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PECULIARITIES OF WELDED JOINTS WEAKENING IN OPERATING STEAM PIPELINES

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The development of recovery in metal of welded joints of heat-resistant pearlitic steel steam pipelines, which are operating for a long time in the creep conditions, is characterized by certain structural changes. Such changes cause the weakening in metal of welded joints. The article considers the peculiar features of structural and deformational changes, as well as the development of diffusion which occur in the process of recovery and leads to weakening in metal of welded joints of steam pipelines at their service of over 270 thou h. 10 Ref., 7 Figures.

Keywords: *welded joints of steam pipelines, recovery, structural state, weakening, dislocations, diffusion, heat-affected zone*

The processes of weakening and damaging of metal of the TPP steam pipelines, which are operating for a long time under creep conditions, are of great practical importance. In the metal of steam pipelines (mostly in their welded joints), which are operating for a long time at the temperature of 545–585 °C and at a stress of 20–25 MPa, certain structural changes, deterioration of properties, damage and fracture take place.

The structural changes at the first and second stages of creep are caused by manifestations of recovery, polygonization and recrystallization processes. Each of the mentioned processes should be considered with account for peculiar features of the other process as that associated with the process being considered. Revealing the features of the recovery, polygonization and recrystallization processes is urgent for reducing the rate of their propagation, and, consequently, for decrease in the level of structure degradation and damage of metal.

The aim of the work is to study the peculiar features of the recovery process, which controls the structural state of the metal of the steam pipeline welded joints, operated for a long time in the creep conditions.

In the steam pipelines, both thermal and dispersion-strengthened steels (12Kh1MF, 15Kh1M1F) are applied. The stability of their structure under the operating conditions depends not only on the free energy of the metal, but also on the presence and distribution of defects in the crystalline lattice. In this regard, it is not possible to describe the kinetics of the process of weakening the welded joint metal using the known exponential law.

The metal of welded joints is characterized by the presence of third-kind stresses, formed in the α-phase crystals at a certain absence of coherence with the precipitation of the second phases (M_3C, M_7C_3, $M_{23}C_6$), to a lesser extent Mo_2C and VC. The absence of coherence is increased at the presence of coagulation of M_7C_3 and, especially, $M_{23}C_6$. Let us note that the feature of coagulation of carbides of the group I, located along the grain boundaries, should be specified, since the processes of their coalescence are essentially different (Figure 1) [1].

The difference between the recovery, which takes place in the metal of operating steam pipelines, from the recovery, which is the removal of cold-hardening in the deformed metal, consists in the fact that when the cold-hardening is removed, the evolution of the previously stored energy occurs, and the recovery in metal of the steam pipelines is realized at simultaneous input of energy (predominantly) and at its insignificant (5–7 %) release. The recovery in the considered structure is provided only by thermal activation and characterized by the absence of an incubation period. In the process of recovery in structure of steam pipelines metal (and their welded joints), the crystallographic orientation of the α-phase is not changed, but there are fine structural changes and some changes in the spot defects. The level of recovery depends on the initial structural state of the welded joints metal,

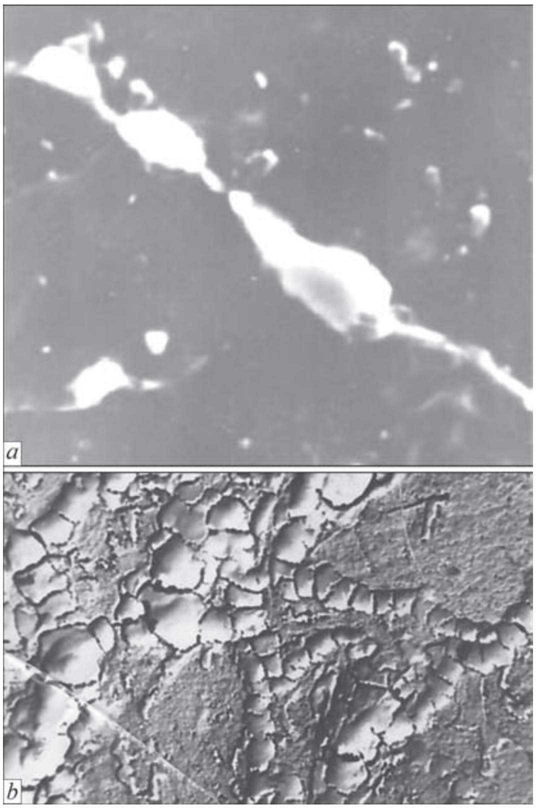

Figure 1. Coagulation of carbides by coalescence: *a* — carbides $M_{23}C_6$ (×7500); *b* — carbides M_7C_3 (×6000)

including that from the previous distribution of dislocations.

The phenomenon of recovery, in general, is peculiar to the metal of the considered welded joints as-applied to their time of service from about 250 thou h. In our opinion, it is very difficult to study the peculiarities of structural changes, caused by the recovery processes applying the known methods of measuring the electrical resistance in the areas of the heat-affected zone (HAZ) of welded joints. The recovery of welded joints metal is characterized by the presence of local weakening (Figure 2) and decrease in the yield strength by 15–20 %, which is associated with the structural heterogeneity of their HAZ. In the process of recovery the diffusion displacement of chromium, molybdenum, vanadium, silicon and manganese occurs in the welded joint metal from the central zones of α-phase grains to their near-boundary zones, which provides the formation of segregations [2, 3]. An increase in the diffusional mobility of chromium, molybdenum and vanadium leads to increase in the amount of Mo_2C and VC, as well as M_7C_3, $M_{23}C_6$. The amount of chromium, molybdenum and vanadium in carbides is increased at coresponding their decrease in the α-phase crystals.

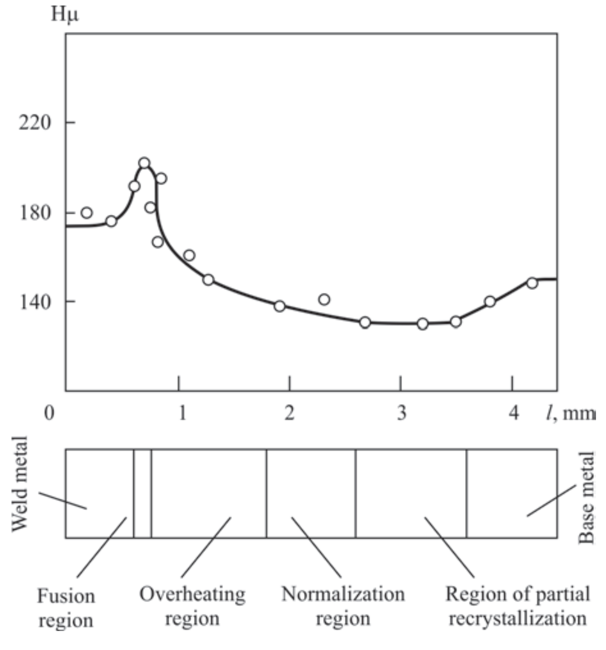

Figure 2. Microhardness of welded joints of steel 15Kh1M1F (life — 280 thou h)

It was established that in the metal of the HAZ regions, as well as in weld metal and in base metal, the processes of weakening occur at different intensity. Locally, at the HAZ regions, the metal can also harden, however, the predominant effect is the weakening (Figure 2). The greatest relative weakening is characteristic for the region of partial recrystallization of the HAZ metal.

Considering the recovery as a slow process of weakening with time, as-applied to the welded joint, let us write the specified dependence [4] in the following form:

$$X = 1 - \exp\left[-kmt\exp\left(-\frac{E}{RT}\right)\right],$$

where X is the fraction of weakened metal with time t; E is the activation energy; T is the temperature; R is the Boltzmann constant; k is the parameter, exponentially dependent on temperature; m is the parameter dependent on structural state of welded joint.

The components of the recovery mechanism are the formation, movement and annihilation of spot defects. In the conditions of operating temperatures and stresses the excessive vacancies are mobile. The vacancies move mainly to grain boundaries, to a lesser extent to the boundaries of subgrains and fragments, as well as to dislocations. It is rational to reveal the sink of vacancies to the grain boundaries, which will allow reducing their concentration.

In the process of recovery, the diffusion movement of chromium, molybdenum and vanadium has a directed nature and occurs according to the vacancy mechanism. The self-diffusion is provided by the gradient of chemical potential of the mentioned elements. The effect of self-diffusion of chromium is noticeably pronounced from 530 °C, and that of molybdenum — from 540 °C. Let us note that the coefficients of self-diffusion of chromium and molybdenum are variable and depend on their chemical properties, as well as on the creep conditions.

The jumps of chromium and molybdenum atoms in the vacancies (dumbbell mechanism of diffusion) occur at different intensity, which is connected with their self-diffusion coefficients D_{Cr} and D_{Mo}, which were determined by revealing the level of chromium and molybdenum in segregations [3]. The self-diffusion is represented as a totality of flows of atoms of chromium I_{Cr}, molybdenum I_{Mo}, and also vanadium I_{v}.

In the metal of the considered welded joints as-applied to their time of service over 270 thou h, the plastic deformation exceeds 0.3 %, which is characteristic for logarithmic creep. The peculiarity of the transition of welded joints metal from the second to the third stage of creep requires study. Following Andrade [4], describing the deformation with time t according to the parabolic law, let us write the expression for determining the deformation ε of metal of the welded joints after their time of service over 270 thou h.

$$\varepsilon = \varepsilon_0 \left(1 + \beta t^{1/3}\right) \exp(k' t),$$

where the factor exp($k't$) reflects the contribution of the established creep, caused by plastic deformation. The value β depends on the stress and temperature, accounts for their excess and change (emergency steam dumping, starts-stops). ε_0 is the deformation of welded joints metal up to 270 thou h of their time of service, which is, for example, 0.5 % for the weld metal.

It was assumed that the level of deformation in the subgrain can depend on the density of dislocations which are adjacent to the subgrain. It was established that decrease in the dislocation density leads to decrease in the stress level in the subgrain. Relatively, as the density of dislocations increases, the stress level $\sqrt{n\sigma_1}$ increases. At the second stage of the creep, at the presence of self-diffusion of chromium and molybdenum, the displacement of dislocations will occur from the central zones of the α-phase grains to their near-boundary regions in an accelerated manner, at the constant working parameters, stress and temperature.

The weakening of metal of HAZ regions of welded joints of steam pipelines during their operation in the creep conditions for 280–290 thou h is about 5–8 % [1–8]. Accordingly, the weakening of HAZ partial recrystallization region is about 10–15 % (Figure 2). Let us note that weakening during operation of welded joints over 280 thou h occurs with some acceleration. The nature of the metal deformation of the HAZ regions after operation of 270 thou h, can be linear [5, 6] or differ from the linear one (Figure 3), which depends on their structural state and requires clarification.

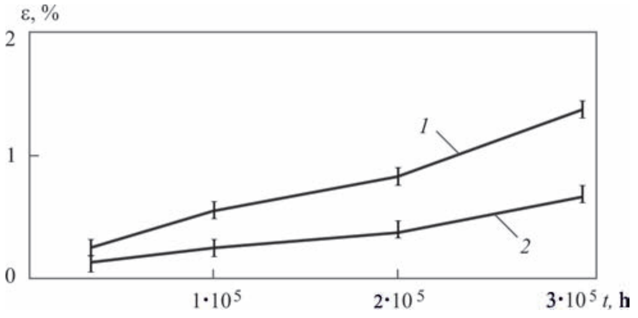

Figure 3. Dependence of deformation ε on duration of service life of welded joints of steel 15Kh1M1F: *1* — metal of overheating region; *2* — base metal (initial structure — bainite 75 %, the rest — ferrite)

In the α-phase crystals (structure of the steam pipeline) the dislocation displacement in the process of recovery occurs according to the directions of the diagonals <III>, mainly along the totality of dodecahedral planes {110}. However (to a less extent), the slipping occurs also on the totality of planes {II2}, as well as {123}. It is necessary to reveal the main combinations of displacement of dislocations in the α-phase crystals from 48 possible slipping systems to reduce their velocity. It was established that a characteristic feature of dislocation formation in crystals is short and medium dislocations with the presence of steps. The dislocations of one system, interacting with dislocations of other systems, form loops (Figure 4). The totality of loops is represented as a network of dislocations (Figure 5). The distribution of dislocations in the α-phase crystal, at a metal deformation of 0.5–8.0 %, is not uniform. In the process of creep, the dislocations moving along the directions <III> and planes {II2} are associated, which leads to the formation of cells corresponding in size (Figure 6). The considered structure is characterized by the presence of «walls» separating the regions with a high dislocation density of 10^6 cm^{-2} with the regions where the dislocation density is relatively low and amounts to 10^5 cm^{-2}. The structural state depends on the normalized energy of packing defects and the deformation level [9, 10]. With increase in time of service of welded joints, the normalized energy of the packing defects increases, and the number of inner dislocations

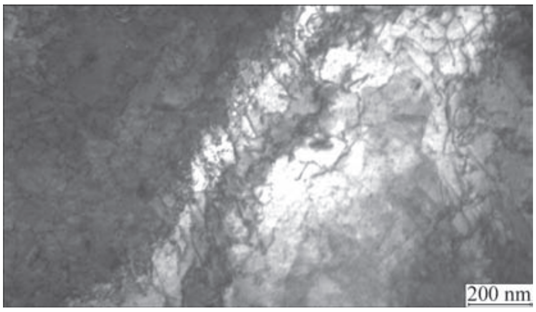

Figure 4. Microstrucutre of overheating region of welded joint HAZ of steel 12Kh1M1F (service life — 276 thou h, ε = 3 %)

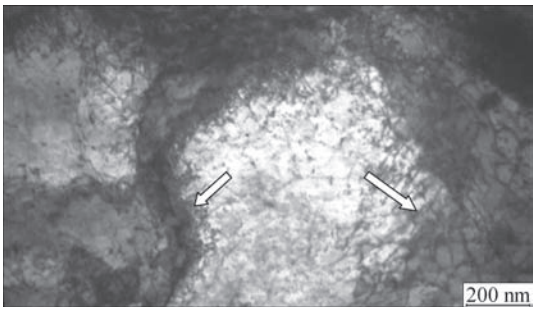

Figure 5. Dislocation structure of weld metal (alloy 10KhMF). Network of dislocations on separate fragments of subgrains of α-phase (shown by arrows), $\varepsilon = 3$ %

in the α-phase crystal decreases. With increase in the degree of deformation, the average sizes of cells are decreased and the difference in the orientation between neighboring cells is increased.

During operation of welded joints of T-pieces of steam pipelines over 270 thou h in the creep conditions, the structures, close to globular ones can be formed in the region of HAZ partial recrystallization (Figure 6). Such structures represent regions of bends on the dislocations and are characterized by the presence of deformation heterogeneity, and also contain cells with a different orientation. The dislocation displacement along one of the possible slipping planes is hindered by the newly formed dislocations moving in another system that crosses it, which leads to their common deceleration of displacement. The presence of the second phases also substantially inhibits the displacement of dislocations moving along the possible systems, which depends greatly on their shape and uniform distribution. The velocity of displacement of dislocations in the structure of welded joints is variable and depends on the peculiarities of diffusion movement of chromium and molybdenum, which is rational to study taking into account the formation of their segregations; coming from chromium and molybdenum transition from the α-phase grains to carbides. In this case, the nature of deformation of base metal and weld metal is close to linear [5].

It was assumed that a change in the number of dislocations in the α-phase crystal leads to the corresponding change in the stress $\sqrt{n\sigma_1}$ in it. To activate the sources of dislocations, both existing as well as new ones, the increment of the outer additional stress is not required under the steady creep conditions. There is a decrease in the level of inhibition of dislocations. The structure overheats (emergency steam dumping) were not taken into account. The change in the stress, at which the sources of new dislocations are activated, is $\Delta\sigma = \sqrt{\sigma}$, where n is the number of dislocations in the crystal. A decrease in the density of dislocations in the central region of the α-phase crystal, for example, up to 10^4 cm^{-2} promotes the reduction in the stress level σ_1 in it. An increase in the strain hardening of the welded joints metal is not occurred.

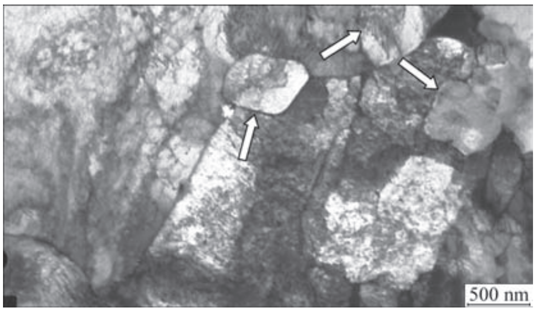

Figure 6. Structure of α-phase crystal of overheating region of HAZ of welded joint of steel 12Kh1M1F. The cells different in size are revealed (arrows) (service life — 276 thou h, $\varepsilon = 7$ %)

The linear nature of the deformation, corresponding to the time of service of welded joints to about 270 thou h, confirms that dislocations are displaced by creeping over and slipping at a velocity, close to linear.

Taking the frequency of action of the dislocation sources as v/n, let us write the expression for determining the deformation rate of the metal of welded joints [4]:

$$\dot{\varepsilon}A\frac{v}{n} = Av\left(\frac{\sigma_1}{X\varepsilon}\right)^2,$$

where A is the coefficient, which depends on the structural state; X is the weakening coefficient; n is the number of dislocation displacements.

Taking into account the number of dislocation sources in the crystal, which vary with time, let us introduce the corresponding clarification to the Mott expression. Let us present:

$$A = (N_1 + N_2)K^2b^2v,$$

where N_1 are the existing sources of dislocations; N_2 are the new sources of dislocations; L is the path of dislocations displacement; b is the Burgers vector.

It can be shown that in welded joints of the considered steels, the unsteady stage of creeping corresponds to approximately 50 thou h of their time of service.

As-applied to the considered welded joints, let us write the specified Dorn expression [9], which provided the plotting of the creep curve (Figure 7):

$$\varepsilon = \varepsilon_{st} - \varepsilon_0 = f(\dot{\varepsilon}_{st}t) = f\left[\left(\frac{\sigma}{G}\right)^n \frac{D_m Gb}{RT} t\right],$$

where $D_m(m_1m_2)$ is, respectively, the diffusion coefficient of chromium and molybdenum; n is the value of sensitivity of the steady creep-to-stress rate; G is the displacement modulus; ε_0 is the deformation at the nonsteady stage of creep; ε_{st} is the deformation at the steady stage of creep.

Let us note that the creep curves for the regions of HAZ , as well as of weld metal and base metal, should be plotted separately.

For metal of the steam pipelines of steels 15Kh1M1F and 12Kh1MF the creep limit is equal to 1 % [7]. The metal of HAZ regions during the time of service of welded joints of 250–270 thou h is deformed approximately from 0.7 to 7 % [5, 7]. It was established that the deformation of the welded joints metal accumulates predominantly at the second stage of creeping (Figure 7) [7].

At the presence of a level of operating stresses and temperatures (T_e = 545–585 °C, P_e = 25 MPa), the creep deformation is caused by creeping over of the dislocations. Wirthman's assumption is confirmed that creep is controlled by the ability of edge dislocations to bypass the obstacles by creeping over. At the established value of A and $n \approx 5$, the dislocation creep model, which envisages the creeping over the edge dislocations, can be described by the more specified Wirthman's equation [10]: $\varepsilon_{st} = (AD_m Gb/RT(\sigma/G)^5$.

It was established that the mechanism of deformation of welded joints metal in the steam pipelines depends on the thermally activated process of dislocation creeping over. An increase in the resistance to creep in the process of recovery is possible by simultaneous realization of the considered mechanisms of inhibition of dislocations displacement. The study of the recovery features will serve as a basis for studying the kinetics of recrystallization, which takes place during the time of service of steam pipelines over 290–300 thou h.

Conclusions

1. It was established that the deformation and diffusion processes as the constituents of the mechanism of recovery cause the weakening of welded joints metal of steam pipelines operating for a long time under the creep conditions.

2. It was revealed that weakening of the regions of HAZ metal , as well as weld metal and base metal of welded joints of steam pipelines, at their time of service over 270 thou h amounts to 5–8 %, which depends on their structural state, as well as on the deformation and diffusion processes.

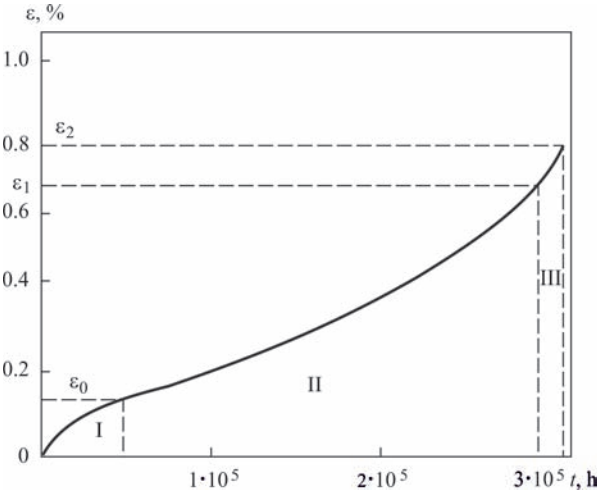

Figure 7. Curve of creep of weld metal (alloy 10KhMF): ε_0 — deformation corresponding to the service life of welded joint — 50 thou h; I–III — regions corresponding to the stages of creeping

1. Dmitrik, V.V., Sobol, O.V., Pogrebnoj, M.A. et al. (2015) Peculiarities of degradation of metal in welded joints of steam pipelines. *The Paton Welding J*., **7**, 10–15.
2. Dmitrik, V.V. (2000) Structure of welded joints from low-alloyed heat-resistant Cr–Mo–V pearlitic steels. *Ibid*., **4**, 26–29.
3. Dmitrik, V.V., Syrenko, T.A. (2012) To the mechanism of diffusion of chromium and molybdenum in the metal of welded joints of steam pipelines. *Ibid*., **10**, 20–24.
4. Rozenberg, V.M. (1973) *Principles of high-temperature strength*. Moscow, Metallurgiya [in Russian].
5. Dmitrik, V.V., Glushko, A.V., Syrenko, T.A. (2017) Structural changes in metal of welded joints after long-term service. *The Paton Welding J*., **7**, 15–18.
6. Dmitrik, V.V., Glushko, A.V., Grigorenko, S.G. (2016) Features of pore formation in welded joints of steam lines in long-term operation. *Ibid*., **9**, 51–54.
7. Khromchenko, F.A. (2003) *Service life of welded joints of steam pipelines*. Moscow, Mashinostroenie [in Russian].
8. Glushko, A. (2016) Research into defectiveness of welded joints of steam pipes operated over a long time. Eastern-Europ. *J. of Enterprise Technologies*, 6, **1**(84), 14–20.
9. Gottstein, G., Shvindlerman, L.S. (1999) *Grain boundary migration in metals: Thermodynamics, kinetics, applications*. New York, CRC Press.
10. Humphreys, F.J., Hatherly, M. (1995) *Recrystallization and related annealing phenomena*. Oxford, Pergamon Press.

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