https://doi.org/10.37434/tpwj2020.02.04

STRUCTURAL CHANGES IN THE METAL OF WELDED JOINTS OF LONG-TERM OPERATING STEAM PIPELINES

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Increasing the service life of steam pipelines is a very urgent task for heat power engineering. The investigation of peculiarities of changing the metal structure in the areas of heat-affected-zone of welded joints of steam pipelines, which are operated for a long time in the conditions of creep, makes it possible to reduce the level of their damage and, consequently, increase the operating time. In the work the features of dislocations movement, dependence of creep rate on the structural state of welded joints are considered, and features of forming vacancies and creep pores are given. It was established that the formation of nuclei pore in the conditions of creep depends on the degree of deformation of metal in welded joints, as well as on its structural state. 10 Ref., 7 Figures.

Keywords: *structural changes, welded joints, operation, steam pipelines, dislocation, pores, damage, operating time*

In the process of long-term operation of steam pipelines made of chromomolybdenum vanadium heat-resistant pearlite steels, at the service parameters T_e = = 545–585 °C and P_e = 25 MPa, their metal is deformed, i.e. a manifestation of creep occurs [1, 2].

The yield strength of welded joints of steels 12Kh1MF and 15Kh1M1F is 320–370 MPa, which is much higher than the value of a mentioned operating stress. When the service period of steam pipelines is increased to more than 270,000 h, the deformation of their metal, corresponding to the second stage of creep, grows with a certain acceleration [3]. The deformation of the steam pipeline metal in accordance with the requirements of the standard documentation [1, 2], should not exceed 1 %. However, the metal of the heat-affected-zone (HAZ) areas of welded joints is deformed to a greater extent [3, 4]. For example, the deformation of the area of partial recrystallization amounts to 3–7 % and that of the overheating area is 2–3 %. The deformation of welded joint metal during their long-term service period is associated with degradation of their structure, which contributes to the formation of creep pores and cracks and leads to decrease in the service characteristics of welded joints (Figure 1) [3–5].

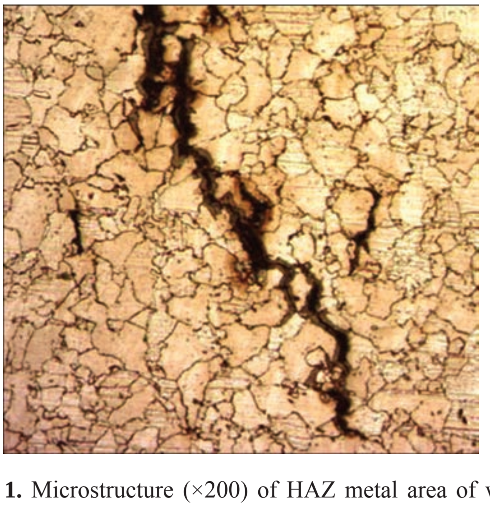

Figure 1. Microstructure (×200) of HAZ metal area of welded joint of steel 12Kh1MF (280,000 h)

The aim of the work is to study the peculiarities of structural changes in the metal of welded joints of steam pipelines, which have been long time operated under the conditions of creep. The study of structural changes will allow specifying the mechanism of damage of the metal of welded joints by pores and cracks of creep.

The metal of the areas of partial recrystallization and overheating of the HAZ at a long-term service under creep conditions (more than 270,000 h) deforms with a certain acceleration, depending on the structural state [3]. The deformation of the areas under consideration corresponds to the second stage of a stable creep. It is advisable to reveal the features of the structural state and the damage during the transition from the second to the third stage of creep, which is important in order to specify the mechanism of formation of pores and cracks, which develop mainly according to a brittle mechanism.

Creep is facilitated by the movement of dislocations, which is associated with the physicochemical processes taking place in the metal of welded joints during their long-term service [3, 5–8]. The main factors that provide the running of diffusion and dislocation processes are thermal activation and stress. It is important to establish both the features of the running of such processes as well as their relationship, which will reduce the level of their occurrence. Reducing the level of occurrence physicochemical occurrence is possible by increasing the stability of the structure of welded joints.

At a long-term service of welded joints, the creep of their metal in the process of returning is negligible

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and noticeable at the initial stage of the recrystallization process. We should note that their mechanisms are different from the mechanisms of returning and recrystallization occurring at annealing the cold-deformed metal. The level of deformation ε is represented as a static dependence of creep rate on time *t* (Figure 2), in which the value of the degree m depends on the structural state of the metal of welded joints. It was found that the dependence of creep on time at the presence of increase in the structural heterogeneity of the HAZ areas will accordingly accelerate. For example, for the partial recrystallization area, the acceleration will be higher than for the normalization area, as well as for the weld metal and the base metal. Let us write:

$$E = kt^m,$$

where *k* is the coefficient of proportionality, which is a function of both temperature and stress, corresponding to the conditions of creep.

It is important to establish the relationship between the deformation of the metal of welded joints, their softening and damage, which is provided by the conditions of the return process at a stable stage of creep. The strength of metal of welded joints at a service period of more than 270,000 h is decreased by about 15−20 % [1−4]. It was found that when establishing the dependence, the movement of dislocations through the barriers (precipitation of carbides of the 1st group) should be considered. It is partially confirmed by the assumption of Wirtman that in the conditions of creep, the main process is climb of dislocations initiated by thermal activation and stress [6, 7]. However, in his theory it was not considered what barriers overcome dislocations when moving under creep conditions. It was taken into account that in the metal of welded joints of steam pipelines a movement of dislocations occurs simultaneously according to two mechanisms: gliding and climb. It is advisable to study the peculiarities of revealing the abovementioned mechanisms, which will allow slowing down their proceeding.

The hindering of dislocations moving under the conditions of creep according to the gliding mechanism contributes to the stability of their structure. It was found that the hindering of dislocations is accordingly provided by the following main factors: Peierls−Nabarro forces (8−11 %); availability of dislocation clusters (9−10 %); atmospheres of impurity atoms (3−5 %); dispersed precipitations of the other phases (74−80 %). We should note that the effect of hindering dislocations can vary qualitatively, which depends on the self-diffusion of chromium, molybdenum, vanadium, and to a lesser extent on silicon, as well as the formation of segregations and new carbides of VC, Mo_2C, $M_{23}C_6$ and M_7C_3.

It was found that the stability of the structural state of the metal of welded joints depends significantly on

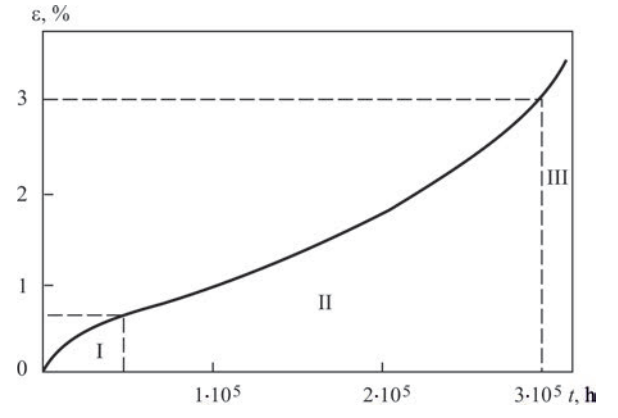

Figure 2. Curve of creep of HAZ metal overheating area of welded joint of steel 15Kh1M1F (I−II are the areas corresponding to the creep stages)

the shape, sizes and distribution density and peculiarities of the other phase precipitations [7]. Such precipitations that intersect the planes of gliding dislocations hinder their movement. Dislocations, when overcoming obstacles, which are the precipitations of especially fine-dispersed carbides of VC and Mo_2C, pass them over. When overcoming obstacles, the dislocations in a form of elongated carbides $M_{23}C_6$ and M_7C_3, located along the grain boundaries, which are perpendicular to the operating stress, can destroy carbides, which requires specification (Figure 3). It was found that the greatest contribution to the system of hindering dislocations (about 80 %) is made by the carbides of VC and Mo_2C, which are not prone to coagulation. In the conditions of creep it is advisable to reduce the rate of coagulation of carbides $M_{23}C_6$ and M_7C_3 (when creating new steels), or replace them with more stable carbides.

It was found that according to the considerations of R. Honeycomb [9], the activation energy of dislocations climb in the metal of welded joints does not fully correspond to the energy of self-diffusion of chromium and molybdenum. It was assumed that the activation energy provides climbing and gliding of dislocations as well as overcoming obstacles during their movement. It was accepted that the crystals of α-phase are characterized by a high energy of packing defects, as well as by the presence of a large number of equilibrium dislocation steps, which contribute to the formation of point defects (vacancies). When the service of welded joints is more than 270,000 h, the diffusive displacement of chromium decreases and that of molybdenum increases [8]. Accordingly, the ability of transformation of the initial structure (recommended by the standard documentation [1, 2]) into a ferrite-carbide mixture changes. Let us complete the expression of Wirtman [9], which

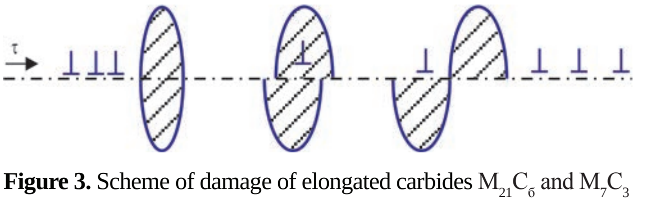

Figure 3. Scheme of damage of elongated carbides $M_{21}C_6$ and M_7C_3

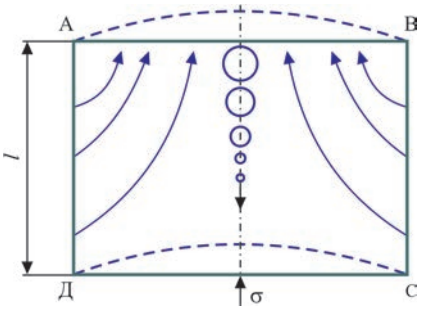

Figure 4. Scheme of vacancy creep (ABCD is the contour of a deformed fragment of the HAZ metal area: O are the pores; --- is the change of contour shape on stress σ

determines the dependence of creep rate on stress and temperature and by the dependence on the structural state. The account of the mentioned dependence allows specifying the level of deformation of metal of welded joints at the presence of changes of external stress (starts-stops of power units). Let us write:

$$\varepsilon = \text{const}\,\frac{\sigma^P}{kT}\exp\left(-\frac{U_S{}^n}{kT}\right),$$

where σ is the working stress; k is the Boltzmann constant; P is the exponent of power that characterizes the change in stress and temperature; n is the exponent of power depending on the structural state; U_S is the activation energy; T is the temperature.

It was found that at the end of the second stage of creep (see Figure 2), the strain rate begins to increase with the approach to the exponent. In the process of long-term service, the structure of welded joints (ferrite-bainite, ferrite-sorbite or ferrite-troostite) is transformed into a mechanical mixture (ferrite + carbides) at a different rate. At the same time, in the near-boundary zones of α-phase crystals segregations, new carbides of VC and Mo_2C are formed and also $M_{23}C_6$ and M_7C_3 coagulate, the creation and coalescence of vacancies occurs. In the metal of the areas of overheating and partial recrystallization of the HAZ of welded joints when their service life is more than 270,000 h, an increasing gliding along grain boundaries (up to 3−7 %) over time is observed. Let us introduce a specification into the mechanism of the viscous Nabarro−Herring flow [6], which allows using it for the metal of welded joints, deformed in a different extent. It was found that directional diffusion of point defects facilitates displacement of dislocations during creep. The pores are formed in the most deformed fragments of the area and then move in the direction where the deformation is smaller (Figure 4). Accordingly, the diffusive displacement of atoms proceeds in the opposite direction. It was assumed that the origin of vacancies occurs along the grain boundaries, and the rate of creep is provided by their diffusion movement.

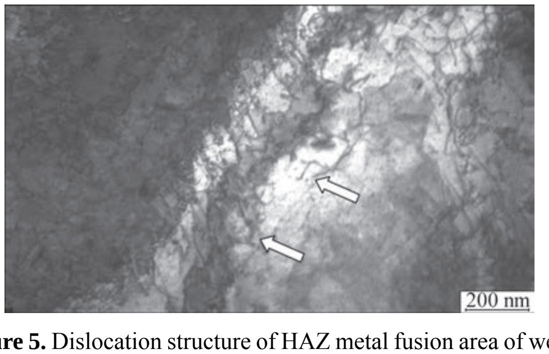

Figure 5. Dislocation structure of HAZ metal fusion area of welded joint of steel 12Kh1MF. Service period is 280,000 h (examples of steps on dislocations are indicated by arrows)

In the centre of the AB boundary (see Figure 4), the concentration of vacancies is the highest. Following [9] let us write:

$$C - C_0 = C_0\frac{\sigma b^3}{kT},$$

where C is the formed concentration of vacancies; C_0 is the equilibrium concentration; b^3 is the volume of vacancy.

The number of vacancies along the boundary between the AD and BC will be the lowest. Then the diffusion rate of displacement of chromium and molybdenum will be:

$$\frac{dV}{dt} = \frac{U_s b^3 l Д_n}{kT},$$

where U_S is the activation energy; l is average grain size; D_n is the coefficients of self-diffusion of chromium and molybdenum.

In determining the creep rate of the HAZ metal, the activation energy and diffusion coefficients of chromium and molybdenum were taken into account [10]. Let us write:

$$\varepsilon = \frac{1}{l^3}\frac{dV}{dt} = \frac{2U_s b^3 Д_n}{l^3 kT}.$$

The creep rate is in the linear dependence on the activation energy and on the diffusion coefficients of chromium and molybdenum, it depends on the level of vacancies nucleation intensity, their displacement and coalescence and the subsequent transformation of vacancies into pores. On the dislocation lines (areas of fusion and HAZ overheating), the steps are formed (Figure 5), which occurs at the mutual intersection of moving dislocations with «sedentary» dislocations as well as during passing of dislocations through the clusters of dislocations. The shape of the steps depends on the angle of intersection of dislocations. The intersection of dislocations leads to vacancies formation. Therefore, the creep occurs at a simultaneous formation of vacancies and the activation energy of creep is in compliance with the activation energy of self-diffusion.

In the conditions of creep, the steps on dislocations are climbing, which is facilitated by the moving (along the line of dislocations) vacancies that feed the steps. A number of steps on the lines of dislocations,

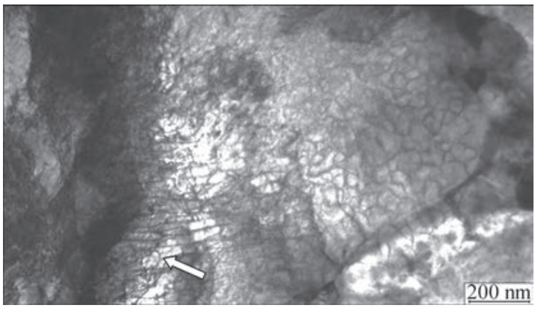

Figure 6. Dislocation structure of area of partial recrystallization of HAZ metal of welded joint of steel 12Kh1MF. Service period is 280,000 h (examples of steps on dislocations are indicated by arrows)

which depends on the number of intersections of moving dislocations with «sedentary» dislocations, is controlled by the level of the metal deformation. For example, a number of steps on the dislocations at the area of partial recrystallization will be higher than at other areas of HAZ metal (Figure 6).

The permissible overheating in the temperature range T_0 = 630–650 °C (emergency steam discharge) contributes to the formation and development of creep pores, which are mostly formed along the grain boundaries, where coagulating carbides of the first group are located [5]. A number of nuclei pores n (size of 0.1–0.3 μm) is increased in a linear dependence on the overheating temperature and also its duration. Let us write:

$$n = \alpha(T)t + n_0,$$

where $\frac{dn}{dt} = \alpha(T)$ is the rate of nuclei pores formation; n_0 is the initial number of pores.

The formation of pores in the metal of welded joints is noticeably influenced by the increase in the number of starts-stops of power units, which is characterized by the presence of variable stresses and requires a further study.

It was found that the creep pores are mainly formed at grain boundaries, located at the angles of 70–90° to the tension axis. However, at the presence of coagulating carbides at their boundaries, the pores are formed also at the angles of 20–60° which should be studied further. It was found that the formation of pore nuclei in the conditions of creep depends on the degree of deformation of the welded joints metal, as well as on its structural state (Figure 7). The assumption of R. Honicomb finds confirmation of the fact that the pores arise as a result of simultaneous manifestation of such processes as coalescence and gliding of vacancies along the grain boundaries, which also requires further specification in the metal of welded joints with respect to their service period of more than 270,000 h.

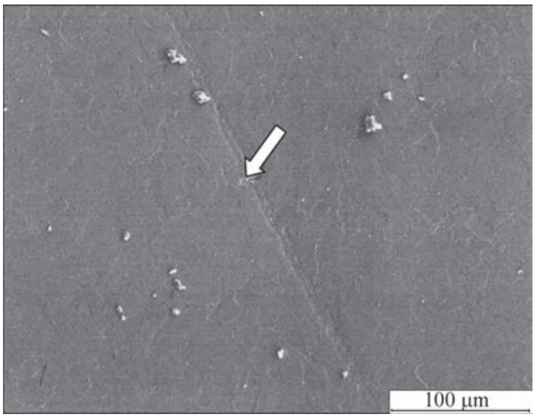

Figure 7. Formation of creep nuclei pores (arrow) during overheating of HAZ metal of welded joint of steel 12Kh1MF (280,000 h)

Conclusions

1. It was grounded that structural changes in the metal of welded joints, which have been long-time operated under creep conditions, facilitate increasing its deformation capacity and the formation of creep pores.

2. It was found that structural changes in the metal of welded joints of steam pipelines are interconnected with the processes of creep and diffusion of alloying elements of chromium and molybdenum.

3. The peculiarities of vacancies formation in the structure of welded joints were revealed, which is provided by the conditions of creep and depend on the structural state of welded joints.

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Received 06.05.2019