block loading with the increasing sequence of application of load were within 830–1046 %, with the decreasing sequence — within 674–1046 %, and with the quasi-random sequence — within 609–1046 % of those of the non-strengthened welded joints under similar sequences of application of loads.

Therefore, it was experimentally proved that under multistage and block loading (see the Table) strengthening of the tee welded joints after accumulation of 50 % damage by the HFMP technology allows not only substantially increasing the levels of the applied stresses, but also extending their residual fatigue life from 3 to 10 times. Under block loading, the scatter of experimental values of cyclic fatigue life of the welded joints was within a narrower range (1,401,400–2,409,000 cycles) than under multistage loading (641,500–2,378,100), and did not depend on the sequence of application of load in a block.

1. Troshchenko, V.T., Sosnovsky, L.A. (1987) *Fatigue resistance of metals and alloys*: Refer. Book. Pt 1. Kiev: Naukova Dumka.
2. Knysh, V.V., Kuzmenko, A.Z., Vojtenko, O.V. (2006) Increasing fatigue resistance of welded joints by high-frequency mechanical peening. *The Paton Welding J.*, **1**, 30–33.
3. Garf, E.F., Litvinenko, A.E., Smirnov, A.Kh. (2001) Assessment of fatigue life of tubular connections subjected to ultrasonic peening treatment. *Ibid.*, **2**, 12–15.
4. Knysh, V.V., Solovej, S.A., Kuzmenko, A.Z. (2011) Influence of preliminary cyclic loading on effectiveness of welded joint strengthening by high-frequency peening. *Ibid.*, **10**, 36–39.
5. Knysh, V.V., Solovej, S.A., Kuzmenko, A.Z. (2008) Accumulation of fatigue damage in tee welded joints of 09G2S steel in the initial condition and after strengthening by high-frequency mechanical peening. *Ibid.*, **10**, 10–15.
6. Knysh, V.V., Kuzmenko, O.Z., Solovej, S.O. (2009) Accumulation of fatigue damage in tee welded joints in as-welded state and after strengthening by high-frequency mechanical peening under block loading. *Mashynoznavstvo*, **9**, 27–31.

EFFECT OF HEAT TREATMENT ON SENSITIVITY OF THE HAZ METAL ON TITANIUM-STABILISED AUSTENITIC STEEL TO LOCAL FRACTURE

Yu.V. POLETAEV

Volgodonsk Institute (Branch) of South Russian State Technical University (Novocherkassk Polytechnic Institute), Volgodonsk, Russia

The mechanism of embrittlement of the HAZ metal of welded joints on steel 12Kh18N12T was revealed. This mechanism was found to be associated with development of the processes of direct and relative softening of grain boundaries in welding and at high-temperature low-frequency low-cycle loading. The efficiency of austenising to improve local fracture resistance of the welded joint HAZ metal was experimentally proved.

Keywords: *arc welding, welded joint, austenitic steel 12Kh18N12T, heat-affected zone, structural and chemical microheterogeneity, evaluation of weldability, optical and electron microscopy, heat treatment — austenising, low-frequency low-cycle loading, local fracture*

No common opinion exists now about the efficiency of austenising as a reliable technological method for prevention of local fracture. Studies [1–3] show that austenising does not always give positive results, while deviation from the set parameters of heat treatment may lead to decrease in load-carrying capacity of welded joints. Therefore, a priori application of the known recommendations without proper evaluation of their effect on structure and properties of the HAZ metal of a specific welded joint may cause deterioration of operational reliability.

The purpose of this study was to reveal the mechanism of embrittlement of the HAZ metal on austenitic steel 12Kh18N12T under the technological and service thermal-deformation effects, and propose the efficient technological method for improving local fracture resistance of the welded joints under low-frequency low-cycle loading. The study was performed on lengths of 12Kh18N12T steel steam pipes with a diameter of 230 mm and thickness of 30 mm cut out after being in operation for 70,000 h to perform overhaul of a run of the steam pipe of boiler 2 in the turbine section of Cherepetskaya power plant. As known from the operation experience, this material is sensitive to local fracture. Therefore, it is expedient to use it as a test one. This material complies with requirements of the regulatory documents in its chemical composition (wt.%: 0.13 C, 1.21 Mn, 0.55 Si, 18.7 Cr, 12.4 Ni, 0.51 Ti) and mechanical properties.

Welded joints were made by the technology accepted to perform erection work on steam pipelines [4]. An annular asymmetric single-bevel groove was made in the pipes. One half of the groove was welded up by using 4 mm diameter electrodes of the TsT-15 grade, and the other — by using electrodes of the TsT-26 grade. The welded joints on steel 12Kh18N12T were tested in the as-welded state and after austenising at T = 1373 K with holding for 1 h and cooling in air.

The as-welded joints featured high heterogeneity of mechanical properties, K_σ, between the weld metal ($\sigma_{0.2WM}$) and base metal ($\sigma_{0.2BM}$): $K_\sigma = \sigma_{0.2WM}/\sigma_{0.2BM}$. Dimensionless criterion K_σ characterises the degree of three-dimensionality of the stressed state. At temperature T = 873 K, all the as-

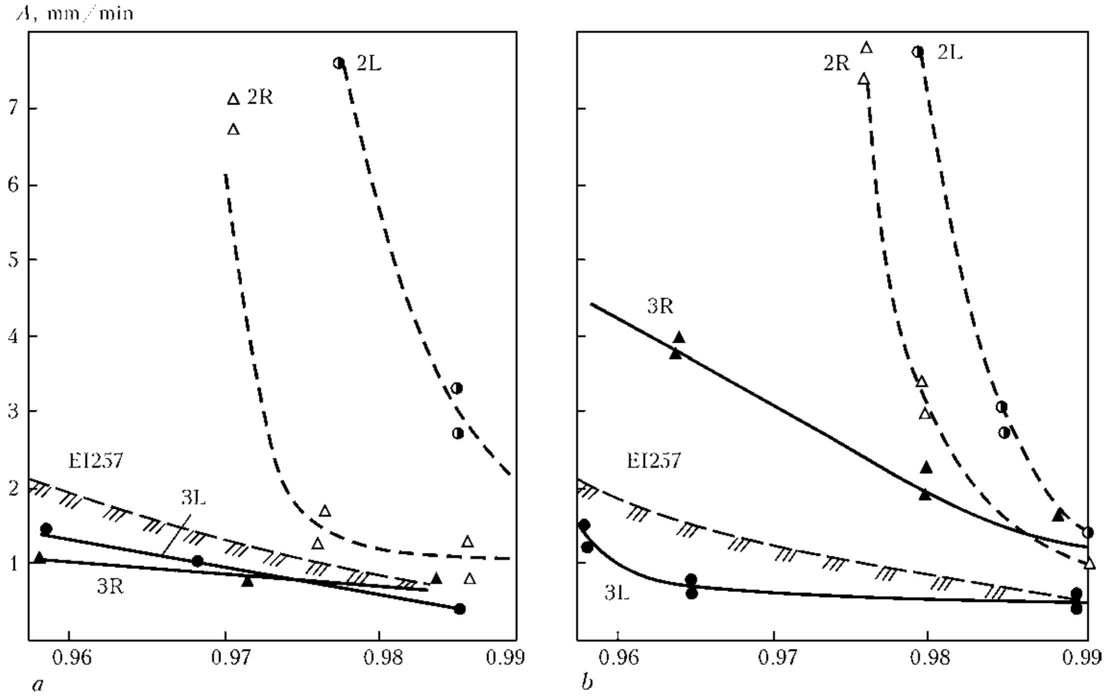

Figure 1. Resistance of steels 12Kh18N12T and EI257 to formation of hot sub-solidus cracks in HAZ metal in a state after operation (*a*), overheating and austenising at 1373 K(*b*): 2R, 2L, 3R, 3L — metal of the pipes adjoining the welds of joints 26L and 3A on their right and left sides (values of relative temperature θ are marked on the axis of abscissa)

welded joints had $K_\sigma > 0.9$–1.0. After austenising the heterogeneity markedly decreased, and the value of K_σ became close to the optimal one.

The sensitivity to formation of hot sub-solidus cracks in the HAZ metal under the simulated thermal-deformation welding cycle was evaluated by the procedure of TsNIITMASH by using A–θ dependencies [5].

The obtained A–θ dependencies for the steel, which are located in a region of compositions that are insensitive to hot cracking, are indicative of its satisfactory weldability (Figure 1). Hot processing (re-forging) and heat treatment also added to increase in hot ductility of the steel and its resistance to intergranular fracture during welding.

Steel 12Kh18N12T contains substantial concentrations of carbon and elements that exhibit a differing ability to form carbides in the condensed state [6].

Strong monocarbide TiC with a wide range of homogeneity, C/Ti = 0.53–0.95, forms in the Ti–C system. Complete fixation of carbide to form titanium carbides in steel 12Kh18N12T is provided at TiC > > 10 [7]. This ratio is approximately equal to four for the investigated heat of steel 12Kh18N12T. Therefore, the presence of non-fixed carbides creates conditions for formation of new particles of the $Cr_{23}C_6$ type strengthening phase in the steel. Owing to the presence of titanium acting as a stabilising element, a high density of fine carbides of the MeC type is provided in grains, and precipitates of carbides of the $Me_{23}C_6$ type are observed along the grain boundaries (Figure 2). As shown by calculations of electron diffraction patterns of these precipitates, carbides of the MeC type have the TiC or probably Ti(C, N) composition, and carbides of the $Me_{23}C_6$ type — the $Cr_{23}C_6$ composition. The closer the second-phase precipitates to the weld, the higher is their quantity along the grain boundaries and in the bulk of grains. Therefore, the most substantial changes take place in a region that directly adjoins the fusion line. These are partial dissolution of fine carbides, growth of grains, and precipitation of carbides of the dendritic shape at new boundaries, which increases with distance to the fusion line. In this case, of a decisive importance are heating above the carbide dissolution temperature and growth of grains accompanied by migration of boundaries. Presumably, while migrating, the boundaries seem to collect some free atoms of carbon and their clusters they run across, and to retain them in the form of segregations with a concentration sufficient to form carbides.

As diffusion of all impurities, including the substitutional ones, is accelerated at high temperatures of welding heating, it is probable that the boundaries collect and retain these elements as well. Formation of such segregations can be favoured by a sink of vacancies and dislocations to the grain boundaries, as well as by adsorption of horophilic elements by the mechanism of ascending diffusion [1].

Therefore, direct softening of the grain boundaries due to precipitation of the dendritic-shape $Me_{23}C_6$ type carbides on them, and their relative softening as a result of the process of titanium carbide precipitation hardening of the austenitic matrix of the HAZ metal on steel 12Kh18N12T after welding heating may be the main cause of an increased sensitivity to local (intergranular) fracture in high-temperature operation.

The sensitivity of the welded joints to formation and development of local fracture was evaluated under

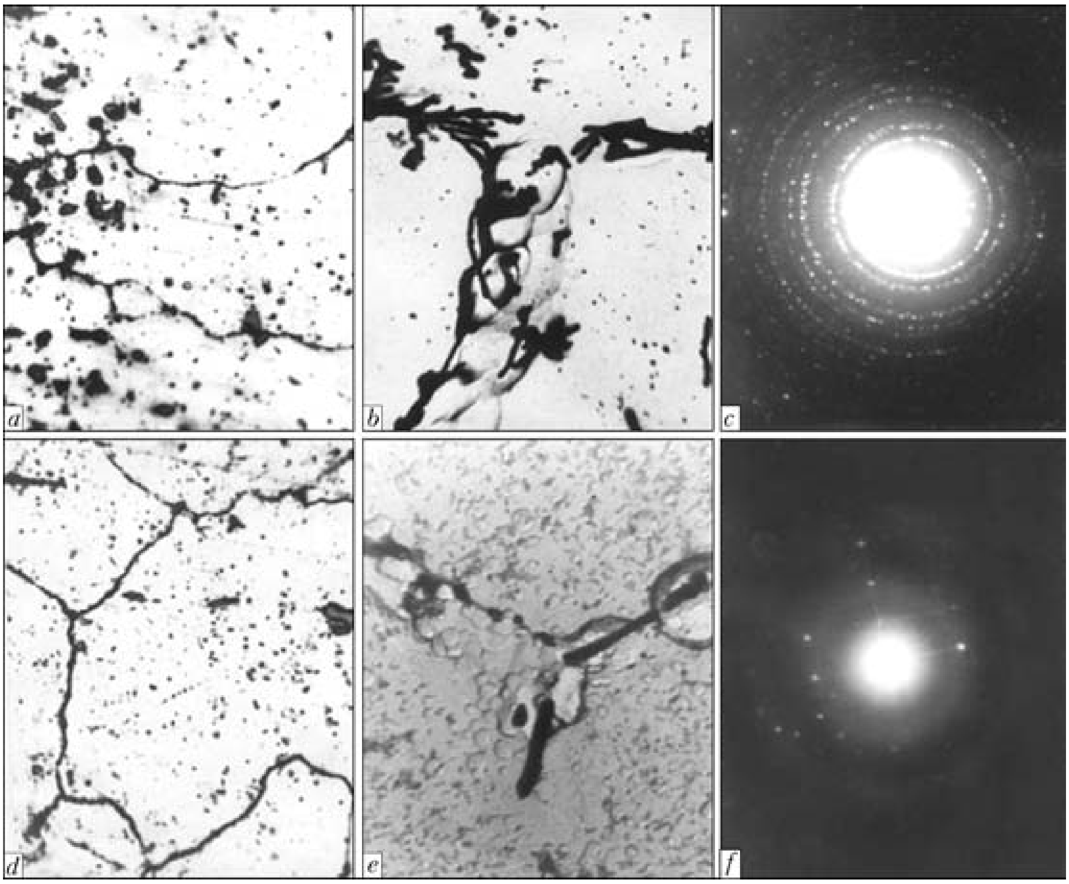

Figure 2. Microstructures of HAZ metal on steel 12Kh18N12T at different distances from the weld and at different magnifications (*a*, *d* — ×700; *b*, *e* — ×5000): *a*, *b* — fusion line; *d*, *e* — 0.1 mm from the fusion line; *c*, *f* — electron diffraction patterns of the carbide phase of TiC and $Cr_{23}C_6$ compositions, respectively

conditions of high-temperature low-frequency low-cycle loading according to the procedure described in [8]. Prismatic specimens with transverse welds, having one edge notch of a differing sharpness made along the fusion line, were tested. The specimens were tested under high-temperature low-cycle loading (trapezoidal cycle) by pure bending at a temperature of 823 K. The chosen time of a tension half-cycle was τ_1 = 24 h, and that of a compression half-cycle was 10 min, which provided low frequency $v = 4.2{\cdot}10^{-2}$ cycle/h.

As might be expected, the shortest life to local fracture was characteristic of the HAZ metal of the as-welded joints (Figure 3). The use of electrodes of the TsT-26 grade, providing a more ductile weld metal and a lower heterogeneity of mechanical properties between the weld and HAZ, led to a small (about 20 %) extension of life of the non-notched specimens. Performing only austenising promoted a marked increase in resistance of the HAZ metal to initiation and propagation of local fracture (Figure 4).

Intensive strengthening and increase in effective stress σ_{eff} in each cycle occurred at strain amplitude ε_a = 0.5 %. In steel 12Kh18N12T, strengthening continued up to formation of a macrocrack in the notch bottom. Formation of the macrocrack about 1 mm long at N_f led to a drop of σ_{eff} in steel 12Kh18N12T. Austenising caused a considerable change in the kinetics of fracture of the welded joints. Three characteristic regions can be distinguished in fracture diagrams. Increase in σ_{eff} in a range of 4–10 cycles from the moment of crack formation (N_f = 4 cycles) is fixed in the first region. Here the crack propagates at a relatively low, constant initial speed. In the second

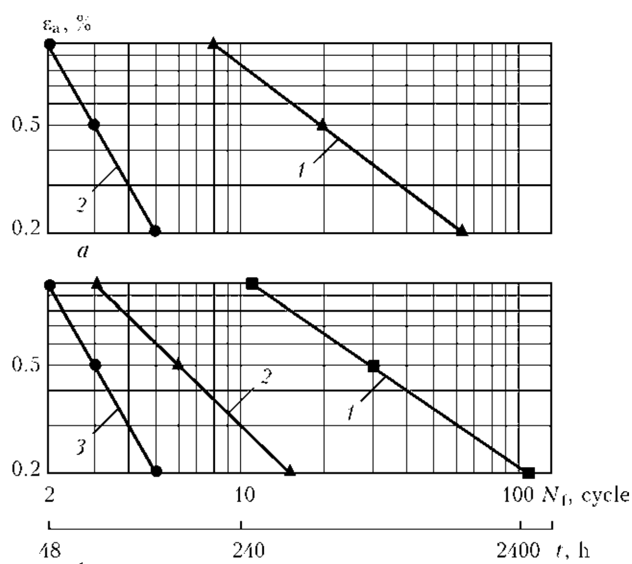

Figure 3. Effect of notch sharpness (theoretical stress concentration factor) on long-time low-cycle strength of welded joints on steel 12Kh18N12T in the as-welded state (*a*) and after austenising (*b*) at T = 823 K and $v = 4.2{\cdot}10^{-2}$ cycle/h: *1* — without notch; *2* — Mesnager type notch (3.0); *3* — Charpy type notch (5.3); *t* — total test time

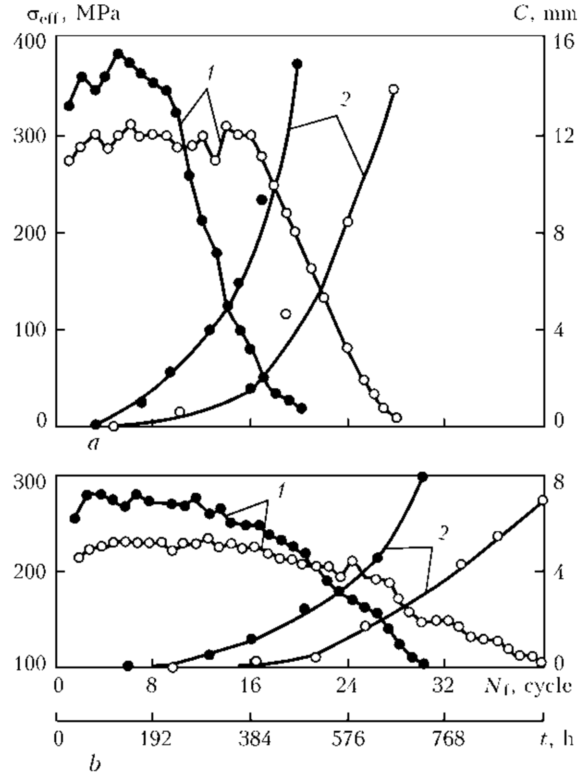

Figure 4. Fracture diagrams of welded joints on steel 12Kh18N12T at ε_a = 0.5 (*a*) and 0.2 (*b*) %: *1* — $\sigma_{eff} = f(N_f)$; *2* — $C = \varphi(N)$; dark circles — as-welded state; light circles — after austenising

region, periodic decrease and increase in σ_{eff} takes place. A stepwise crack growth leads to a drop in σ_{eff}, and its deceleration — to increase in σ_{eff} because of a work hardening taking place under repeated loading.

In welded joints on steel 12Kh18N12T in the as-welded state, the macrocrack forms at N_f = 3 cycles, while an intensive decrease in σ_{eff} related to a high crack growth rate in a specimen takes place after the fifth loading cycle. During 17 cycles from the moment of its initiation, the crack grew to a depth of about 1.5 mm. No loss of the load-carrying capacity of the specimen was fixed. Acceleration of the local fracture was observed in this region. In the third region, in a range of 16–28 cycles an intensive decrease in stresses σ_{eff} occurs in each cycle, this evidencing a loss of the load-carrying capacity of the specimen. This region corresponds to a propagation of crack at a higher acceleration. From the moment of its initiation, during 24 loading cycles the depth of the crack became equal to about 14 mm.

One should note a number of important points in the process of fracture of the welded joints at ε_a = = 0.5 %. For the as-welded joints on steel 12Kh18N12T the loss of the load-carrying capacity occurs at a crack depth of about 1 mm. It takes only two loading cycles to reach this point. After austenising, the loss of the load-carrying capacity of specimens takes place at a crack depth of about 2 mm, which in this case requires 12 cycles. Moreover, both in the as-welded state and after austenising the cracks grow almost at the same acceleration in the regions of intensive, constant decrease in σ_{eff}.

Therefore, austenising extends the stage of subcritical fracture, but exerts no positive effect in the overcritical range, i.e. in a region of the loss of the load-carrying capacity.

Initial damage of the HAZ metal after welding, as well as further changes in its structural-phase state in the low-frequency low-cycle loading process determine the kinetics of local fracture of the welded joints. Austenitic steels usually feature a structurally unstable state, and under the combined effect of high temperature and plastic deformation the dispersed phases may precipitate in them by the $\gamma \rightarrow \alpha$ plus carbide phase scheme. Precipitation of carbides leads to increase in strength and decrease in ductility, while their coagulation changes properties in the reverse direction. The strength of steel greatly depends on the shape, character and size of carbide particles. While strengthening the matrix, fine titanium carbides lead to localisation of strains and fracture in the near-boundary regions of grains. Individual coarse carbides of the $Me_{23}C_6$ type, which precipitate mainly along the grain boundaries, may retard the propagation of cracks during the plastic deformation process [1, 9]. The intensity of carbide formation depends on the level of stresses σ_{eff}, time of loading, temperature and other factors of low-cycle loading, and affects the kinetics of local fracture.

Strengthening, i.e. increase in σ_{eff} in cycles, is fixed at the first stage of low-cycle loading. Growth of the

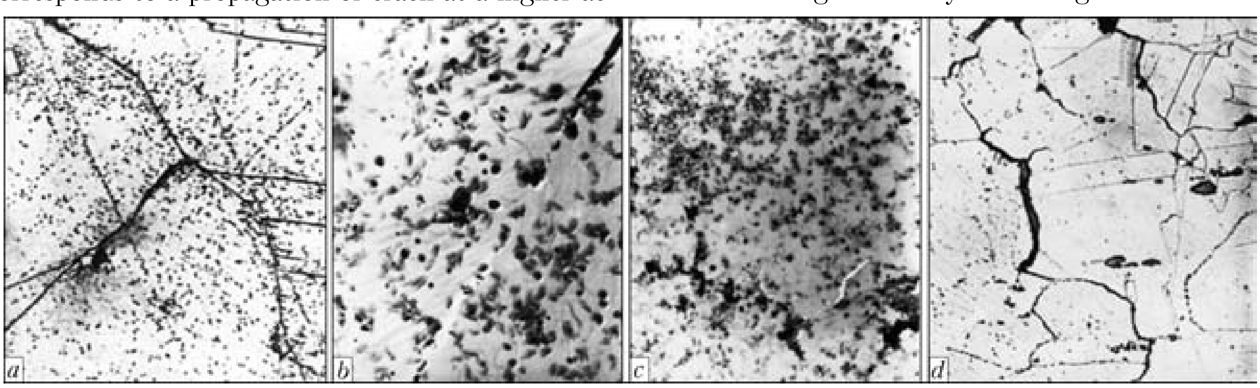

Figure 5. Microstructures of HAZ metal after the low-frequency low-cycle loading tests (ε_a = 0.5 %, τ_l = 24 h and T = 823 K): *a* — formation of discontinuity at a junction of three grains (×1000); *b*, *c* — precipitation of carbide phase in structure of TiC (×5000); *d* — network of wedge-shaped cracks (×300)

deformation resistance is related primarily to precipitation of fine carbides that effectively block the dislocations at which they initiate. The titanium carbides form fine precipitates mostly at extended dislocations, i.e. at thin disks of stacking faults [9, 10]. These precipitates are very stable and, together with the defects forming as a result of intersection of dislocations, form the rows of walls impassable for the dislocations, which can be regarded as a superimposed network of boundaries that hamper sliding [11]. This character of precipitation of the carbide phase led to a substantial strengthening of the matrix. This added to decrease in quantity of the mobile dislocations capable of causing plastic deformation and thus decreasing local stresses σ_l. As a result, the rate of relaxation of σ_l (creep) was markedly decreased, and the intergranular slip process developed, thus providing localisation of deformation at the embrittled grain boundaries. It is this fact that explains why no traces of rough internal sliding were fixed in steel 12Kh18N12T, and the deformation occurred by the mechanism of fine sliding, the traces of which can be detected by electron microscopy (Figure 5).

The key factor that determines conditions of propagation of wedge-shaped intergranular cracks is relaxation microplasticity in the bulk of grains near the ternary junctions. Further development of the carbide formation processes in the bulk of grains and along their boundaries leads to formation of intergranular wedge-shaped cracks.

Investigation of phase composition of the HAZ metal of the welded joints on steel 12Kh18N12T after the tests showed that the steel contained carbides TiC and $Cr_{23}C_6$. The effect of temperature and elasto-plastic deformation with long-time holding led to the process of dissolution, precipitation and coagulation of the carbide particles, the kinetics of which determined the stability of structure and properties of the steel.

The total content of carbide precipitates increased several times with growth of ε_a and quantity of the loading cycles. Thus, the HAZ metal in the state after austenising contained approximately 0.10–0.15 wt.% of the carbide phase; after the tests at $\varepsilon_a = 0.2$ %, $\tau_1 = 24$ h and $T = 823$ K ($N = 120$ cycles) the weight of the carbide precipitates was 1.10–1.25 % of that of the dissolved steel; and after the tests at $\varepsilon_a = 0.5$ %, $\tau_1 = 24$ h and $T = 823$ K ($N = 30$ cycles) the weight the carbide precipitates was 2.9–3.3 % of that of the dissolved steel.

Therefore, the favourable influence of austenising related to decrease in the initial structural and chemical heterogeneity of HAZ, which formed during welding, provides the effect of temporary increase in resistance of the welded joints on steel 12Kh18N12T to local fracture.

CONCLUSIONS

1. While promoting the intensive development of the processes of direct (due to precipitation of chromium carbides of the dendritic type) and relative softening of the grain boundaries (due to precipitation hardening of the matrix by TiC carbides), the thermal-deformation welding cycle was found to cause a high initial damage of structure and sensitivity to formation and development of local fracture of the HAZ metal on steel 12Kh18N12T.

2. Austenising is an efficient technological method for improving the local fracture resistance under low-frequency low-cycle loading, as it provides decrease in the initial structural and chemical heterogeneity.

3. Cyclic plastic deformation was proved to intensify the processes of direct and relative softening of the grain boundaries and stimulate decrease in resistance of the HAZ metal to development of local fracture of the welded joints on steel 12Kh18N12T under high-temperature (823 K) low-frequency low-cycle loading. It is because of this fact that austenising provides the effect of temporary increase in local fracture resistance of the welded joints on steel 12Kh18N12T, this being in agreement with data of practical observations.

1. Zemzin, V.N., Shron, R.Z. (1978) *Heat treatment and properties of welded joints*. Leningrad: Mashinostroenie.
2. Zemzin, V.N., Zhitnikov, N.P. (1972) Conditions of cracking in near-weld zone of joints during heat treatment. *Avtomatich. Svarka*, **2**, 1–5.
3. Yarkovoj, V.S., Muromtsev, B.I., Komissarov, V.G. (1969) Long-term strength of parent metal and welded joints of steels 08Kh18N9 and 07Kh16N9M2. *Ibid*., **6**, 38–40.
4. Khromchenko, F.A. (1982) *Reliability of welded joints on boiler pipes and steam pipelines*. Moscow: Energoizdat.
5. Tarnovsky, A.I., Poletaev, Yu.V., Feklistov, S.I. (1983) Applications of A–θ dependencies for evaluation of susceptibility of austenitic class steels and alloys to formation of hot near-weld cracks in welding. In: *Novel in welding technology of nuclear power plant equipment*: Trudy TsNIITMash, **179**, 82–84.
6. Kulikov, I.S. (1988) *Thermodynamics of carbides and nitrides*: Refer. Book. Chelyabinsk: Metallurgiya.
7. Livshits, L.S. (1979) *Metals science for welders (welding of steels)*. Moscow: Mashinostroenie.
8. Poletaev, Yu.V. (2010) *Long-term low-cycle strength of welded joints and choice of austenite-stable steels*. Novocherkassk: LIK.
9. Lozinsky, M.G., Romanov, A.N., Malov, V.V. (1977) Study of austenitic steel structure at different forms of elastic-plastic high-temperature deformation cycles. In: *Structural factors of low-cycle fracture of metals*. Moscow: Nauka.
10. Lyuttsau, V.G. (1977) Current concepts of a structural mechanism of deformation ageing and its role in fracture propagation at low-cycle fatigue. *Ibid*., 5–21.
11. Mints, I.I., Berezina, T.G. (1972) Stability of dislocation structure of cold-worked steels Kh18N12T and Kh16N9M2 in conditions of high-temperature ageing. *Fizika Metallov i Metallovedenie*, 34(**3**), 615–620.