FEATURES OF FORMATION OF DISSIMILAR METAL JOINTS IN HOT ROLL WELDING IN VACUUM

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Features of formation of the boundary of solid-phase joint of dissimilar materials are presented, and its influence on tensile strength is shown, depending on ductility of materials being joined. Experimental results are compared with the theoretical model, which allows for plastic deformation of materials at their joining temperature, as well as shear forces arising in material rolling and having a determinant role in the process of solid-phase joining of materials. The paper gives experimental results of X-ray microprobe analysis, metallography, as well as investigations of the boundary of solid-phase joint of samples, including tensile, micro- and nanohardness tests. Obtained data led to the conclusion about the possibility of forming strength characteristics of dissimilar metal joint boundary.

Keywords: *vacuum roll welding, solid phase, joint boundary, formation features, strength, ductility*

Solid-phase welding of dissimilar materials by hot rolling in vacuum opened up new promising directions in application of this joining process in industry [1–5]. Known methods of joining dissimilar materials are based on plastic deformation of material and, as a rule, in the uniaxial direction. Theory of solid-phase joining was developed for the case of these technologies [3]. Features of distribution of atoms in metals at pulsed impact were studied in [6]. Processes of plastic deformation have been experimentally studied in [7–9]. Problem of mass transfer was studied in [7, 10, 11], and the phenomenon of phase formation under the conditions of increased rates of dissimilar material deformation in pressure welding — in [7, 12].

Method of hot rolling in vacuum [13–17] essentially changes the theoretical concept of the phenomenon of solid-phase joining of large massive plates from dissimilar materials across their thickness and along their length. Solid-phase welding of dissimilar materials by rolling method is achieved through plastic deformation of materials. Material of a higher ductility deforms to a greater extend and slides over the material of a lower ductility. At sliding and action of forces pressing the plates together, friction forces are induced, cleaning of subsurface layers proceeds, and at further deformation solid-phase joining of materials takes place [18–21].

Dry sliding friction between the ductile solid materials is an example of macroscopic property, controlled by localized plastic deformation on the mesolevel, whereas the structure on the atomic level and composition of contacting surfaces are the determinant factors for solid-phase joining of materials. Interrelation of the contacting solids and disordering on the atomic level were theoretically traced in the interface zone [22].

The purpose of this work is investigation of the processes occurring in solid-phase welding of dissimilar materials by the method of hot rolling in vacuum, determination of the regularities of variation of tensile strength of the solid-phase joint boundary σ_t, comprehensive investigation by the methods of X-ray microanalysis and metallography of the sample joining boundary and its tensile, micro- and nanohardness testing to study the processes affecting the strength of the joint boundaries.

Solid-phase joining of dissimilar metals was performed at high temperature in a vacuum rolling mill DUO-170 (Figure 1). The machine consists of a vacuum system, ensuring a vacuum of $p = 1\cdot10^{-2}$–$1\cdot10^{-3}$ Pa, furnace for sample heating up to temperature $T \approx 900$–1200 °C and roll chamber providing rolling speed v_0 = = 0.03–0.30 ms^{-1} and cogging force P = (2–32)$\cdot10^2$ MPa.

Metallographic investigations were conducted in an optical microscope «Olympus GX-51». X-ray microanalysis spectra were obtained in scanning electron microscope ZEISS-EVO-50 fitted with energy-dispersive analyzer INCA-450. Changes of micro- and nanohardness were studied on the surface in the direction normal to the material joint boundary in micro-LECO LM-700 and nanohardness meter Nana Indenter G200, MTS Systems, USA. Tensile testing was performed using Instron 5581 machine, fitted with a vacuum chamber with a furnace for heating up to 1100 °C.

Experiments on solid-phase joining of stainless and carbon steel of steel 20 type were conducted in a vacuum rolling mill. Solid-phase joining of dissimilar materials was performed by the method of hot rolling of a pack of plates at the temperature of 1100 °C and in the vacuum at $p = 1\cdot10^{-2}$ Pa. Then samples for rupture testing were cut out of the plate of obtained bimetal composite, which were tested in Instron 5581 machine. In Figure 2 it is clearly seen that tensile strength σ_t of the joint zone is higher than that of the weaker material, namely that of steel 20. In this case, rupture of the obtained composite ran through steel 20, tensile strength σ_t was equal to 430 MPa. Boundary of the solid-phase joint is much stronger that steel 20.

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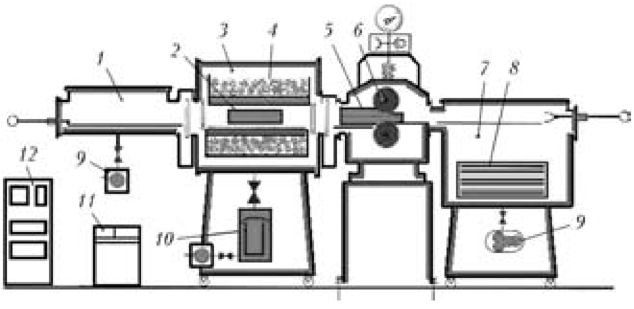

Figure 1. Diagram of vacuum rolling mill for joining dissimilar materials in the solid phase [14]: *1* — loading chamber; *2* — pack of plates being welded in the furnace; *3* — vacuum furnace; *4* — ceramic insulator; *5* — welded pack of plates in the roll chamber; *6* — rolls; *7* — chamber for unloading and collection of finished products; *8* — finished products in rolled stock collector; *9*, *11* — control consoles for technological process of rolling; *10* — vacuum system consisting of diffusion and roughing pumps; *12* — automated system of monitoring and control of technological process of rolling

To understand the processes running in joining of dissimilar materials in the solid phase, a pack consisting of dissimilar 12Kh18N10T–Cu–Nb–Ti materials was selected. Cu–Nb materials in the range of 0.58–0.73 at.% by the equilibrium diagram are intersoluble at the temperature of 800–1000 °C. Copper is the less strong material in this composition. Therefore, it is of interest to clarify the influence of adjacent materials on the strength of copper interlayer. With this purpose, rupture testing of samples was performed (Figure 3), depending on copper interlayer thickness and testing temperature. Testing was conducted in a vacuum chamber fitted with heater up to 1100 °C. A variable parameter in this experiment is thickness of the copper interlayer (0.075, 0.35 and 1.5 mm).

Conducted testing showed that rupture always runs through the least strong material, in this case — through copper. At testing of material with different thickness of copper interlayer the tensile strength of the joint rises with reduction of copper interlayer thickness. Figure 4 shows the dependence of tensile strength σ_t of stainless steels and copper interlayer of different thickness on temperature.

From the results of experiments on determination of the composite tensile strength it follows that its

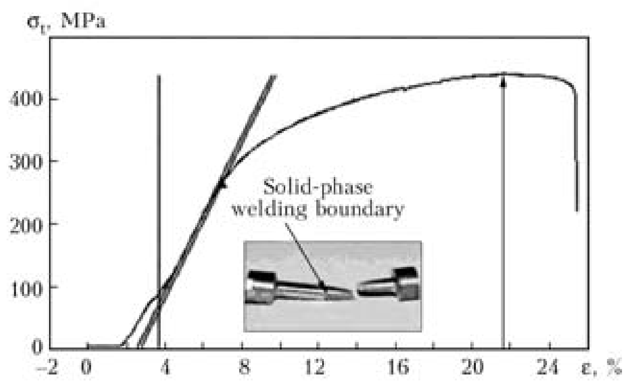

Figure 2. Diagram of tensile testing of 12Kh18N10T–steel 20 composite at the temperature of 20 °C (photo shows a sample broken in steel 20)

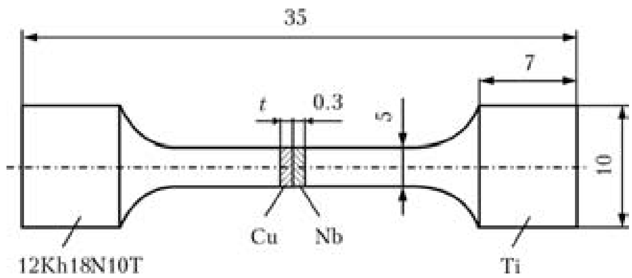

Figure 3. Diagram of a sample for rupture testing of materials welded in the solid phase

strength depends on the thickness of copper interlayer: the thinner it is, the higher the composite material tensile strength. So, at copper interlayer thickness of 1.5 mm σ_t of the composite approaches the value of σ_t of copper (200 MPa) at T = 20 °C. Under the same conditions, but at a thinner interlayer of copper (0.35 mm) the composite tensile strength rises, and at copper interlayer thickness of 0.075 mm σ_t value of the composite increases, becoming closer to tensile strength of the composite material and is equal to 550 MPa. The same effect is observed at the temperature of right up to 1000 °C.

This effect can be explained using the spectra of distribution of these materials on the boundaries of solid-phase joint of metals (Figure 5).

Let us consider the boundaries of 12Kh18N10TN–Cu and Cu–Nb joint in a laminated composite. In keeping with the above mechanism of solid-phase joining of materials and based on the spectra given in Figure 5, we can see that the stainless steel atoms consisting of iron, chromium, nickel and niobium, mechanically mix with copper and are transferred into the copper interlayer located between the two metals. Atoms of 12Kh18N10T and niobium move due to dry sliding friction of rubbing surfaces into the copper interlayer from two sides towards each other to a depth of several tens of micrometers. Such a mechanism of mechanical mixing and displacement of atoms of one material into another was calculated by the method of molecular dynamics in [23]. Thus, the copper interlayer is strengthened by iron, chromium and nickel,

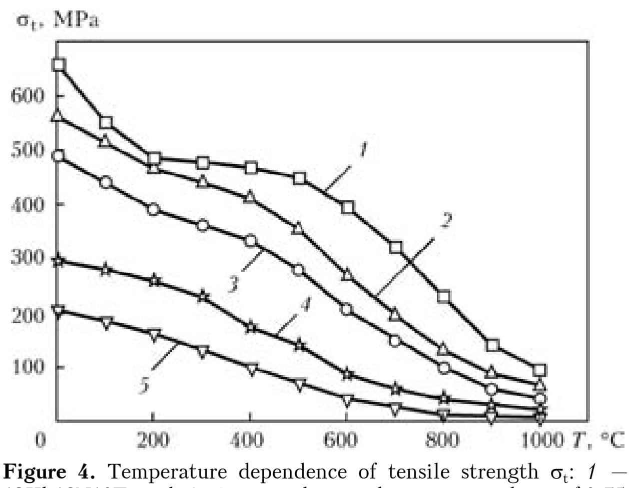

Figure 4. Temperature dependence of tensile strength σ_t: *1* — 12Kh18N10T steel; *2*–*4* — stainless steel–copper interlayer of 0.75, 0.35 and 1.5 mm thickness, respectively; *5* — copper

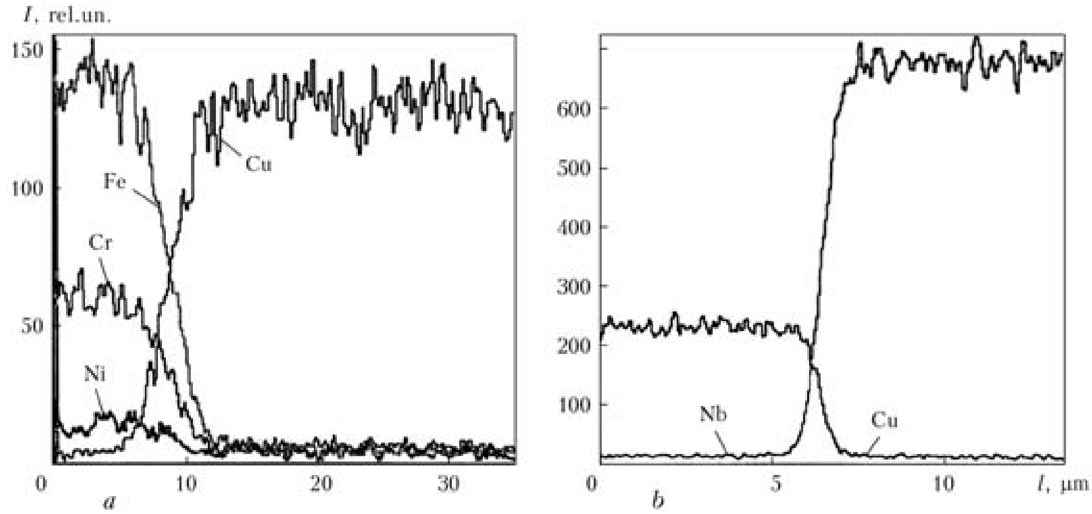

Figure 5. Spectra of X-ray microanalysis near the boundaries of solid-phase joint of metals: *a* — 12Kh18N10T–Cu; *b* — Cu–Nb

on the one side, and niobium atoms, on the other side. Figure 4 shows the dependence of tensile strength on temperature of solid-phase joining of 12Kh18N10T–Cu–Nb–Ti composition produced by the method of hot rolling in vacuum: it is the higher the thinner the copper interlayer and the more it is filled by atoms of metals adjacent from both sides. In the considered case the highest strength in the experiment is achieved at copper interlayer thickness of 0.075 mm, close to that of stainless steel, and it decreases at increase of copper interlayer thickness.

To confirm the change of strength of joint boundaries, investigations of the nature of material properties, their micro- and nanohardness were performed. Nanohardness was measured as close as possible to the boundary of solid-phase joint. So, the nanoindenter allows approaching the joint boundary to a distance of about 0.15 μm, while microhardness meter LM-700 with minimum load of 10 N for copper allows obtaining valid results at not less than 6 μm distance from the joint zone.

Joint structure determined during metallographic examination of solid-phase joint of 12Kh18N10T–Cu–Nb–Ti materials, is shown in Figure 6, from which it is seen that the joint boundaries form clear junctions, without formation of intermetallic zones on the boundaries. This is particularly important at measurement of nano- and microhardness of samples.

In Figure 7, which shows the change of micro- and nanohardness on the boundary of the joint of two metals, it is clearly seen that materials change their strength properties to the right and left of the joint boundary (coordinate 0). The less strong material (copper) becomes stronger near the joint boundary, both from the side of stainless steel, and from the niobium side. On the other hand, strength decreases on the boundary of the joint of stainless steel and niobium with copper.

Work [24] gives the calculation model, which allows prediction, based on material formation, of tensile strength of dissimilar metal joint boundary. Unlike the model described in [3], the developed one allows for the forces of the metal displacement relative to each other, created by rolls along the boundary of metal joining.

In keeping with the proposed model tensile strength on the boundary of dissimilar metal joint can be found from the following expression:

$$\sigma_t^{M_1+M_2} \equiv \frac{\sigma_t^{M_1+M_2}}{\sigma_t^{M_1}} = \frac{1}{2}\frac{kT}{E_A}\frac{P_{p\parallel}}{P_*}\frac{\sigma_{Sp}^{M_2}}{\sigma_{S0}^{M_1}}\frac{\sigma_{S0}^{M_2}+\sigma_{Sp}^{M_1}}{\sigma_{S0}^{M_2}-\sigma_{Sp}^{M_1}} \times$$
$$\times \ln\left(\frac{\sigma_{S0}^{M_2}}{\sigma_{Sp}^{M_1}}\right) \equiv \frac{Q_{M_1+M_2}(\sigma_{S0}^{M_2}/\sigma_{Sp}^{M_1})}{Q_{M_1+M_1}(\sigma_{S0}^{M_1}/\sigma_{Sp}^{M_1})}, \quad (1)$$

where $\sigma_t^{M_1+M_2}$ is the tensile strength of the boundary of joint of metals M_1 and M_2.

It should be noted that the values of $Q_{M_1+M_1} \times (\sigma_{S0}^{M_1}/\sigma_{Sp}^{M_1})$ parameter for similar metals are always greater than a unity.

In expression (1) value E_A should be referred to a more ductile metal M_1 ($\sigma_t^{M_2} > \sigma_t^{M_1}$).

It follows from formula (1) that limit values of the range of tensile strength on the boundary of the joint of two dissimilar materials can be determined assuming that $M_1 \to M_2$ or $M_2 \to M_1$. Then, for the value for the lower limit of the range we have $\sigma_t^{M_1+M_2}|_{M_2 \to M_1} = \sigma_t^{M_1}$. At $M_1 \to M_2$ it is not difficult

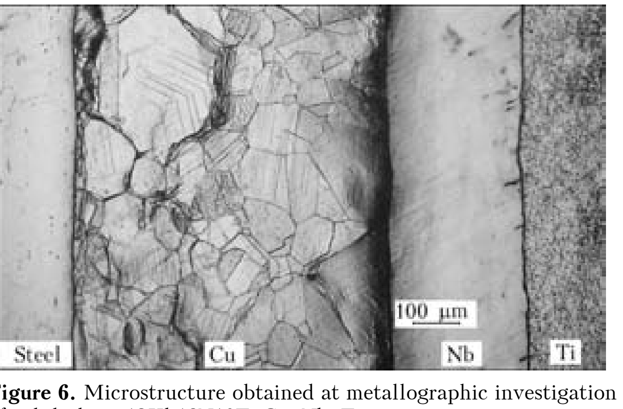

Figure 6. Microstructure obtained at metallographic investigation of solid-phase 12Kh18N10T–Cu–Nb–Ti joint

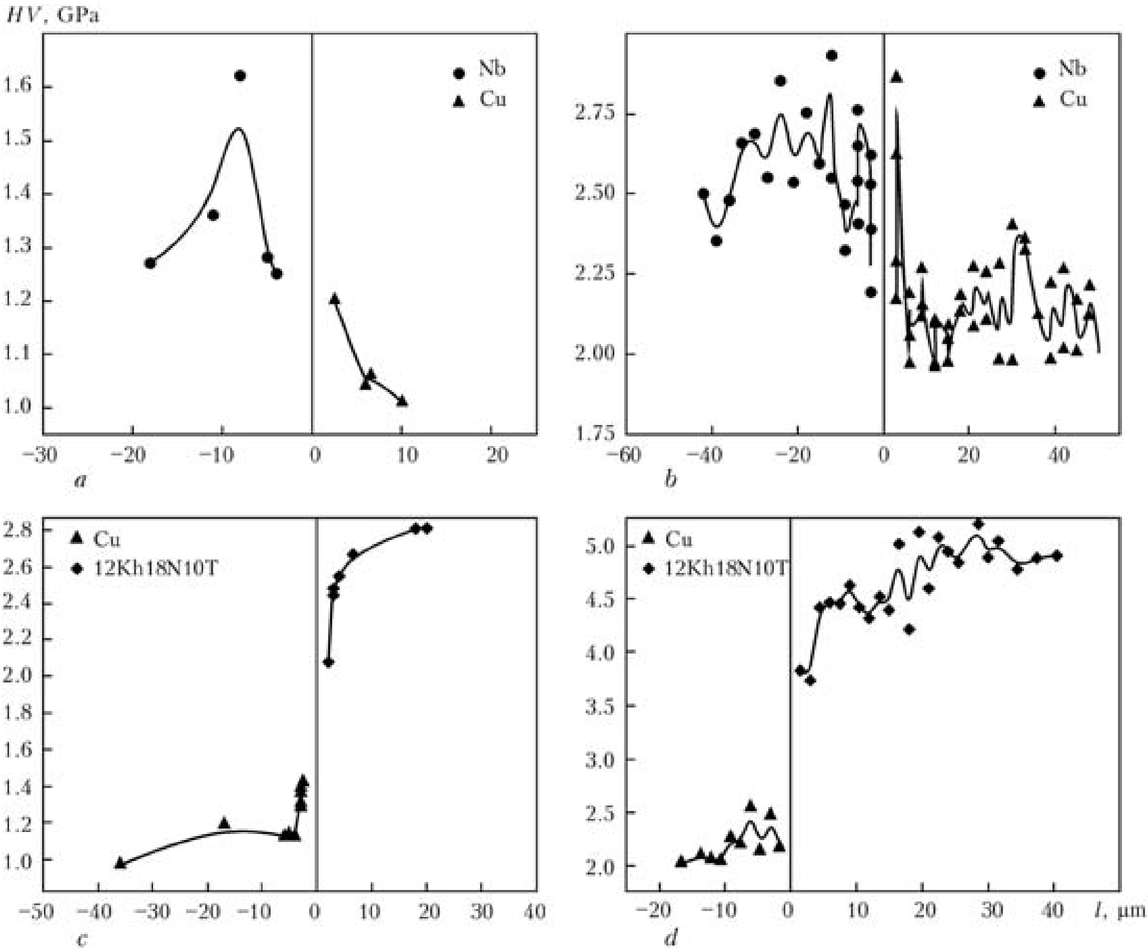

Figure 7. Change of micro- (*a*, *c*) and nanohardness (*b*, *d*) at maximum load on the boundary of Nb–Cu (*a*, *b*) and Cu–12Kh18N10T (*c*, *d*) joint

to determine the upper limit of this range $\sigma_t^{M_1+M_2}|_{M_2 \to M_1} = \sigma_t^{M_2}$.

Thus, the value of tensile strength on the boundary of solid-phase joint of two dissimilar metals should satisfy the following inequality:

$$\sigma_в^{M_1} \le \sigma_t^{M_1+M_2} \le \sigma_t^{M_2}. \qquad (2)$$

Let us evaluate the tensile strength on the boundary of the joint of two dissimilar metals from expression (1). For this purpose in (1) we will introduce the coefficient of widening of the ductility range $g = \sigma_{S0}^{M_2}/\sigma_{S0}^{M_1}$. It should be noted that $\sigma_{S0}^{M_1}$ and $\sigma_{S0}^{M_2}$ are determined by tensile strength of metals M_1 and M_2, respectively.

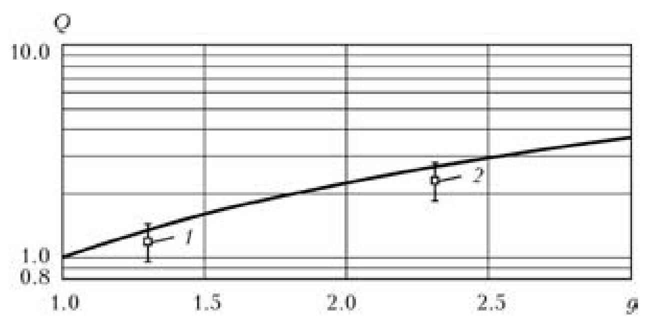

Figure 8. Dependence of relative tensile strength *Q* of metal joint on the coefficient of widening of ductility range *g*: *1*, *2* — experimental *Q* values for joint 12Kh18N10T–steel 20 and 12Kh18N10T–Cu

In Figure 8, which gives dependence of $Q = \ln \frac{\sigma_t^{M_1+M_2}}{\sigma_t^{M_1}}$ on parameter g, experimentally measured points *1* and *2* have coordinates $Q = 1.2 \pm 0.24$, $g_1 = 1.2$; $Q_2 = 2.738 \pm 0.55$, $g_2 = 2.311$, and are described well by the theoretical model given in [24]. Error of measurements of relative tensile strength $Q_{1,\,2}$ was determined by the error of measurement of hard alloy microhardness. It follows from this model that with increase of the coefficient of widening of the ductility range of two dissimilar metals joined in the solid phase, strength characteristics of the composite boundary are increased compared to tensile strength of the softer metal. Such an increase proceeds until the composite strength range is determined by the harder metal. In this case the relative tensile strength of the composite boundary is determined by the tensile strength of the harder metal.

In vacuum hot rolling surface activation occurs at the expense of shear plastic deformation [18], caused by dry sliding friction of the surfaces to be welded in the solid phase. This mechanism of surface cleaning the most effectively destroys the oxide films and ensures mixing of surface atoms at sliding of one material over the other (Figure 9).

It is experimentally established that dry sliding between ductile metals results in wear and intensive plastic deformation at rolling.

Shear plastic deformation of two dissimilar materials leads to rotation of the crystalline lattice [25] at simultaneous sliding of one material over another one. Juvenile surfaces of the materials being joined cleaned from oxides are thus produced. Mechanical mixing and mutual transfer of the atoms of the two metals occur at friction of one material over the other one that is clearly visible in Figure 5. Excitation centers form on the cleaned surfaces being welded, which are related to dislocation nucleation and transfer of atoms entrapped on the boundary of materials being joined into the metal bulk.

Figure 9 does not need any additional description, as all the acting forces and points of their application are shown in the drawing, and do not require any special explanation. Calculation of the forces shown in Figure 9, which act on the sample at rolling, is given in [18].

Considering the assumption made in [22] that dislocations initiate on the contact surface and propagate in-depth of the material, entraining the atoms of metals rubbing against each other, captured on the surface (this is a manifestation of deformation by dislocation sliding), it may be assumed that simultaneous plastic deformation of materials is required to achieve their solid-phase joining. Here, in addition to dislocation sliding, also accommodating rotations of the crystalline lattice are required that is achieved at hot rolling in vacuum, which combines both material deformation and shear displacement of material.

Each dislocation is an effective path, along which runs the flow of dissimilar material atoms directed away from the joint boundary. Mutual transport of atoms proceed along these channels. Here, the probability of simultaneous excitation of atoms of two opposing surfaces is quite high. Further deformation of material leads to movement towards each other of atoms of metals having a higher energy, promoting migration through the formed channels of the defective structure to a rather large distance. During experiments (see Figure 7) metal atoms were detected, which migrated into another material to the depth of up to 15–20 μm. Atoms of dissimilar materials approach each other to the distance of the action of interatomic forces that leads to energy release in the form of collective processes of electronic interaction. These phenomena are reduced to collectivization of valence electrons by positive ions, leading to formation of a strong metallic bond between the system of atoms forming the crystalline lattice, connected by electrons and ions of the two materials. This bond results in establishment of a redistributed composition of atoms of dissimilar materials being joined, in a narrow range (1–20 μm), ensuring solid-phase joining of dissimilar materials. Thus, the formed joint boundary of the two dissimilar metals becomes stronger during intensive plastic deformation with simultaneous sliding of the surfaces being welded through application of hot rolling in vacuum. During welding the joint boundary is formed from materials involved in the direct contact of materials being welded. Strength properties of the joint boundary proper are determined by the properties (strength and ductility) of materials welded in the solid phase. The intermediate layer is formed at the expense of many microstructural factors and deformation mechanisms, observed in the experiments (see Figures 4 and 5). Here a multitude of characteristic features are found, which include intensive plastic deformation, associated friction losses and adiabatic heating, mechanical mixing, nanocrystallization, transfer of the softer material towards the harder one, and vice versa. Plastic deformation is loosely related to interphase adhesion, namely «gripping» on the interface (as a starting factor) causes lattice deformation, that inevitably leads to plastic flow of the material. Adhesion forces are highly sensitive to the nature of the bonds between the parts and to interface crystallography. Thus, it is anticipated that plastic deformation values (and, therefore, friction) will also depend on these factors, and there is experimental proof of it (see Figures 7 and 8). Such a nature and deformations observed in the experiments

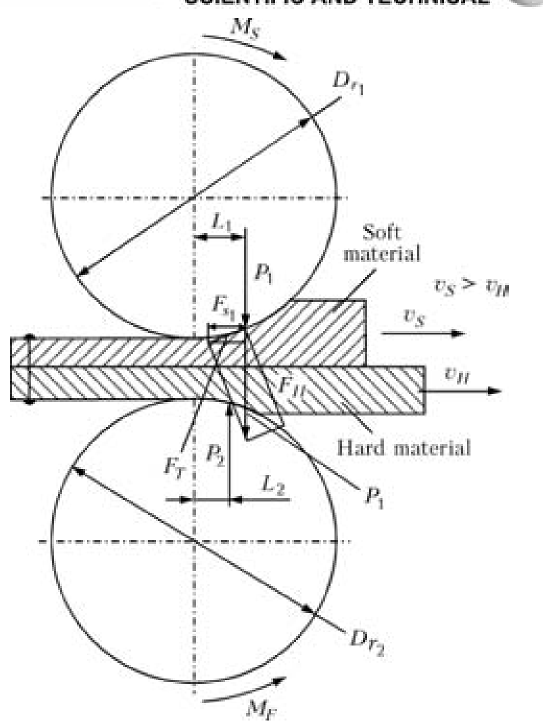

Figure 9. Schematic image of forces applied to material plates in the pack at rolling: F_{s_1} — acting on plates in the pack, depending on material strength properties; M_S, M_F — moments arising at deformation of the soft and hard materials in the pack in welding; v_S, v_H — relative speeds of material displacement; P_1, P_2 — acting in the point of application of forces at plate deformation; L_1, L_2 — arm of forces P_1, P_2; F_τ, F_{II} — tangential forces arising at rotation and deformation of plates by rolls; D_{r_1}, D_{r_2} — roll diameters

on solid-phase welding, are unique for this rolling system, providing sliding-friction between materials in their solid-phase joining. It turns out that the acting dynamic forces, caused by rolling of a multilayer pack, induce similar reactions in all the systems of friction surfaces to be welded, while the strength of boundaries in a multilayer joint depends on ductility of materials welded in the solid phase.

CONCLUSIONS

1. Solid-phase joint is produced due to intensive plastic deformation with materials sliding over each other with coming together of these materials up to lattice parameters, mechanical mixing of atomic layers of the material, participating in sliding-friction and excitation of atomic layers of opposing surfaces, having a higher energy and moving along the formed channels of the defective structure to a rather large distance.

2. Transfer of atoms of dissimilar metals from one plate into another during solid-phase welding by the method of hot rolling in vacuum was experimentally confirmed.

3. During welding the joint boundary forms from materials involved in the direct contact of materials being welded. Strength properties of the joint boundary are determined by the properties (strength and ductility) of metals welded in the solid phase.

4. Strength limit of dissimilar metal boundary is much higher than the tensile strength of the weaker metal.

5. Joint boundary of two dissimilar materials, produced in hot rolling in vacuum, is a new material, produced by intensive plastic deformation and mechanical mixing of metal atoms, involved in shear and mixing of the subsurface atomic layers of dissimilar materials being welded.

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