma_{0.2}$ is observed in zone *B* at constant temperature of DW and in zone *A* in DW with temperature cycling. According to analytical estimations, higher values of yield strength are observed in zone *A* in DW with temperature cycling in comparison with zone *B* without temperature cycling due to larger subgrain strengthening from the

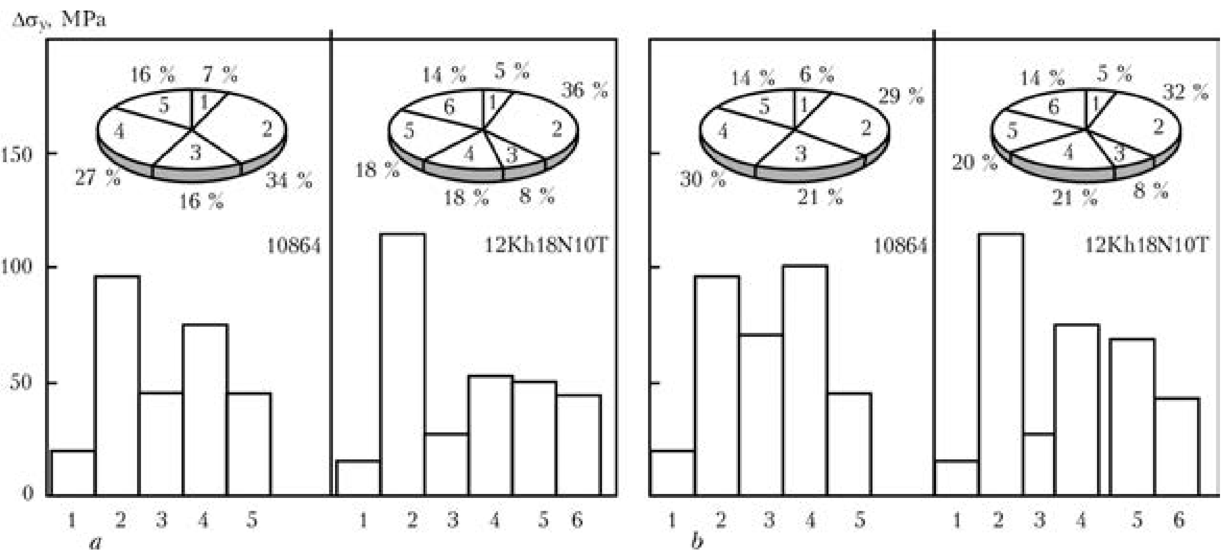


Figure 6. Effect of structural factors on metal yield strength and fraction of constituents of yield strength in joint butt during DW using traditional scheme at constant temperature (*a*) and DW with temperature cycling (*b*) in zone 0: 1 — $\Delta\sigma_0$; 2 — $\Delta\sigma_{s.s}$; 3 — $\Delta\sigma_g$; 4 — $\Delta\sigma_s$; 5 — $\Delta\sigma_d$; 6 — $\Delta\sigma_{d.s}$

side of steel 10864 and steel 12Kh18N10T as well as because of rise of dislocation density and phase precipitates from the side of steel 12Kh18N10T.

Analytical estimation was not carried out in zone *B* of the specimen, produced by DW with temperature cycling, since high quality of joint formation in this zone is out of doubts on any parameter.

The worst conditions of joint formation using traditional scheme of welding is observed in zone 0, which has no shear deformations and oxide films are preserved. Fracture of specimen starts in this zone and it is, in particular, obvious at life duration testing.

Results of analytical estimation of joint strength in different zones of the joint butt are well correlated with the results of SSS modelling during DW and they confirm efficiency of DW with temperature cycling of dissimilar materials.

Developed technology was used for production of commercial products including welding of five parts on four ends simultaneously.

Conclusions

1. Experimental investigations of structure, distribution of microhardness in metal joints, caused by plastic strain, and analytical estimation of joint strength in different zones confirm the results of computer modelling of SSS, showing non-uniform distribution of plastic strains along the area of the joint butt in DW of dissimilar materials and different conditions of joint formation, including presence of zone of deformation stagnation.

2. Analytical estimation of effect of different structural factors on strength characteristics of metal showed that yield strength in the central zone of the joint butt (zone 0) has the lowest value from the side of steel 10864 as well as 12Kh18N10T in DW of these steels using traditional scheme.

3. Sub-grains, grain and dislocation strengthening make the largest contribution in rise of metal yield strength of the same zone in DW with temperature cycling.

4. DW of dissimilar metals with temperature cycling allows controlling SSS, intensifying plastic strain over the joint butt, processes of re-solidification and diffusion, and full strength of the joints with steel 10864.

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