INFLUENCE OF AUSTENITIZING MODE ON LOCAL FRACTURE SUSCEPTIBILITY OF WELDED JOINTS OF 03Kh16N9M2 STEEL

Yu.V. POLETAEV
Volgodonsk Affiliate of South-Russian State Technical University, Volgodonsk, RF

Influence of parameters of thermal cycle of austenitizing on formation of structural and chemical homogeneity and local fracture resistance of HAZ metal in production welded joints of austenitic steel 03Kh16N9M2 was investigated. It is established that development of processes of formation and growth of carbides and carbonitrides, stimulating welded joint susceptibility to local fracture, is difficult in low-carbon HAZ metal. Inexpediency of conducting high-temperature heat treatment, i.e. austenitizing of welded joints of 03Kh16N9M2 steel, is proved experimentally, as repeated heating up to T = 1323–1373 K for 1–4 h did not promote an improvement of HAZ metal resistance to local fracture.

Keywords: *arc welding, welded joints, low-carbon austenitic steel, heat-affected zone, structural and chemical microinhomogeneity, austenitizing, high-temperature low-frequency loading, local fracture*

With increase of unit power and working parameters of nuclear power plants with liquid-metal coolant the total extent of welded joints of austenitic steel increases markedly and is equal to tens of kilometers, while site welded joints are not subjected to austenitizing. Under these conditions the problem of ensuring the quality, strength and brittle fracture resistance of welded joints, including local fracture of HAZ metal at working temperature above 773 K, becomes particularly urgent.

At present there is no common opinion on effectiveness of austenitizing as a reliable technological method of prevention of local fracture of welded joints in high-temperature service [1–4]. It is established that austenitizing promotes lowering of long-term strength of welded joints [2, 5, 6] and increases the probability of appearance of intercrystalline fracture in the fusion zone [7–9], which is an even more embrittled zone of welded joint HAZ.

Thus, apriori application of autenitizing without an appropriate assessment of its influence on the structure and service properties of HAZ metal of specific welded joints of each studied steel grade can promote lowering of operational reliability.

The objective of this work is experimental substantiation of the possibility of eliminating austenitizing of welded joints on low-carbon austenitic steel 03Kh16N9M2 without the hazard of lowering of the resistance to local fracture of HAZ metal under the conditions of high-temperature (823 K) low-frequency low-cycle loading.

03Kh16N9M2 steel was studied using production melts of 6.5 and 40 t weight, melted from pure charge in the main electric arc furnace of the A.A. Zhdanov Izhora Plant. Chemical composition of this steel was, wt.%: 0.03 C; 1.22 Mn; 0.21 Si; 16.07 Cr; 10.37 Ni; 2.05 Mo; 0.20 Cu; 0.01 S and 0.007 P, and its mechanical properties corresponded to the requirements of normative documents.

Welded joints of 03Kh16N9M2 steel were made by standard technology of manufacturing welded assemblies of BN-800 reactor plant under the conditions of OJSC EMK-ATOMMASH. Manual arc welding was conducted with specially developed electrodes of TsT-46 grade. Welded joints were tested in as-welded condition and after austenitizing at T = 1323 K (soaking duration is 1–4 h) in keeping with the recommendations on heat treatment of welded structures of nuclear power plants with fast-breeder reactors from steel of Kh18N9 type. Heat treatment mode simulated the conditions of heating and cooling of large-sized welded structures. Also tested were welded samples subjected to austenitizing at T = 1373 K with 1 h soaking that corresponded to possible deviation from maximum temperature at furnace heating. Heterogeneity of mechanical properties between the weld metal and metal of HAZ is as-welded condition is quite high. The highest hardness of welded joints is observed in weld metal, and the lowest — in the base metal. Increased strength and hardness of weld metal is explained by its developed substructure and work hardening in welding. Microhardness measurement in PMT-3 instrument (100 g load) also revealed a section of «work-hardened» base metal, adjacent to the fusion line of about 0.1–0.3 mm length that is commensurate with the dimensions of overheated zone. Microhardness of this section is on the level of microhardness values of weld metal. Austenitizing eliminates the work hardening and leads to smoothing of mechanical heterogeneity, without, however, eliminating it completely.

Unlike steel stabilized by titanium [10], in the HAZ metal of non-stabilized 03Kh16N9M2 steel a considerable dissolution of carbides occurs after welding. This is attributable to the fact that chromium carbides are less stable than titanium carbides, and dissolve in

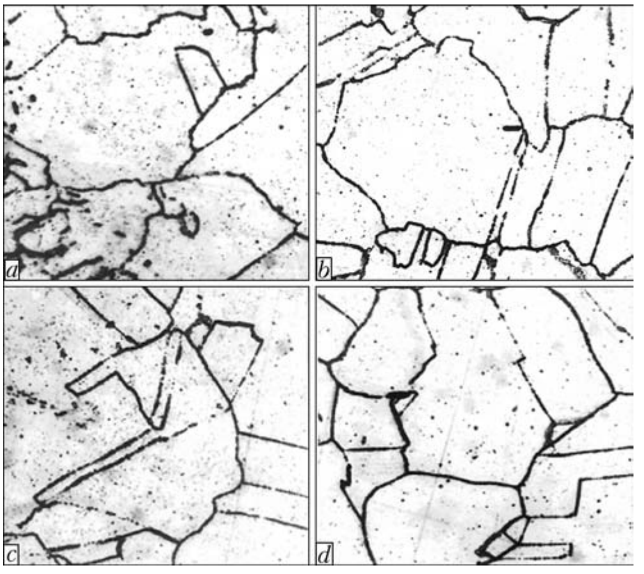

Figure 1. Microstructures (×700) of HAZ metal of 03Kh16N9M2 steel at different distance from the weld: *a* — fusion line; *b* — 0.1 mm; *c* — 0.5 mm; *d* — base metal

the HAZ metal during welding. Base metal of 03Kh16N9M2 steel has an equilibrium structure with a large number of twins, while finely dispersed carbides are absent in the grain body. Second phase precipitates are found on some part of grain boundaries. Electron microscopy studies and electron diffraction are indicative of the fact that these are plate-like carbides of $Me_{23}C_6$ type [10]. Now a large part of intergranular boundaries is free from precipitates. In HAZ metal sections directly adjacent to the fusion line (Figure 1), grain size became larger as a result of welding heat impact. Second phase precipitates are noticeable on some part of new boundaries. As shown by electron diffraction, these are also carbides of $Me_{23}C_6$ type. It is obvious that this section was heated above 1373–1473 K during welding that resulted in grain growth

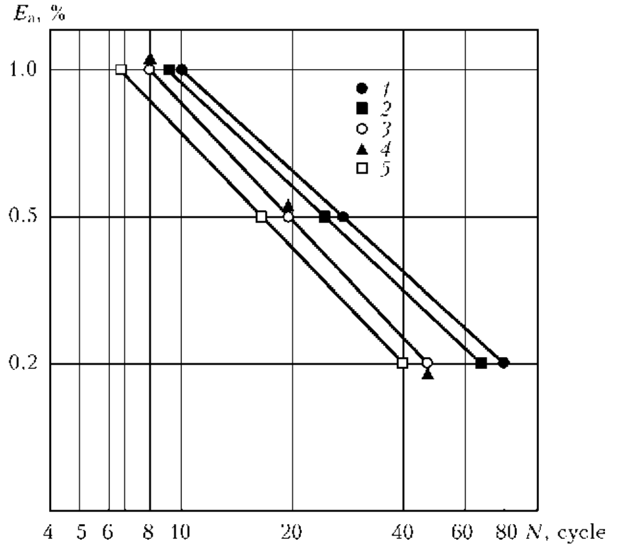

Figure 2. Influence of austenitizing on fatigue life of welded joints of 03Kh16N9M2 steel with Mesnager notch at T = 823 K: *1* — base metal; *2* — welded joint in as-welded condition; *3* — same at T = 1323 K, τ = 1 h; *4* — same at T = 1323 K, τ = 4 h; *5* — same at T = 1373 K, τ = 1 h

in it. During cooling in the temperature range of carbide initiation (723–1123 K), precipitation of fine dendritic carbides took place on some part of the boundaries with maximum free energy and largest segregations of carbon atoms. The farther from the fusion line, the smaller is the quantity and dimensions of precipitates along the grain boundaries.

After heat treatment HAZ metal microstructure practically did not change and consisted of austenite holyhedrons with individual inclusions of large chromium carbides. Weld metal structure, which had a dendritic structure in as-welded condition, changed to the greatest degree. After austenitizing weld metal acquired the structure of polyhedral austenite with a large amount of uniformly distributed globular ferritic phase.

Thus, while changing the metal structure, heat treatment leads to reduction of structural and mechanical heterogeneity of the welded joint, without, however, eliminating it completely. It is believed that austenitizing leads to increase of welded joint resistance to local fracture, which was not, however, confirmed by test results.

Assessment of welded joint susceptibility to formation and development of local fractures at high-temperature low-cycle loading was performed in keeping with the operational procedure of work [11]. Tested were prismatic samples with a transverse weld with one edge notch made along the fusion line. Samples were deformed by the schematic of alternating cyclic bending with soaking duration of 24 h in the tension half-cycle at T = 823 K.

As is seen from Figure 2, none of the heat treatment modes restores welded joint properties to base metal level. This is indicative of incomplete healing of microdamage on grain boundaries, arising during welding [5]. Welded samples in as-welded condition and after austenitizing at T = 1323 K with soaking for 1 h have practically the same fatigue life. Increase of soaking up to 4 h led to extension of fatigue life by only 1.2 times. At the same time, heating up to T = 1373 K increases brittle fracture susceptibility of welded joints.

Fracture diagrams and curves of fatigue crack growth rate are shown in Figures 3 and 4, respectively. In as-welded condition during the first four loading cycles welded joint strengthening is observed, namely increase of σ_{ef} in the cycles. Then the deformation process is stabilized and a crack forms at N_{fr} = 18 cycles. After austenitizing, the duration of the process of welded joint strengthening rises noticeably. After heating at T = 1323 K with 4 h soaking strengthening goes on for eight cycles. Then the deformation process is stabilized and a crack forms at N_{fr} = 21 cycles. After heat treatment at the temperature of 1323 and 1373 K with 1 h soaking the shape of $\sigma_{ef} = f(N)$ curve is unstable. After four cycles strengthening is over, and the deformation process is stabilized. Then strengthening is observed again, which goes on right up to crack formation (at N_{fr} = 17 and 14 cycles, respectively).

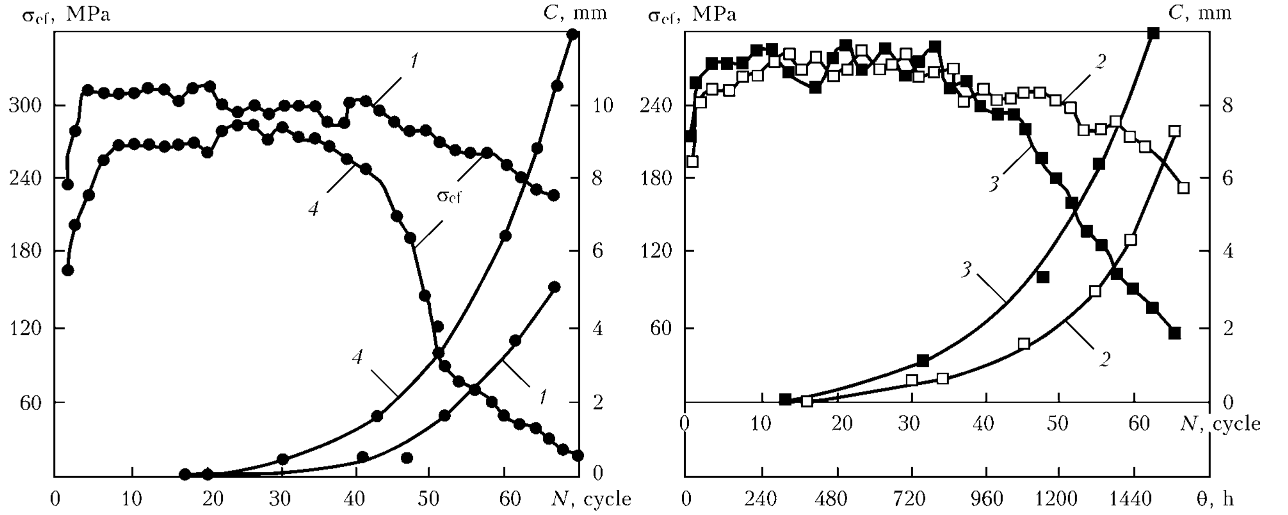

Figure 3. Fracture diagrams of welded joints of 03Kh16N9M2 steel at E_a = 0.5 %, τ = 24 h, T = 823 K: *1* — as-welded condition; *2* — austenitizing at T = 1323 K, τ = 1 h; *3* — same at 1373 K, τ = 1 h; *4* — same at 1323 K, τ = 4 h

Kinetics of fracture development was studied on the base of 50 cycles from the moment of crack formation. At testing in as-welded condition in the range of the first 14 loading cycles stable crack development with a constant rate equal to $7\cdot10^{-3}$ mm/cycle (see Figure 4) is observed, while strengthening and softening sections can be seen on $\sigma_{ef} = f(N)$ curve (see Figure 3). At N = 14 cycles the first salient point forms on $V = f(N)$ curve. In the range of 14–26 cycles accelerated crack propagation occurs. After 26 cycles the sample looses its load-carrying capacity that points to a constant relatively small lowering of σ_{ef} in each cycle and second salient point on $V = f(N)$ curve. At further deformation crack propagation process is characterized by a practically constant acceleration. After 50 loading cycles crack depth was about 5 mm, and its growth rate was about $100\cdot10^{-3}$ mm/cycle.

Shape of $\sigma_{ef} = f(N)$ curves in welded joints after heat treatment at T = 1323 and 1373 K with soaking for 4 h, during the first four cycles is characterized by stable development of the crack at a constant rate of $38\cdot10^{-3}$ mm/cycle. At subsequent loading σ_{ef} rises as a result of considerable resistance to crack propagation. After N = 14 cycles loss of sample load-carrying capacity takes place that is particularly noticeable after the 22nd cycle. Intensity of fracture propagation rises. After 50 loading cycles the crack has reached the depth of 11.8 mm and growth rate of $236\cdot10^{-3}$ mm/cycle.

Shape of $\sigma_{ef} = f(N)$ curves for welded joints after autenitizing at T = 1323 and 1373 K with 1 h soaking is the same. The fracture process, however, is characterized by different intensity. In a sample treated at T = 1323 K loss of load-carrying capacity occurs after 24 cycles. In the range of 24–50 cycles periodically recurring sections of softening and stabilization can be singled out on $\sigma_{ef} = f(N)$ curve, that is indicative of a jump-like nature of crack growth and its subsequent deceleration, so that several salient points and sections with different acceleration of crack propagation are observed on $V = f(N)$ curve. In a sample treated at T = 1373 K loss of load-carrying capacity occurs after 14 loading cycles. At subsequent cycles an abrupt lowering of σ_{ef} value is observed, which is due to intensive crack propagation. In the range of 14–50 cycles two sections with different inclination to abscissa axis can be singled out on $V = f(N)$ curve. After 50 loading cycles, in welded joints, treated at T = 1323 and 1373 K, crack depth was equal to 6.9 and 9.9 mm, respectively, and crack growth was $138\cdot10^{-3}$ and $198\cdot10^{-3}$ mm/cycle.

Lowering of welded joint crack resistance after austenitizing is related to a change of fracture location. Welded joints in as-welded condition are characterized by formation and development of local fracture in the HAZ metal at the distance of 1–3 grains from the fusion line (Figure 5, *a*). Here, development of several cracks occurs with approximately the same intensity. After austenitizing local fracture develops predominantly along the fusion line (Figure 5, *b*). Even at formation of several cracks the crack along

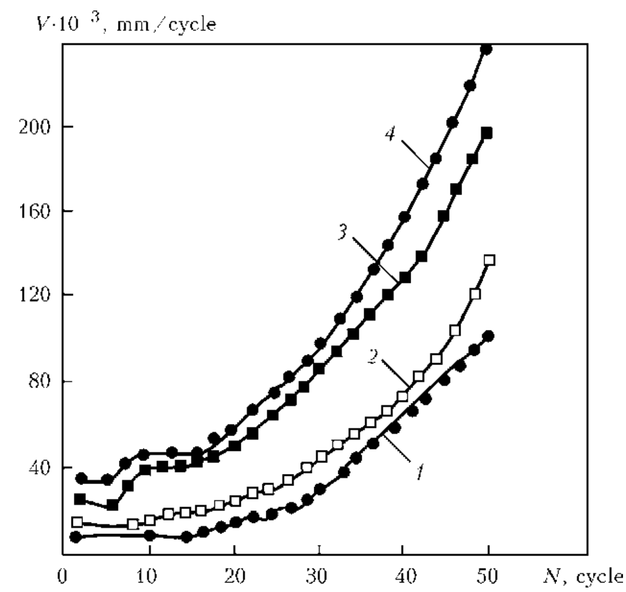

Figure 4. Dependence of intensity of local fracture of 03Kh16N9M2 welded joints on autenitizing mode: *1–4* — same as in Figure 3

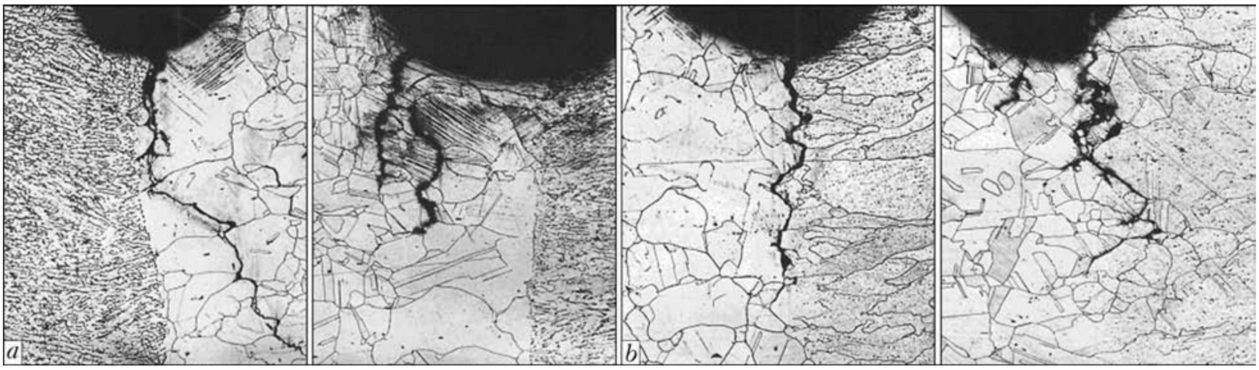

Figure 5. Nature of fracture of 03Kh16N9M2 welded joints with Mesnager notch in as-welded condition (*a*) and after austenitizing (*b*) (×100)

the fusion line develops more intensively. In both the cases brittle (tear) intergranular fracture is observed.

Change of fracture site can be explained as follows. In as-welded condition the HAZ metal forms a work-hardened zone of 0.1–0.3 mm length adjacent to the weld and having a higher hardness on the level of that of weld metal. At deformation of such a heterogeneous joint, strain localizing, damage accumulation and intergranular fracture at low-frequency low-cycle loading will occur on the boundary of the hard (strengthened) and soft regions. Austenitizing eliminates post-weld work-hardening of the metal of HAZ and weld and facilitates producing a more homogeneous joint. In this case, however, weld metal also has higher strength than the base metal, thus leading to strain localizing already on the fusion line. High chemical and structural heterogeneity of this HAZ region promotes a more intensive development of intergranular fracture.

Thus, it is experimentally proved that austenitizing in the temperature range of 1323–1373 K of 1–4 h duration does not promote any increase of local fracture resistance of 03Kh16N9M2 steel welded joints under the conditions of low-frequency low-cycle loading. More over, at deviation from the recommended heat treatment mode, lowering of crack resistance is observed, which is related to localizing of intergranualr fracture on the fusion line. Obtained results allowed substantiating elimination of performance of high-temperature heat treatment, i.e. austenitizing of 03Kh16N9M2 welded joints.

Based on the results of evaluation testing of production welded joints, a permission of RF GOSTEKhNADZOR was obtained, and certified procedures and recommended parameters of welding mode, and welding consumables for welded structure fabrication from 03Kh16N9M2 steel were incorporated into PN AEG-7-008–89, PN-AEG-7-009–89 and PN AEG-7-010–89 normative-technical documents that will allow a long-term and reliable operation of welded joints in as-welded condition at up to 923 K temperature.

CONCLUSIONS

1. Integrated study of the influence of austenitizing mode parameters on formation of a stable and local fracture resistant structure of HAZ metal in production welded joints of 03Kh16N9M2 austenitic steel was performed.

2. It is established that low content of carbon in 03Kh16N9M2 steel makes it difficult for the process of formation and growth of the most probable $Me_{23}C_6$ carbide to run, that ensures a low sensitivity to welding heating and preservation of the structurally stable condition of HAZ metal at subsequent high-temperature low-frequency low-cycle loading.

3. It is proved experimentally that performance of high-temperature heat treatment, i.e. austenitizing at T = 1323 K of 1–4 h duration, does not promote an increase of local fracture resistance of 03Kh16N9M2 steel welded joints. Deviation (heating up to T = 1373 K) from the recommended austenitizing mode promotes the manifestation of local fracture susceptibility of HAZ metal under the conditions of low-frequency low-cycle loading, simulating the non-stationary mode of high-temperature operation of welded structures of nuclear power plants with liquid metal coolant.

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