https://doi.org/10.37434/tpwj2020.06.03

STRUCTURAL CONDITION AND FATIGUE DAMAGEABILITY OF WELDED JOINTS OF STEAM PIPELINES

V.V. Dmytryk, A.K. Tsariuk, O.S. Garashchenko and **T.O. Syrenko**
National Technical University «Kharkiv Polytechnic Institute»
2 Kirpichova Str., 61002, Kharkiv, Ukraine E-mail: garashchenko.helena@gmail.com

At present time, a number of TPP power units having operated about 250000 h. in a relatively stationary operating condition, changed to a maneuver mode. This transition caused a need in studying damageability of their equipment according to the mechanism of fatigue and, in the first turn, welded joints of steam pipelines made of heat-resistant steels, operating under the conditions of creep. A further increase in fatigue damageability causes an improvement in the requirements to the initial structure of both the welded joints being produced as well as the parts to be repaired using welding. 14 Ref., 12 Figures.

Keywords: metal damageability; welded joints; fatigue cracks; structural condition; conditions of creep, dislocations

The operating time of a number of equipment of TPP power units, which are operated in the conditions of maneuver mode, exceeded 270000 h. As the operating time of the equipment increases, its damageability grows, respectively, which is realized both according to the mechanism of creep and the mechanism of fatigue [1, 2]. In our opinion, each of the mentioned mechanisms as well as their joint manifestation requires a separate consideration.

The intensity of the formation of fatigue cracks in welded joints of steam pipelines made of 15Kh1M1F and 12Kh1MF steels is predetermined by the presence of a certain structural, chemical and mechanical heterogeneity. This heterogeneity has a tendency to grow in the process of increasing the operating time of welded joints, which leads to an increase in the intensity of their damageability according to the mechanism of fatigue [3]. The formation of fatigue cracks in TPP equipment, as well as in welded joints of steam pipelines in relation to their operating time of up to 250000 h was considered in [4–6].

It was established that the joint manifestation of deformation processes and structural-phase changes in the metal of welded joints contributes to the reduction of their service life [6–8]. In the process of long-term operation, the initial structure of welded joints metal is transformed into a ferrite-carbide mixture [9], and its residual deformation increases [8]. Accordingly, the fatigue damageability of welded joints increases, which has its own characteristics. Taking into account that the propagation of fatigue cracks occurs mainly according to a brittle mechanism [5–8, 10], it is necessary to study the structural condition of welded joints as a controlling effect of crack propagation.

A tendency of accelerated formation of fatigue cracks is observed, which is associated, respectively, with the structural transformations in the metal of welded joints, which for a long time (over 270000 h) are operated in the conditions of creep and low-cycle fatigue. Therefore, to reduce fatigue damageability, it is advisable to increase the level of stability of the structure of welded joints.

The aim of the work is to specify the relationship between the structural condition of long-term operated (270000–300000 h) welded joints of steam pipelines made of steel 15Kh1M1F and 12Kh1MF and their fatigue damageability.

Procedure of studying microstructural condition. The microstructural condition of metal in the welded joints was studied using the methods and procedures of light and electron microscopy. Also the known procedures of transition from data in the cross-section plane to volumetric data were used. Accordingly, statistical methods were applied. The X-ray diffraction investigation of carbide phases was performed in the powder diffractometer «Siemens D-500» at a monochromatized copper radiation with a graphite monochromator on a reflected beam. The calculation was performed according to the Rietveld method.

A number of carbide phases and their sizes were determined in an experimental way. Metallographic analysis was performed in accordance with the requirements of standard documentation. By studying the crystal structure, determination of the chemical

V.V. Dmytryk — https://orcid.org/0000-0002-1085-3811, O.S. Garashchenko — https://orcid.org/0000-0002-9572-6095, T.O. Syrenko — https://orcid.org/0000-0001-7333-7753

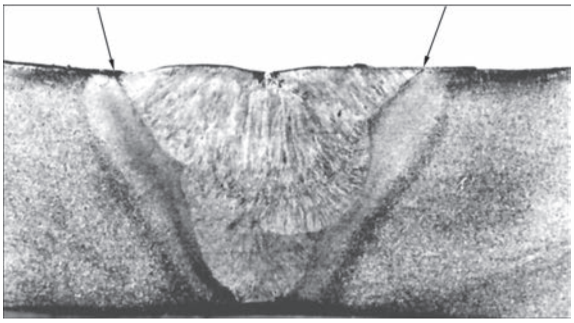

Figure 1. Macrostructure (×1.0) of welded joint of steel 15Kh1M1F (places of the largest stress concentrators are indicated by arrows)

composition and measuring of the average size of carbides in two mutually perpendicular directions, carbide phases were classified.

Metallographic examinations were carried out on 12 specimens of the same type, cut out from the existing steam pipelines made of steels 12Kh1MF and 15Kh1M1F. The operating time of the specimens was 270000–300000 h.

Studying the mechanism of fatigue crack initiation. The initiation and propagation of fatigue cracks in the elements of steam line systems occurs mainly in the areas of elevated stress concentration, which is predetermined by designing, technological and operational factors, as for example, in the upper zone of fillet welds, where the formation of undercuts is possible or in the area of fusion of the heat-affected-zone (HAZ) of welded joints (Figure 1).

Fatigue cracks have a wedged shape (Figures 2, 3) [4–6].

It was established that the influence of corrosive environment contributes to the accelerated propagation of fatigue cracks [4, 5] in the studied welded joints, which requires a separate consideration.

It is important to specify the peculiarities of initiation (incubation stage of formation) of fatigue cracks in welded joints, which significantly depends on their structural condition and plastic deformation.

The initial structure of the HAZ areas, as well as the base metal and the weld metal of welded joints

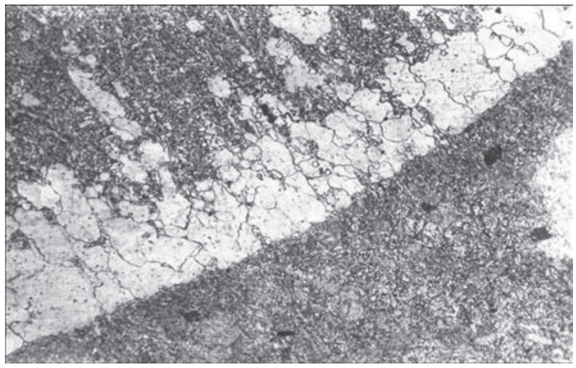

Figure 3. Fatigue crack at the stage of propagation. Welded joint of steel 15Kh1M1F (×2000)

with a different intensity is transformed into a ferrite-carbide mixture. The variable structural condition of long-operated welded joints largely depends on the level of their initial structural heterogeneity. The existence of such heterogeneity, which increases more with the longer operation period of welded joints, contributes to the formation of fatigue cracks. And first of all, the formation of cracks is predetermined by a probable existence of local rejection structures, which so far are not considered by standard documentation, but they are revealed in the existing welded joints of steam pipelines. In most cases, rejection structures have a local nature and their full detection by nondestructive testing methods is not possible. For example, in the area of HAZ fusion, which is subjected to welding heating to the temperature range T_L–T_S and has the sizes of 0.10–0.15 mm, in the initial structure enlarged ferrite grains can be formed, which are grouped in chains (Figure 4).

Ferrite grains can shift towards the area of HAZ overheating (size is 1.5–2.1 mm), which is subjected to welding heating to the temperature range T_S – 1150 °C (approximately). In the areas of fusion, overheating and normalization, the formation of large austenitic grains is possible (grain size number is 3–4, GOST 5639–82), which can be attributed to rejection structures. In the areas of overheating and normalization during welding of thick-walled pipes Widman-

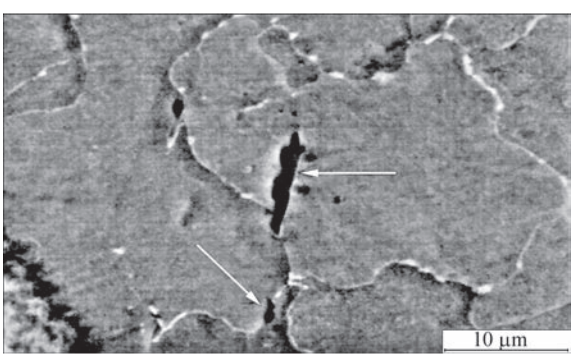

Figure 2. Fatigue cracks at the stage of initiation (arrows). Welded joint of steel 15Kh1M1F

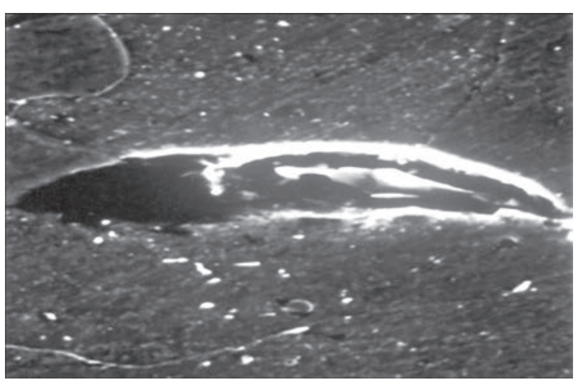

Figure 4. Rejection structure of the area of fusion of heat-affected-zone of welded joint of steel 15Kh1M1F

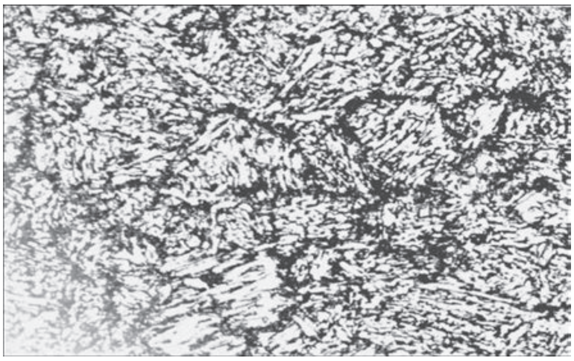

Figure 5. Microstructure (×300) of the area of partial recrystallization of HAZ of welded joint of steel 15Kh1M1F

stätten structure can be formed, which should also be considered as rejection one.

In the structure of the area of partial recrystallization of HAZ (welding heating to the temperature range A_{C1}–A_{C3}) globularized perlite (Figure 5) can be formed. The mentioned structure should also be classified as a rejection one.

Existence of local rejection structures, as well as structures that can be conditionally attributed to rejection ones, promotes the accelerated transformation of the initial structure of long-term operated welded joints into a ferrite-carbide mixture, i.e. degradation of the structure. The main features controlling the structural condition of welded joints (operating time is 270000–300000 h) [6–8, 11–13] are the following: transition of alloying elements from the α-phase to carbides; presence of segregation in the boundary zones of α-phase grains; coagulation of carbides. At the presence of initial rejection structures, the structural condition is formed, characterized by the accelerated formation of fatigue damageability, which is approximately by 20–25 % larger as compared to the presence of the initial structure, in which these rejection structures are absent. We should note that damageability increases with an increase in the operating time of welded joints (after 300000 h), which requires an additional study.

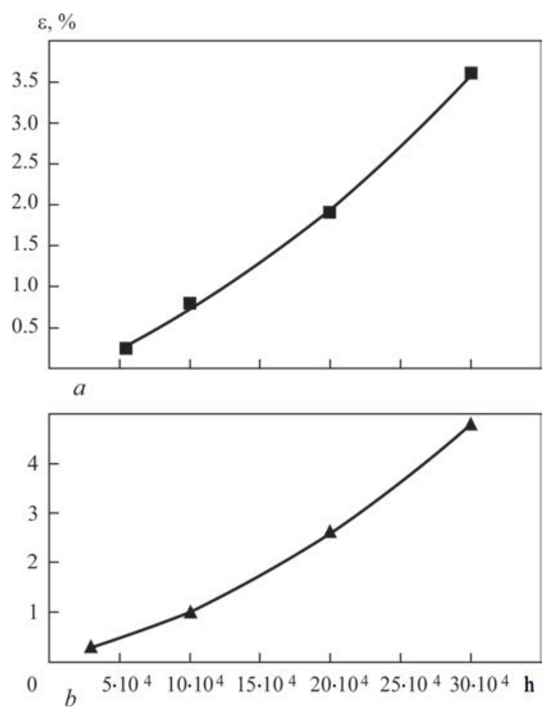

Figure 6. Dependence of deformation of HAZ areas of welded joints of steel 12Kh1MF on their operating time: *a* — metal of overheating area; *b* — areas of partial recrystallization

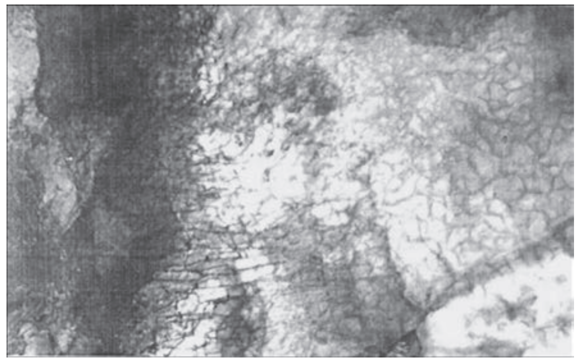

Figure 7. Dislocation structure of outer (near-surface) part of the area of partial recrystallization of HAZ of welded joint of steel 12Kh1MF. Service life is 280000 h, ε = 4 %

It was found that in the abovementioned structures, which are considered to be rejection ones, the transition of chromium, molybdenum and vanadium from the α-phase to carbides is more intensive, it is approximately by 10–20 % higher than in the similar structures, which meet the standard requirements. The transition of chromium, molybdenum and vanadium promotes an increase in the deformation ability of α-phase grains and reduction in heat resistance [8]. At the presence of the considered structures, the resistance to deformation during long-term operation of welded joints decreases, and the damageability by fatigue cracks increases by approximately 15–25 %.

It was grounded that the initial rejection structures are formed in the conditions of an increased welding heating, whose application may be allowed both in producing new welded joints, as well as during welding repair of damaged elements of steam pipelines. We should note that to produce the initial structure of welded joints (especially, thick-walled ones) with the improved quality characteristics its is rational to determine welding heating by its modeling.

Discussion of investigations results. In the standard documentation it is envisaged that the deformation of steam pipelines should not exceed 1.0–1.5 % [11, 14]. However, the deformation of separate areas of HAZ at the duration of operation of welded joints being more than 250000 h is about 3–7 % [4–7]. The initiation of fatigue cracks occurs in the process of microdeformation of the metal of welded joints. The metal of the area of a partial recrystallization of HAZ of welded joints (Figure 5) at their operating time

Figure 8. Dislocation structure of the area of partial recrystallization of HAZ (middle part) of welded joint (see Figure 7)

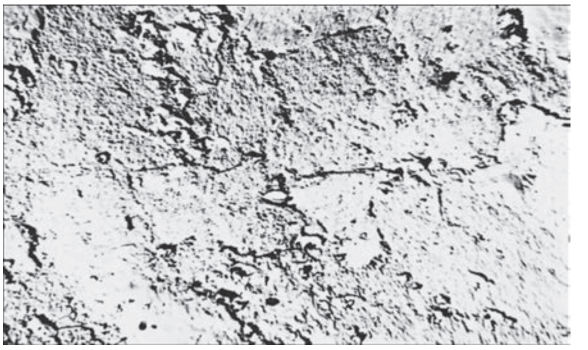

Figure 10. Polygonal structure (×4000) of the area of partial recrystallization of HAZ of welded joint of steel 12Kh1MF. Life is 186000 h

of 270000–300000 h is deformed by approximately 4–7 %, and the base metal — by 0.5–0.7 %.

Figure 6 shows the dependence of the deformation of the HAZ areas of welded joints of steel 12Kh1MF (ε, %) on their operating time.

It was established that in the surface (outer) zone of the metal of the area of a partial recrystallization of HAZ the relatively highest local density of dislocations in the grains of matrix ferrite is observed (Figure 7). The density of dislocations in the middle and surface (inner surface of the steam pipeline) zones of the welded joint of the steam pipeline is much lower (Figure 8). In the structure of long-term operated welded joints, a change in the dislocation structure is observed. The largest change is typical to the areas of fusion, overheating and partial recrystallization of HAZ, the smaller is typical to the weld metal and the base metal. In the process of plastic deformation at the grain boundaries of the α-phase (matrix ferrite and tempering bainite), new dislocations are generated and dislocation annihilation occurs, which is confirmed by a decrease in the values of microhardness to 10–20 % as compared to the initial microhardness. The rate of weakening exceeds the strengthening.

The increase in local dislocation density is facilitated by $M_{23}C_6$ and M_7C_3 carbides coagulating in length, located at the grain boundaries of the α-phase. The formation of dislocations is associated with the diffusion movement of chromium and molybdenum from the central zones of α-phase grains to their boundary zones and the formation of segregation [11]. To a lesser extent, dislocations are formed in the grains of the α-phase (matrix ferrite), which is facilitated by the diffusion movement of vanadium and the formation of new, especially fine-dispersed VC carbides.

Microyield as an effect of microplastic deformation in the volume of α-phase grains is provided by running the processes of return and the initial stage of recrystallization [12]. The composition of the dislocation structure changes, which leads to the elimination of fragments of separate grain boundaries, and then to a complete elimination of such boundaries (Figure 9).

In the α-phase grains a polygonal structure is formed (Figure 10). Also blurring of separate initial subboundaries is observed. Near precipitations of the second phases, a developed network of dislocations with a curved shape is formed (see Figure 8). A local density of dislocations in the area of partial recrystallization of HAZ is much higher than in other areas, as well as in the base metal and in the weld metal.

Regarding butt welds (straight areas of steam pipelines), cyclic deformation of the metal has its own peculiarities. Respectively, in the HAZ areas, in the weld metal and in the base metal, the dislocation structure is developed in a differently way. The plastic yield, originating from the grain boundaries of the α-phase grains is also different. At a deformation of 5–7 %, which is

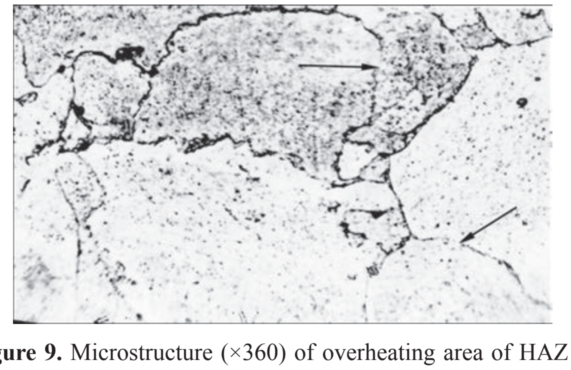

Figure 9. Microstructure (×360) of overheating area of HAZ of welded joint of steel 12Kh1MF (removal of fragments of grain boundaries is marked by arrows). Life is 280000 h

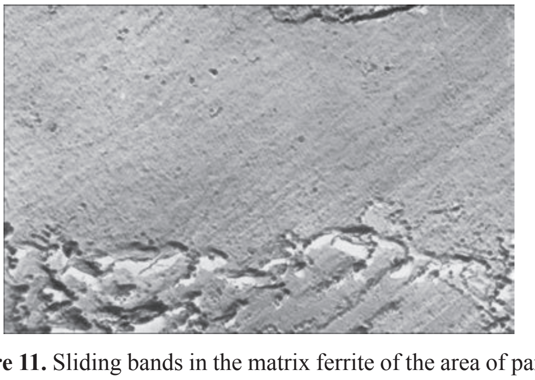

Figure 11. Sliding bands in the matrix ferrite of the area of partial recrystallization of HAZ of welded joint of steel 12Kh1MF. Life is 290000 h (×1100)

typical to the area of partial recrystallization of HAZ of welded joints from steel 15Kh1MF (operating time is 290000 h), in the grains of matrix ferrite, slip bands are revealed (Figure 11). At a lower level of deformation, the manifestation of slip bands is not observed.

It should be assumed that in the process of crack initiation (cyclic damageability) the study of the peculiarities of the formation of stable slip bands as a volume factor has a fundamental importance. The presence of slip bands in the structures of HAZ areas has different features (shape, length, quantity) from similar bands in the weld metal and in the base metal.

It was established that accumulations in the conditions of creep and low-cycle fatigue in the metal of welded joints of plastic deformation, is provided by the simultaneous movement of dislocations by the mechanism of sliding and the mechanism of climb. The presence of the climb mechanism is confirmed by the formation of creep pores near the coagulating carbides along the grain boundaries of the α-phase [7]. The movement of dislocations occurs to a greater extent according to the system {II2} <III> and to a lesser extent according to the systems{II2} <III> and{I23} <III>. When the dislocations intersect with the contact vector, which is normal to their sliding planes, steps are formed. Steps in the structure of welded joints can be single or sparse (deformation is ≤ 1 %). Their number increases at a deformation of 2–8 %. The formation of the configuration of steps is provided by the peculiarities of movement and intersection of dislocations, including the mobile dislocations with sedentary dislocations located along the grain boundaries. In the presence of precipitations of the second phases contacting with the steps, embryonic fatigue microcracks are formed (see Figures 2, 3). Their direction coincides with the greatest tangential stresses within the slip bands. Thus, embryonic fatigue microcracks have a crystallographic nature. The dislocation structure largely depends on the amplitude of the operating stress as well as on the energy of defects in the packing of the α-phase, which causes a local accumulation of dislocations in the grains of the α-phase, which is close to plane one (see Figure 7). The level of formation of sliding bands in the matrix ferrite is higher than in the tempering bainite (initial structure of welded joints bainite is 75–90 %, ferrite is the rest).

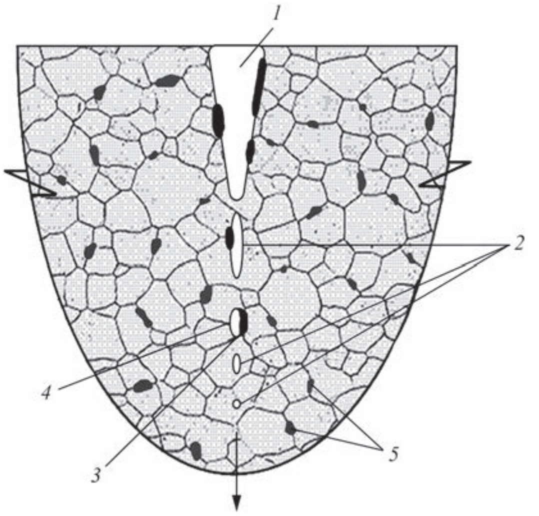

Figure 12. Scheme of fatigue crack formation: *1* — crack; *2* — fatigue micropores; *3* — carbide coagulating in length; *4* — creep micropore; *5* — carbides

In the places of contact of steps with precipitations of the second phases, at a long operation of welded joints in the conditions of creep, embryonic fatigue microcracks are formed. Micropores are originated the fusion of which provides the further formation of wedge-shaped microcracks (see Figures 2, 3). The study of the peculiarities of forming fatigue cracks, taking into account the structural condition, allowed providing the scheme of their formation (Figure 12).

It should be noted that the formation of fatigue microcracks is also contributed by the creep pores, located mainly on the grain boundaries of the α-phase in places where coagulating carbides $M_{23}C_6$ or M_7C_3 are located. The propagation of fatigue microcracks has an intercrystalline nature, and the mechanism of their propagation in the metal of welded joints (operating time is 270000–300000 h) is mostly brittle. The initiation and propagation of fatigue cracks is facilitated (to a large extent) by an increase in the cyclic nature of loads of welded joints of steam pipelines (over the last 5–8 years, a number of starts-stops of TPP power units has increased by about 30–50 %).

It is shown that in the slip bands, classified as fatigue ones, in the α-phase grains (operating time of welded joints is 270000–300000 h) the formation of microdiscontinuities is observed, which can be formally considered as embryonic micropores, the average diameter of which is approximately 100–400 Å. The shape of micropores may differ from spherical and ellipsoidal, which allows considering micropores as microcracks. The formation of embryonic fatigue micropores in the slip bands was for the first time discovered by V.S. Ivanova [10]. The initiation of fatigue microcracks mainly occurs by coalescence micropores and microdiscontinuities, which is possible at a directed diffusion of vacancies. As the operating time of welded joints increases (over 270000 h), the energy of activation of vacancies movement decreases, which is facilitated by the structural transformations occurring in their metal and the accelerated formation of microdiscontinuities.

An increase in the operating time of welded joints (over 300000 h) is characterized by a further change in the structural condition and features of forming fatigue cracks, which requires an additional study.

Conclusions

1. The structural condition of welded joints of steam pipelines made of steel 15Kh1M1F long time operating (270000–300000 h) in the conditions of creep and low-cycle fatigue, has a significant impact on their fatigue damageability.

2. The presence of structures in the metal of welded joints that can be attributed to the rejection ones, contributes to their accelerated degradation, which leads to approximately 15–20 % increase in the level of forming fatigue cracks in the metal of welded joints operating for a long time in the conditions of creep and low-cycle fatigue.

1. Dimić, I., Arsić, M., Medjo, B. et al. (2013) Effect of welded joint imperfection on the integrity of pipe elbows subjected to internal pressure. *Technical Gazette*, 20(**2**), 285–290.
2. Lazić, V., Aleksandrović, S., Arsić, D. et al. (2016) The influence of temperature on mechanical properties of the base material and welded joint made of steel S690QL. *Metalurgija*, 55(**2**), 213–216.
3. Katavić, B, Jegdić, B. (2007) Analysis of damages on water boiler shield pipes. *Welding and Welded Structures*, **4**, 123–130.
4. Khromchenko, F.A. (2002) *Residual life of welded joints of steam pipelines*. Moscow, Mashinostroenie [in Russian].
5. Trukhnij, A.D., Korzh, D.D., Kochetov, A.A., Rezinskikh, V.F. (1986) Investigation of low-cycle fatigue of steels 34KhM1A and EI415 after long-time operation in steam turbines. *Teploenergetika*, **3**, 32–35 [in Russian].
6. Dityashev, B.D., Popov, A.B. (2007) Complex approach to determination of residual life of steam pipelines of thermal power stations. *Ibid*., **2**, 21–25 [in Russian].
7. Dmitrik, V.V., Baumer, V.N. (2007) Carbide phases and damageability of welded joints at long-time operation. *Metallofizika. Novejshie Tekhnologii*, 2(**7**), 937–947 [in Russian].
8. Glushko, A.V., Dmitrik, V.V., Sirenko, T.A. (2018) Creep of welded joints of steam pipelines. *Ibid*., 40(**5**), 683–700 [in Russian].
9. Lazić, V., Arsić, D., Nikolić et al. (2016) Selection and analysis of material for boiler pipes in a steam plant. *Procedia Engineering*, **149**, 216–223. doi:10.1016/j.proeng.2016.06.659.
10. Ivanova, V.S. (1979) Fracture of metals. Moscow, Mashinostroenie [in Russian].
11. (2003) RD 10-577–03: *Model guidelines for inspection of metal and prolongation of the service life of main components of boilers, turbines, and piping systems of thermal power stations*. Moscow, NPO Prombezopasnost [in Russian].
12. (1987) MU 34-70-161–87: *Guidelines on metallographic analysis and examination of damage causes of steam pipeline welded joints from steels 12Kh1MF and 15Kh1M1F of thermal power stations*. Moscow, VTI [in Russian].
13. Dmitrik,V.V., Glushko, A.V., Tsaryuk, A.K. (2019) Recrystallization in the metal of welding joints of steam trucks. *Problems of Atomic Science and Technology*, 123(**5**), 49–52.
14. Dmitrik, V.V., Sirenko,T.A. (2012) To the mechanism of diffusion of chromium and molybdenum in the metal of welded joints of steam pipelines. *The Paton Welding J*., **10**, 20–24.

Received 11.03.2020