Experimental methods for assessing the propensity of welded joints to local fault

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Abstract. The problem of increasing the resistance of welded joints of power equipment against local destruction in the conditions of non-stationary mode of high-temperature operation is relevant. In the studies performed, the analysis of the causes and nature of LR was carried out from the standpoint of classical physics of high-temperature deformation and intergrain destruction by the creep mechanism. Most of the test methods developed simulate just such loading conditions. However, the most objective assessment of the susceptibility of the welded joints to LR can be given by the method of testing welded joints under conditions of high-temperature low-frequency low-cycle loading. Key words: Welded joint, technological samples, weldability, creep, mechanism of intergranular fracture, low-cycle loading, local loading.

1 Introduction

The operation of power equipment at temperatures above 500 ^{0}C requires a comprehensive assessment of the heat-resistant properties of welded joints, which determine the reliability, durability and safe operation of the structure [1]. When carrying it out, the influence of the main structural and mechanical factors should be taken into account: the initial defectiveness of the material; stability of the structure and properties during operation; type of stress state; operating conditions, etc. [2]. When choosing steel, only "classical" methods for assessing heat resistance (long-term strength, ductility, creep limit) can lead to premature equipment failure and accidental consequences. So, for example, the assessment of the heat resistance of welded joints of austenitic steam pipelines made of steels EI-257 and 12H18N12T, carried out only using standard static test methods, did not allow at the stage of laboratory research to reveal the tendency of welded joints to intergranular fracture in the heat-affected zone (HAZ), conventionally called local fracture (LR). For this reason, the choice of steels for creating ultra-high parameters steam pipelines at the Cherepetskaya GRES turned out to be erroneous, and the massive destruction of welded joints led to significant material damage [3–5].

LRs are formed and developed in the HAZ, at temperatures above 500 ^{0}C, under conditions of metal creep, at operating stresses lower or higher than those allowed. Typically, cracks originate on the outer surface of the welded joint, from surface defects, in zones of

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structural stress concentration and propagate equidistantly to the weld along the heat-affected zone, at a distance of 1...3 grains from the fusion line.

The results of the performed studies of the mechanism of local fractures show [6-8] that they are caused primarily by the sensitivity of steel to the thermal deformation cycle of welding and heat treatment, as well as the development of the process of intergranular fracture during creep of the welded joint under high-temperature operation. Processes that contribute to a sharp decrease in the strength of grain boundaries can be combined into two groups:

- causing direct softening of the grain boundaries and accumulation of damage along them during welding;

- leading to a relative softening of the boundaries due to the hardening of the grain body.

It should be noted that in order to conduct a reliable assessment of the susceptibility to LS of welded joints, a comprehensive theoretical and experimental study is required using a number of original and standard methods that allow obtaining reliable results that substantiate practical methods for preventing LS and the choice of reasonable technologies for manufacturing welded structures of power equipment.

2 Research methods

Known test methods can be combined into the following three groups: 1. Evaluation of the propensity to LR based on the results of testing technological hard samples; 2. Evaluation of changes in steel properties after exposure to imitation thermal (TCS) or thermal deformation welding cycle (TDCS) according to the HAZ mode;

3. Evaluation of the susceptibility to LR of welded joints according to the characteristics of their heat resistance. Each of the methods of the above groups has its own characteristics and rational limits of application.

Technological samples are the simplest type of testing (Fig. 1). The data obtained with their help are of a qualitative nature and can be used for preliminary rejection of various steel melts. Among the technological samples, the most common samples are BWRA, TsKTI, TsNIITMASH, and TsNIIMS [8]. In naturally stressed samples (BWRA and TsNIITMASH), stresses are created due to the rigidity of the joint during welding of the choke. In tee and butt samples - due to surfacing of load rollers. After welding, the samples are placed in a furnace and kept for a certain time at a given temperature, or subjected to periodic loading by surfacing load rollers. The criterion for assessing the tendency to local destruction of naturally stressed samples is time, and for samples with loading - the number of cycles before cracks occur.

A decrease in the strain rate promotes the development of intergranular slippage. The rate of deformation during welding is proportional to the rate of cooling. Decreasing the cooling rate can cause a tendency to intergranular fracture, as it increases the residence time of the HAZ metal in the brittle temperature range (BRT). Therefore, in the technological express test of the PWI E. O. Paton provided for the use of electroslag welding [9].
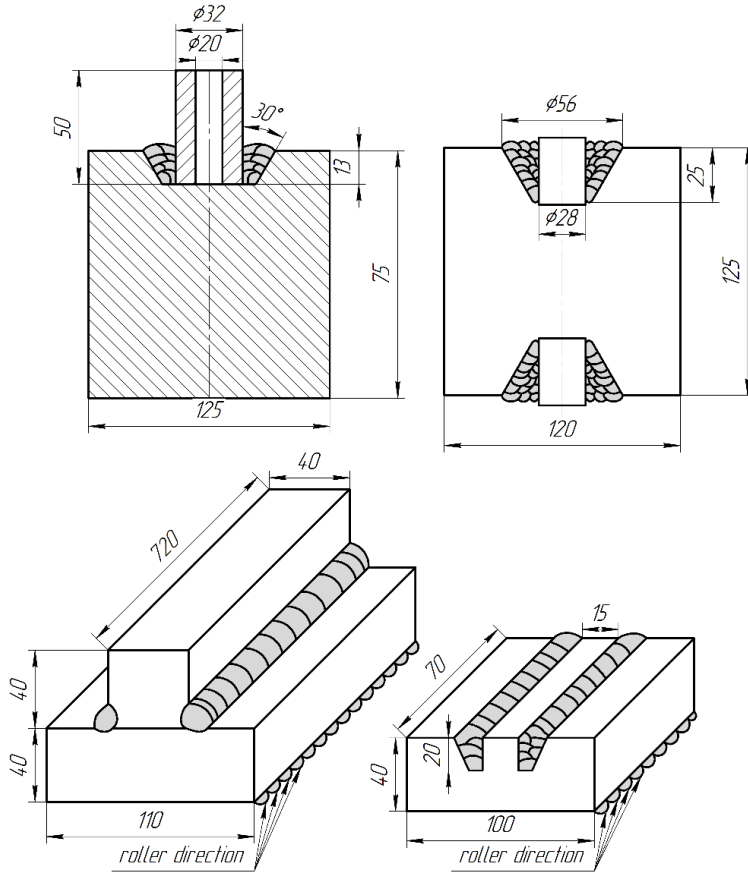
Fig. 1. Welded specimens for technological testing of susceptibility to CVD: a - BWRA sample; b – TsNIITMASH sample; c – TsNIIMS brand test; (d) butt test of CKTI.

When tested using an express test, austenitic steels with carbide and intermetallic hardening, including steels 12H18N12T and EI-257, showed an increased tendency to local destruction. Steels 08H18N9, 08H16N9M2 and EI-257 with a carbon content reduced to 0.02% turned out to be not prone to destruction. Using the tee test and its more rigid version, the TsKTI butt test, we also revealed a different tendency to local destruction of steels 08H16N9M2, 08H18N9 and 12H18N12T. At the same time, it was not possible to detect damage on samples of steel 08H16N9M2 after holding up to 5000 hours, at T = 500 ^{0}C [9].

The second group includes methods for testing samples of the base metal subjected to a thermal or thermal-deformation cycle of welding in special installations. In this group, the most well-known methods are [8]: IMET-1, Rensler Polytechnic Institute - RPI, Moscow State Technical University. N. E. Bauman and IMET-TsNIICHM. These methods were developed primarily to assess the likelihood of hot cracking in the HAZ directly during welding. It is assumed that there is a direct relationship between the damage of the HAZ metal during welding heating and the tendency to local destruction. Indeed, TDCS in some materials can cause the formation of hot near-weld cracks, in others - only nucleation microcracks, which are not detected by conventional inspection methods, but being stress concentrators, can lead to brittle local fractures of welded joints during high-temperature operation.

To determine the tendency to local fracture, data are used that characterize the weldability of steels in terms of TIC- IMET-1 and FIR methods, or the critical strain rate in TIC - MVTU

and IMET-TsNIICHM methods. The criterion for the resistance of steels to local fracture is ductility and strength.

The use of methods of the second group led in some cases to conflicting results, due to the lack of reasonable recommendations for choosing Tmax when simulating TCS. The TsNIITMASH method [11], which is free from the indicated drawbacks, makes it possible to more reliably reveal the tendency of austenitic materials to damage in the HAZ during welding. In accordance with the test procedure, the tests are carried out in the following sequence. At the beginning, the temperature of the upper limit of TIH -, the temperature of the beginning of the ductility dip and the temperature of plasticity recovery during cooling according to TCS for each steel grade are determined (Fig. 2).
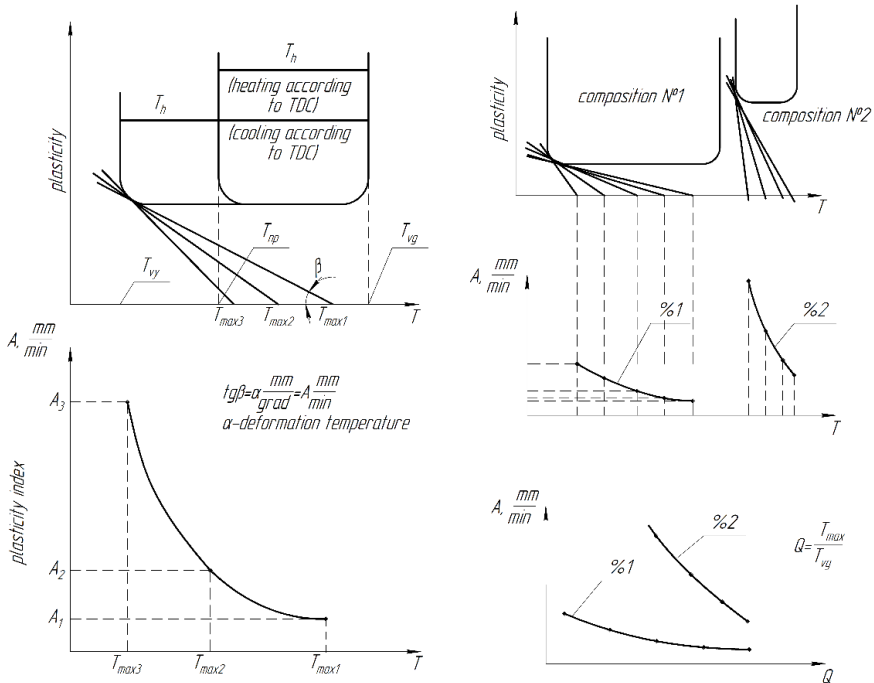

Fig. 2. Evaluation of the tendency of steels to form hot cracks in the HAZ during welding using the $A - \Theta$ dependence (scheme): a - an example of plotting the dependence of the indicator A on the maximum heating temperature of the $T_{\max i}$ thermal cycle of welding; b – comparison $A - \Theta$ of dependences of two compositions differing in value T_{vg}.

After that, the samples are heated by a passing current to a temperature $T_{\max i}$ specified in the interval $T_{np} < T_{max} < T_{vg}$. In the process of cooling in the temperature range, the $T_{max}...T_{vg}$ samples are subjected to tension, changing the strain rate from experience to experience. At the same time, the plasticity index A (mm/min) is determined, corresponding to the critical strain rate when tested according to the IMET-TsNIICHM method. As a result of a series of tests, a dependence of the index is obtained, A which increases sharply with a decrease $T_{\max i}$ in the case of compositions with a low TIC and a high margin of plasticity. Otherwise, this dependence increases very slowly.

The disadvantage of the methods of the second group is the impossibility of taking into account when using them a number of factors that have a decisive influence on the properties

of the HAZ metal and the welded joint as a whole. These include the processes of diffusion redistribution of individual elements, primarily carbon, joint stiffness, the effect of stress concentration, etc.

The next group of methods is intended for direct determination of heat resistance, taking into account the probability of LR of welded joints, and allows obtaining the most objective quantitative data on the performance of structures at high temperatures. A common method for assessing the tendency of welded joints to local failure is the CKTI method [12], which involves testing cylindrical specimens for long-term pure bending at operating temperatures and various strain rates, typically between 10 and 0.01%/h (Fig. 3).

It can be seen that with a decrease in the strain rate, the plasticity of the welded specimens drops sharply. The evaluation criterion in these tests is the relative elongation before cracking in the HAZ at a low strain rate, simulating a long service life. This data can be obtained by extrapolating the plasticity values obtained at higher strain rates. Comparison of the data obtained with the results of operation shows that the ultimate plasticity, at a strain rate of 0.67%/h, below which there is an increased tendency to local destruction, is ~5% [3]. Tests using the CKTI technique confirmed the high resistance against local fracture of welded joints of steel 08H16N9M2, an increase in the reliability of welded joints of steel 12H18N12T after austenitization, and as a result of the use of CT-26 electrodes [13]. At the same time, the CKTI method has its limitations, since it does not take into account the influence of sign-variable low-cycle loading due to non-stationary operation.

Using this technique, it is not possible to obtain LR in the HAZ metal of austenitic steels with high ductility. So, when testing welded samples of steel 08H16N9M2 at the limiting deformation for this method (25%), local cracks could not be obtained [13].
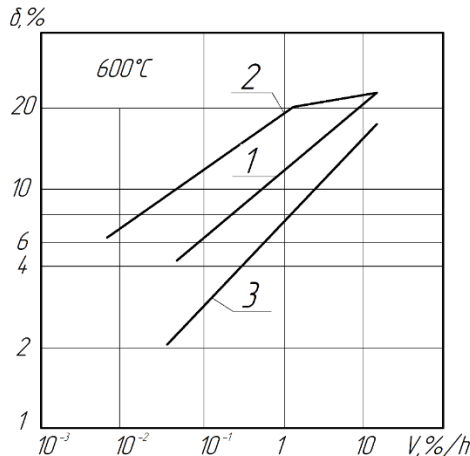

Fig. 3. Change in plasticity during bending test of welded specimens of steel 12H18N10T depending on the strain rate: 1 - initial state; 2 - austenitization at 1150 ^{0}C -1 hour + stabilization at 800 ^{0}C - 10 hours; 3 - stabilization at 800 ^{0}C - 10 hours.

Moreover, the CKTI technique does not provide for the assessment of the relaxation resistance of welded joints and the intensity of development of local fracture, which is an important material characteristic for determining the residual life of the structure.

The accumulated experimental and operational experience shows that a reasonable choice of a reliable and durable structural material can be made based on the results of a comprehensive study involving a number of standard and original laboratory test methods that reproduce the operating conditions of welded joints.

The technique developed by us [1] makes it possible to evaluate the bearing capacity of welded joints at high temperature, at the stage of formation and development of LR, taking

into account the relaxation ability of the material, under conditions of low-frequency low-cycle loading (low-cycle loading with long time exposures at the creep temperature).

It should be noted that during operation, stresses and strains change cyclically as a result of scheduled and emergency start-ups and shutdowns of equipment and pipelines (Fig. 4). For fast reactors
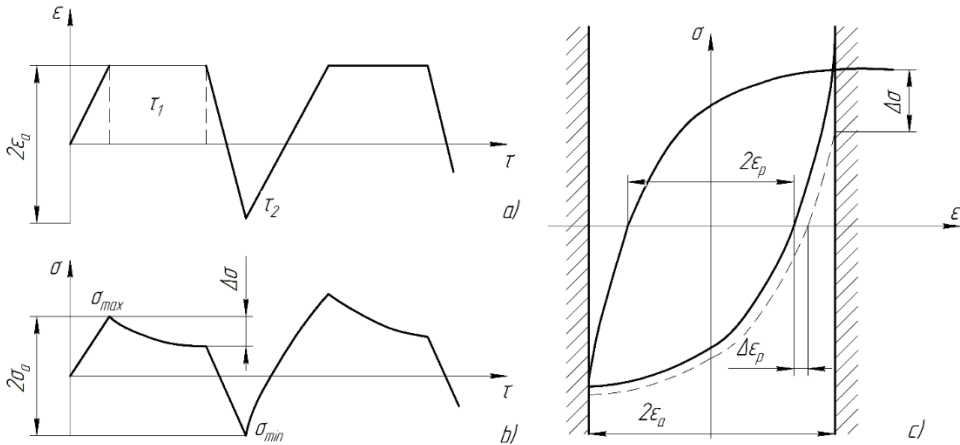

Fig. 4. The structure of the cycle (a), the scheme of stress relaxation (b) and the hysteresis loop (c) under cyclic isothermal loading with controlled deformation with holding.

In neutrons, characteristic transients are due to controlled power changes, emergency shutdown of the pump-heat exchanger loop (at which the power drops to 50% of the nominal), slow or fast emergency protection, etc. The estimated number of such cycles is chosen from 1000 to 2000. When calculating the strength, it must be assumed that with a plant resource of $\sim 1.10^{5}$ hours, the stationary mode of its operation can be violated after 100 hours. Turbines, boilers and steam pipelines of thermal power plants are characterized by daily starts and stops [16].

In accordance with the developed method, the assessment of the LR intensity of welded joints is performed based on the results of the analysis of the local fracture kinetics described using fracture diagrams. Fracture diagrams are graphical dependences of the fracture parameter (crack depth C or crack growth rate V) on the force factor (load P or stress σ) or the number of cycles N.

To assess the bearing capacity of welded joints at the stage of partial destruction (durability) from the moment of formation of macrocracks, an analysis is made of the patterns of propagation of these cracks under conditions of low-frequency low-cycle loading (LLC), taking into account the influence of the structural-phase, technological and operational factors. Based on the analysis of the partial loss of bearing capacity (considered as acceptable), the survivability and the corresponding service life of the welded elements are estimated. This makes it possible to outline ways to increase survivability and ensure the availability of determining the degree of damage during periodic inspection of units during operation.

Laboratory test methods fairly reliably assess the performance of welded joints under static and cyclic loading, taking into account the separate influence of design and technological factors. A comprehensive assessment of these factors is usually carried out based on the results of bench and operational tests. Basically, these methods are designed for testing structural elements (pressure vessels, pipe system assemblies, etc.) operating under constant internal pressure at high temperatures.

For bench testing of welded joints of steam pipes, the most widely used installations [1]: TsKTI, TsNIITMASH and VTI im. F.E. Dzerzhinsky, in which various operating conditions of stationary steam pipelines are reproduced. A diagram of one of the TsNIITMASH installations for testing full-scale pipes loaded with a bending moment by internal pressure is shown in fig. five.
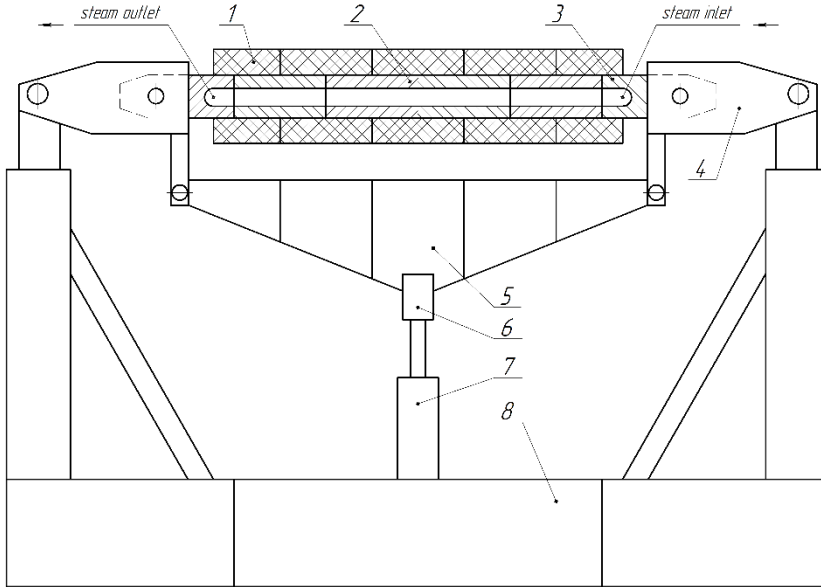

Fig. 5. TsNIITMASH IM installation for testing welded joints of steam pipes (scheme) [14]: 1 - thermal insulation; 2 - sample; 3 - capture; 4 - cheek; 5 - traverse; 6 - fork; 7 - hydraulic cylinder; 8 - frame.

Tests of pipes made of steel 12H18N12T in the static bending mode did not cause damage to the welded joints. And only under loading with a cyclic sign-variable bending moment, it was possible to estimate the tendency to LR of welded joints at 833 K.

Of particular difficulty is the creation of benches for testing models of vessels operating at high temperatures under pressure [14, 15].

Given the high cost and complexity of bench tests, they should be carried out as the final stage of laboratory research, during which the destruction mechanism has already been established and measures have been outlined to eliminate it. The purpose of bench tests is to verify the recommendations of laboratory studies, taking into account the scale factor.

3 Conclusions

1. The accumulated experimental and operational experience shows that a reasonable choice of a reliable and durable structural material, technological recommendations can be made based on the results of a comprehensive study involving a number of standard and original laboratory test methods that reproduce the operating conditions of welded joints.
2. It is shown that LRs of welded joints are formed under the combined action of static and cyclic bending loads. The theory of destruction of the HAZ metal under static loading (creep) is mainly described in the works of domestic and foreign scientists; however, the LR mechanism under conditions of high-temperature low-cycle loading has not been sufficiently studied.

3. The practical absence of laboratory methods reproducing the non-stationary loading mode of welded joints does not allow a reliable assessment of their tendency to LR.

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