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STRUCTURAL CHANGES IN METAL OF WELDED JOINTS OF STEAM PIPELINES

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The structural changes in metal of welded joints of steam pipelines, operated for a long time under the creep conditions, predetermine the need in study of dislocation displacements, occurring in their structure. The paper deals with peculiarities of dislocation displacements, which cause the deformation of metal in regions of heat-affected zone of welded joints, and also with the dependence of deformational changes on the duration of their operating time. It was found that dislocation displacements and deformation of welded joints depend to a definite extent on their initial structure. 8 Ref., 8 Figures.

Keywords: *welded joints of steam pipelines, structural changes, dislocation, carbides, heat-affected zone, deformation, diffusion, polygonization*

During the long-time service of welded joints of steam pipelines under the creep conditions, the structural changes take place in their metal, the intensity of which is much higher as compared with similar changes in the base metal. The structural changes can be considered as an initial stage of metal degradation. These changes cause the decrease in adhesive forces between the atoms both in crystals of α-phase, and also at the interface of phases (to a greater extent). For example, they take place at the interface of grains of α-phase and coagulating carbides $M_{23}C_6$ [1], thus leading to initiation and further development of creep pores.

The aim of the work is the clarification of peculiar features of physical and chemical processes, occurring in metal of welded joints of steam pipelines, which operate for a long time under creep conditions, to decrease the rate of structural transformations. The revealing of these peculiarities gives opportunity to increase the reliability and life of welded joints by producing their preset initial structure.

The intensity of physical and chemical processes in metal of welded joints, which provide the appropriate structural changes, is higher than that in base metal of steam pipelines, which is predetermined by their higher initial structural heterogeneity. During the process of long-time service (more than 250 000 hours) the structural heterogeneity is noticeably increased, thus leading to deterioration of service characteristics of welded joints.

In the process of long-time service of steam pipelines of heat-resistant pearlitic steels (12Kh1MF and 15Kh1M1F) under creep conditions (temperature is 545–585 °C, pressure is 20–25 MPa) the polygonization effect is manifested in grains of α-phase. To reveal the polygonal structure, the sections were subjected to electrolytic polishing in 150 ml solution of perchloric acid, 600 ml of ethyl alcohol and 100 ml of glycerine, and then to twice etching: firstly in 2 % solution of nitric acid with a washing in alcohol, and then in 2 % solution of picric acid, using the improved procedure [2]. To study the dislocation structure the methods of electron microscopy of thin foils were used.

At the beginning stage of polygonization structure formation the sharp reduction of mechanical properties is not observed, which can be explained by the effect of decreasing the length of sliding lines by the boundaries of subgrains. The presence of diffusion transfer of chromium and molybdenum from the central zones of α-phase grains to their near-boundary zones contributes to the appearance of new vacancies and thresholds on dislocations, thus leading to increase in the polygonization intensity. The highest degree of polygonization in structure of welded joints is typical for the region of a partial recrystallization of the heat-affected zone (HAZ), Figure 1. It was as-

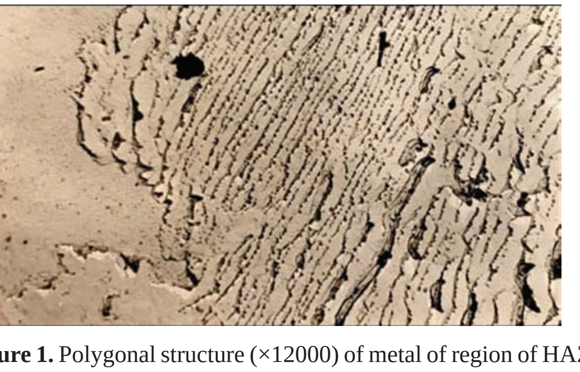

Figure 1. Polygonal structure (×12000) of metal of region of HAZ partial recrystallization. Welded joint of steel 12Kh1MF, ε = 8 %

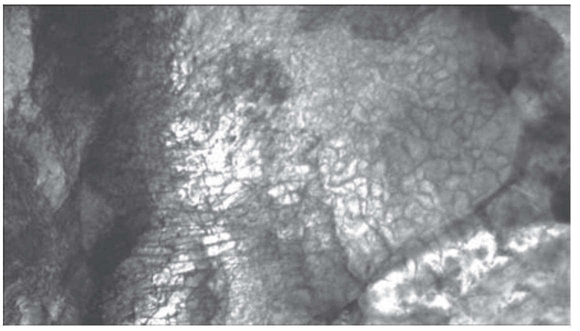

Figure 2. Substructure (×50000) of creep in region of a partial recrystallization of HAZ metal of welded joints of steel 15Kh1M1F, ε = 5 % (operating time is 280 000 hours)

Figure 4. Initial stage of primary recrystallization. Structure (×200) of weld metal of steel 10KhMF (operating time of welded joints is 276 000 hours)

sumed that the effect of formation of the polygonal structure, as a level of development of substructure of α-phase grains, is a function of stress and temperature. During operation of steam pipelines in the condition of starts-stops and overheating (emergency steam ejection), which is typical for creep conditions and fatigue, as a function constituent: the rate of deformation of their metal was taken into account.

At a long operating time the dislocations are originated and multiplied in steam pipeline metal, which is connected with their motion. The presence of defects, precipitations of other phases, as well as diffusion processes, represent the origination of dislocations as a heterogeneous process.

Under the action of stresses and temperature the displacement of dislocations in sliding plane, as well as ascending displacement of dislocations, have a discontinuous nature, which was caused by their certain braking. At the first stage of creep the dislocations are displaced at a low rate and the formation of subgrains is slightly noticeable. At the second stage of creep the rate of motion of dislocations is increased, the substructure with a well-developed network of dislocations is formed, that is noticeable at a high magnification (Figure 2). In deformed (ε = 2–3 %) polygonal grains of α-phase the boundaries of subgrains lead to decrease in length of the sliding lines (Figure 3).

The intensity of formation of polygonal structure at HAZ regions of welded joints is remarkably different. The intensity is the highest in the region of a partial recrystallization of HAZ, and it is the least in the base and weld metal. At operating time of welded joints above 270 000 hours the appearance of subgrains in the body of α-phase grains is observed, however, the grains themselves are not increased in sizes, and the new grains are not formed. Precisely, their increase is at the initial stage, which is confirmed by a local liquidation of the grain boundaries (Figure 4). Dislocations, which are located at the grain boundaries, are braked by precipitations of other phases, released from these precipitations, and then replaced by other dislocations, which are displaced similarly to the previous ones (Figure 5). The removal of grain boundaries from coagulating precipitations of other phases is observed, which was firstly noted by T.G. Berezina [3]. The initial process of recrystallization takes place in structure of welded joints at their operating time of more than 250 000 hours. Locally the regions of grain boundaries disappear in those places where the level of their free energy is increased, including the places of contact with coagulating precipitations $M_{23}C_6$ [4].

It was revealed, that the sizes of subgrains in the volume of grains are characteristic for each region of HAZ, and also for weld metal and base metal. Their sizes, in comparison with appropriate structures of regions, have remarkable differences. The largest size of subgrains is noted in the structure of region of a partial recrystallization and overheating. Number of subboundaries is increased to a greater extent at the first unsteady stage of creep and to a less extent at the steady

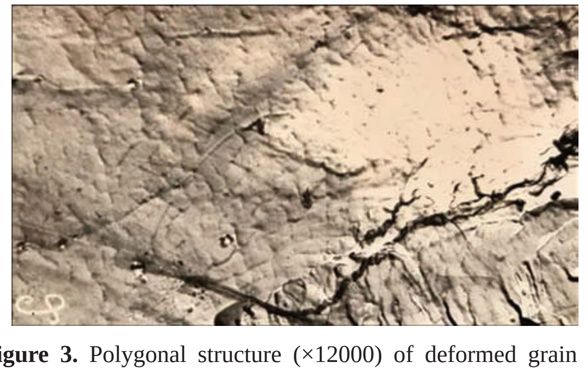

Figure 3. Polygonal structure (×12000) of deformed grain of α-phase. Overheating region of HAZ. Welded joint of steel 15Kh1M1F, ε = 3 %

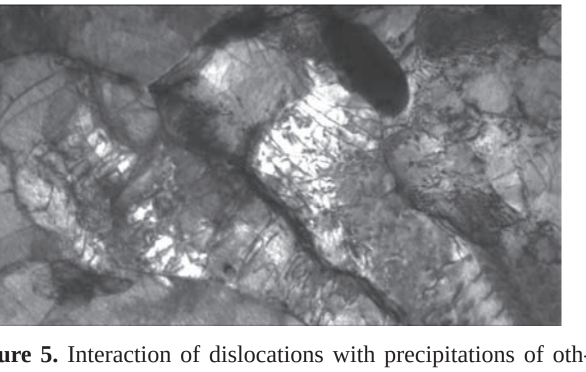

Figure 5. Interaction of dislocations with precipitations of other phases. Structure (×50000) in region of overheating of steel 15Kh1M1F, ε = 3 % (operating time is 280 000 hours)

one. However, the thickness of lines of subboundaries is increased at the steady stage of creep and to the least degree in the region of a partial recrystallization.

The maneuverable condition of service (starts-stops) promotes the appearance of fatigue features in metal of steam pipelines and their welded joints. Increase in number of vacancies also promotes the accelerated descending of dislocations and formation of a subgrained structure. Etching of grain boundaries (operating time of steam pipelines is more than 270 000 hours) becomes more clear, and direct etching of grains is decreased. The linear dislocations are lined up along the boundaries of blocks in the form of vertical walls with small angles of inclination (see Figure 1). A large part of dislocations is annihilated [5].

During long-time service of steam pipelines under the creep conditions (more than 270 000 hours) the total deformation of steam pipelines is approximately 0.5–0.7 %, and the deformation of HAZ regions is 0.7–8 % [1, 6]. It is rational to consider the mechanism of plastic deformation of welded joint metal by using the theory of dislocations [7, 8].

Dislocation in passing under the action of tangential stresses through a crystal of α-phase performs the work τ. Effective force, which provides the motion of dislocations, is $F = \tau\bar{b}$, where $\bar{b}$ is the Burgers vector. Applied stress σ, parallel to $\bar{b}$, under the action of force $F_{\text{cr.o}}$ causes the creep over of dislocations, $F_{\text{cr.o}} = \sigma\bar{b}$. The creep over of dislocations is occurred by separation or joining the half-plane of atoms of chromium and molybdenum, and also by formation of vacancies. Taking α-phases in crystal as a full-value, initial concentration of atoms of chromium and molybdenum C_0, similar to concentration of vacancies, and their real concentration C_1 (after definite operating time), we shall write the change in free energy $kT\ln(C_1/C_0)$, where k is the Boltzmann's constant, T is the absolute temperature. Creeping over of dislocations under the action of force $F_{\text{cr.o}}$ takes place at the presence of gradient of chromium and molybdenum concentration:

$$F_{\text{cr.o}} = \frac{kT}{b^2}\ln\frac{C_1}{C_0}.$$

It was found by using the surface microprobe analysis that after operating time of welded joints of more than 276 000 hours the chromium concentration (segregation) in near-boundary zones of α-phase grains can amount to 3.0–4.0 %, and in the central zones it can be 0.2–0.4 % [1]. It was revealed, that the segregation of molybdenum begins to increase remarkably after operating time of welded joints of more than 260 000 hours, which leads to increase in pore formation. It should be noted that the level of segregation is noticeably different in specimens, subjected to creep-rupture tests and cut from real steam pipelines, as to their similar operating time.

In crystals of α-phase the displacement of dislocations is realized by two combined mechanisms: creep over and sliding. During creep over of dislocations of joining and separation of atoms (mostly chromium and molybdenum) the displacement of vacancies takes place on steps of a half-plane. Simultaneously, the thresholds are formed on the half-plane, which are capable to displacement without change in their shape. Motion of dislocations, which cross the potential barriers, is controlled by Peierls forces. The set concentration of dislocations in welded joint metal was considered as a density of dislocations, i.e. as the total length of all the dislocations per a unit of volume. It was found that the density of dislocations in the HAZ regions, as well as in weld metal and base metal noticeably differ (see Figures 2, 3, 6). For example, the average density of dislocations in the region of a partial recrystallization of HAZ was approximately 10^9 cm^{-2}, and in the weld metal it is close to 10^8 cm^{-2}. In formation of density the important role is played by the rate of creep over of dislocations, which depends on volume diffusion (self-diffusion of chromium and molybdenum), as well as on annihilation of dislocations. Local removal of grain boundaries (see Figure 4) depends greatly on grain-boundary diffusion, the intensity of which is much higher under the creep conditions than that of volume one [1].

In study of plastic deformation of welded joints metal the following was taken into consideration: peculiarities of structural state of HAZ regions, weld metal and base metal; number of mobile dislocations in crystal of α-phase; average motion of dislocations; dependence of change in density of dislocations and rate of their motion on stress, time, temperature and diffusion displacement of alloying elements.

Level of plastic deformation (γ) in crystal of α-phase was considered as a shear deformation $\gamma = bN\bar{x}$, where b is the displacement caused by motion of dislocations over all the crystal volume, N is the density of dislocations which pass through single cross-section of crystal, $\bar{x}$ is the average displacement of dislocations.

Under the conditions of creep the rate of deformation of metal of HAZ regions, as well as weld metal

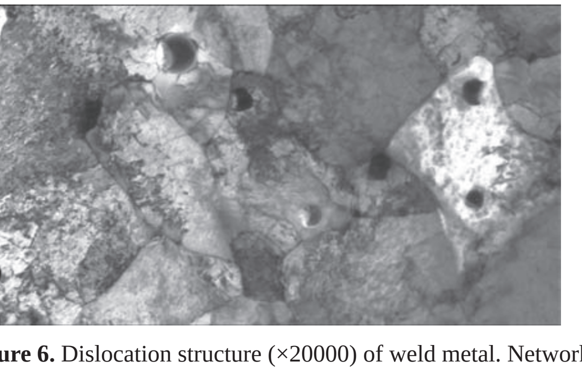

Figure 6. Dislocation structure (×20000) of weld metal. Network is seen on separate fragments of subgrains of α-phase (on steel 10KhMF), ε = 0.7 %

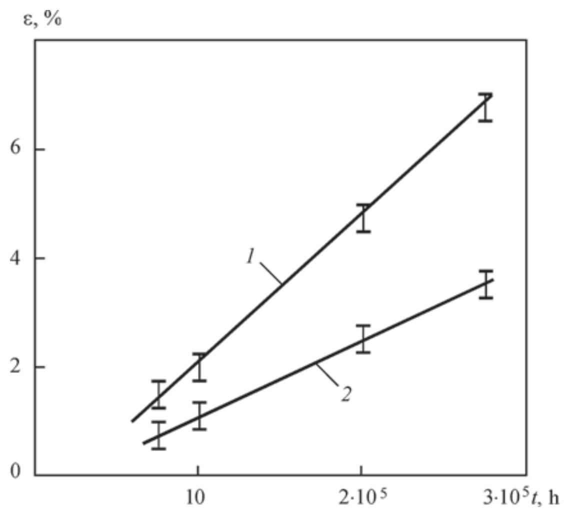

Figure 7. Dependence of deformation ε on service time of welded joints of steel 12Kh1MF: *1* — metal of region of a partial recrystallization of HAZ; *2* — region of overheating

and base metal, which depends on long-time service of welded joints, is greatly differ (Figure 7). The rate of deformation depends also on their structural state (Figure 8). Determination of deformation rate should be made for the development of methods of its decrease:

$$\frac{\partial\gamma}{\partial t} = bNV,$$

where V is the rate of deformation.

It is rational that the welding heating and subsequent tempering provided the formation of such a dislocation constitution that could guarantee higher physical and mechanical properties of welded joints. These properties can be obtained by formation of initial structure, the composition of which is as follows: 75–90 % of bainite, ferrite — the rest, at a uniform distribution of precipitation of other phases in body of grains of α-phase, and also along their boundaries. It is not admissible to have the locally grouped and enlarged ferrite grains in weld metal. At the fusion regions of HAZ the welding heating should provide a smooth transition between the structures of weld metal and base metal, as well as an absence of enlarged ferrite grains. At the overheating region the number of austenite grain should not be less than 5 (GOST 5639–82). At the region of a partial recrystallization the new products of austenite decay in the form of chains of globularized pearlite are not admitted. The mentioned constituents of initial structure promote the increase in intensity of physical and chemical processes and, respectively, the structure transformations and, therefore, they should be considered as rejected.

To define the residual life of welded joints more precisely, it is rational to study integrally the main regularities of effect of a dislocation structure on their service characteristics. It is rational to determine the effect of the following factors on dislocation constitution: hardening by α-phase alloying; dispersion hardening; elastic interaction of dislocation with spot

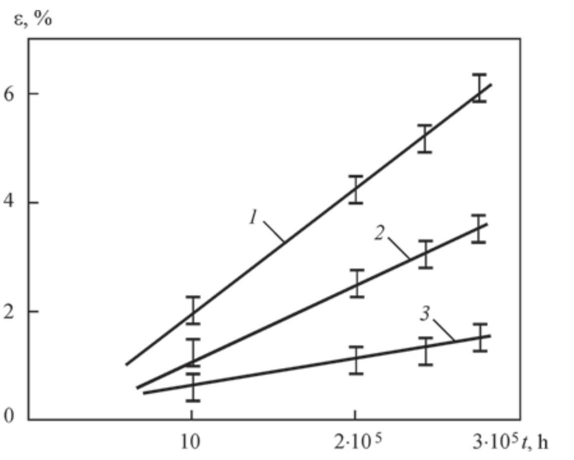

Figure 8. Dependence of deformation of metal of region of a HAZ partial recrystallization of welded joints of steel 15Kh1M1F on service time: *1* — globularized pearlite; *2* — sorbite; *3* — troostite

defects and Cottrell clouds; chemical interaction of dislocations with dissolved atoms and Suzuki clouds; hardening as a result of ordering of interstitial elements in the field of stresses.

Conclusions

1. It was found that increase in stability of structure of welded joints of steam pipelines, which are long-time operated under the creep conditions, can be provided by hardening effect of dislocations and precipitations of other phases.

2. It was established that the producing of initial structure of welded joints with improved quality characteristics provides the sufficient decrease in intensity of dislocation displacements in α-phase crystals.

3. It was established that the metal deformation at the region of a partial recrystallization of HAZ in structure of welded joints is the highest and depends on type of new products of austenite decay.

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