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DELAYED FRACTURE RESISTANCE OF WELDED JOINTS OF ROTOR STEEL 25Kh2NMFA AFTER WELDING REHEATING

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The work is dedicated to experimental investigation of influence of repeated thermal effects under conditions of manual arc welding of hardening heat-resistant steel on delayed fracture resistance of metal in HAZ region of earlier performed passes. Applicable to different schemes of temper bead deposition using Implant method there were determined quantitative characteristics of change of delayed fracture resistance. It is shown that obtained crack resistance in welding without preheating can be compared with resistance in welding with heating. Effect of reheating on change of structural and hydrogen factor, influencing crack formation was evaluated. 22 Ref., 7 Figures.

Keywords: *hardening heat-resistant steel, welding reheating, delayed fracture, structural and hydrogen factors, Implant method, quantitative change of cracking resistance*

A classical problem of production of welded joints from hardening steels is high level of risk of cold cracks appearance in metal of heat-affected zone (HAZ) or weld. Multiple investigations showed that the main conditions of cold crack formation are generation of hardening structures in a joint zone, saturation of this zone with hydrogen (diffusion-mobile) and effect of tensile (welding) stresses due to shrinkage of metal being heated in welding and crystallized weld [1, 2]. For such types of defects following from their physical and chemical nature the next synonymous terms are also used, i.e. crack formation, related with effect of hydrogen or hydrogen-assisted cracking, hydrogen-induced cracking, delayed cracking [3, 4] or delayed fracture [5].

Cracking resistance is regulated by technological conditions of welding. For example, there is favorable fact in increase of metal cooling duration after completion of austenite transformation with formation of martensite that is related with effect of «self-tempering of martensite». Partial tempering of hardening structure will rise with increase of transformation temperature interval [3, 6, 7]. Temperatures below the transformation completion ones, including intervals of low-temperature matensite decay (around 160–70 °C [8–10]), provide tempering effect. In addition to redistribution of carbon in the process of such low-temperature tempering there also will be thermally activated diffusion scattering of hydrogen and decrease of its concentration of a dangerous zone. In this connection, the main technological methods in welding of hardening steels are preliminary (concurrent) heating and post weld heating-through of the welded joint (cooling down) at temperature close to heating temperature [11]. However, such operation can be difficult for performance and rise energy expenses of welding works.

Welding heating results in accumulation of heat and creation of effect similar to concurrent heating [12]. Continuous deposition of beads allows reaching significant decrease of metal cooling rate in the zone of welding. Work [13] shows that deposition on steel surface of an area in several passes being performed without breaks was accompanied by two times decrease of HAZ metal cooling rate in comparison with performance of single bead using the same mode (manual arc welding by 3 mm diameter electrodes, I_w = 120–130 A, U_a = 24 V, preheating 250 °C: $w_{6/5}$ in deposition of area of 20×60 mm — 3.3 °C/s, in performance of single bead — 6.7 °C/s). The positive moment in such an approach is possibility of performance of welding operations in repair of products of hardening steels without heating, as, for example, in process of «transverse hill» welding [14]. However, in separate cases uncontrolled increase of temperature of metal of welded joint due to heat accumulation can result in undesirable structural changes and deterioration of mechanical properties. In such cases it is necessary to limit the temperature in the joint zone and provide cooling rates eliminating formation of the structures having negative effect on properties of separate areas of the welded joints (for example, residual austenite in bainite-martensite structure, upper bainite) [12, 15, 16].

In welding of modern power machine building steels of bainite and martensite classes the temperature between the passes is limited at approximately 250–300 °C level [17–20]. At that a procedure of multipass welding with small-section beads is recommended. Function of such a method, first of all, lies in achievement of fine-grain structure in overheating area of HAZ metal resulted from initially performed passes due to next application of temperatures of normalizing interval as well as partial tempering of quenched areas in performance of next passes. The joints with such structure are less susceptible to cracks in high tempering after welding. Applicable to the joints of martensite chromium steels, which are characterized with reduced weld metal impact toughness, a multi-pass welding with thin beads allows rising impact energy. Improvement of toughness is related with obtaining finer and disoriented crystallization structure and partial metal tempering in earlier performed layers; finer the beads the higher the result is. As a variant of welding with deposition of temper beads it was recommended a method using grinding of initially performed beads to the middle of their thickness for better heating of metal in this zone; however, the method is difficult and requires special training of welders, rises cost and time of work performance that limits its application [22].

Welding reheating of metal in the area of earlier performed layers, in addition to structure refinement and partial tempering also promotes increase of cold crack resistance [22]. However, how big, in quantitative concept, is the growth of technological strength under conditions of multipass welding shall be specified.

The aim of work is the quantitative evaluation of change of resistance of HAZ metal of hardening steels to delayed fracture under effect of welding reheating.

Rotor steel of the next alloying system, wt.% 0.23–0.27 C; 1.8–2.2 Cr; 1.3–1.6 Ni; 0.4–0.6 Mo; 0.05 V was used in the investigations as a test material. The values of carbon equivalent P_{cm} 0.4–0.51 wt.% (calculated on Ito and Bessyo equation) [4] corresponds to change of alloying elements within the limits of steel content. The tests were carried out on known method Implant [3]: samples of investigated steel of 8 mm diameter with spiral stress concentrator in a working part in form of 0.5 mm depth V-groove with expansion angle 40° and rounding radius in the tip 1 mm were used. Implant samples were welded to base plate (of steel 20 of 16 mm thickness) by manual arc welding by coated electrodes of 3.2 mm diameter using

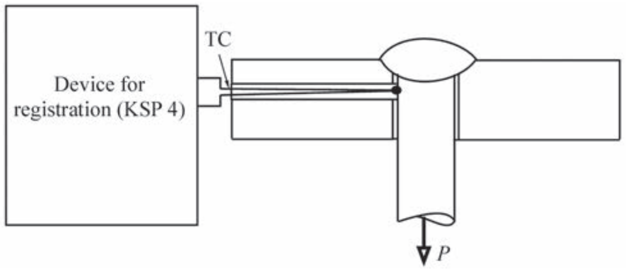

Figure 1. Scheme of measurement of temperature in Implant sample

alloying system of deposited metal 0.07C2CrMoV. After electrodes baking at 400–450 °C, 2 h, content of diffusion hydrogen in the deposited metal $[H]_{dif}$ (alcoholic analysis [11]) made approximately 0.96 cm^3/ 100 g of Me. Control of temperature in HAZ of the samples (in welding with heating and at measurement of thermal cycles) was carried out using chromel-alumel thermocouple (TC) in a ceramic insulating shell, passed through a hole drilled from the edge of the base plate at around 4 mm depth in parallel with its surface (Figure 1). TC were welded to the samples with the help of capacitor-discharge machine, another end was connected to recording potentiometer. Application of load to tested joints was performed after cooling of metal in HAZ of the samples to room temperature, i.e. the joints were cooled under natural conditions to 100 °C, below, for making it faster, with blowing by air. A criterion of cracking resistance was a critical stress σ_{cr} promoting delayed fracture. Test joints, which withstood the load without failure for not less than 24 h are considered to be not susceptible to delayed fracture. Measurements of hardness were carried out by Vickers method at 5 kg loading.

In welding of the samples with the plate and in deposition of new beads the next mode of welding (if not indicated additionally) was used: I_w = 95–100 A, U_a = 22 V, $v \approx 0.194$ cm/s (7 m/h), heat input $q/v \approx$ ≈ 8.5–9.0 kJ/cm (at calculated efficiency of arc η = = 0.8). The following schemes of welding of test joints with simple (without grinding) bead and with grinding of the first bead to the middle of thickness (half bead) (Figure 2) were used:

- welding with one bead («1 bead» – basic variant of comparison);
- welding in two layers with deposition of one bead on the first (1 + 1);
- welding in two layers with deposition of two beads in the second layer on one bead in the first layer (1 + 2);
- welding in three layers with deposition on the first single bead of two beads in the second and third layers (1 + 2 + 2) as well as in three layers using 1 + 2 + 5 scheme;
- welding with half bead (1/2) in the first layer with deposition in the second layer of one bead (1/2 + + 1) and two beads (1/2 + 2), grinding of the first bead was carried out on joint cooling stage using manual grinding machine.

Deposition of new beads on initial weld was carried out after decrease of metal temperature of the first bead to 100 °C, except for 1 + 2 + 5 variant (Figure 3, where at measurement of thermal cycles on scheme from Figure 1 the maximum temperature of heating does not exceed approximately 600 °C due to removal of place of TC welding to the plate surface for a value of around 4 mm that exceeded real width of harden-

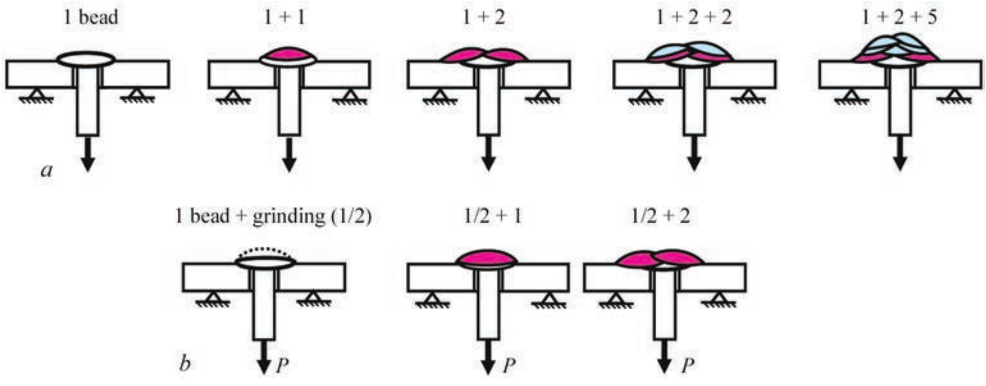

Figure 2. Technological schemes of welding of test joints: *a* — welding with simple beads; *b* — welding with first bead grinding

ing area). It should be noted that such position of TC was acceptable for control of approximate temperature in the sample before deposition of the next beads. In the latter variant, deposition of the new beads was accompanied with gradual increase of temperature in the joint that to some extent reconstruct the conditions similar to «transverse hill» welding.

The results of tests of the welded joints produced with preheating as well as without heating (Figure 4) show that reheating of HAZ metal in the area of the first bead results in increase of cold cracking resistance. Effect of deposition of two or more beads on the first weld (schemes 1 + 2, 1 + 2 + 2, etc.) is highly obvious. Deposition of only one bead (for example, schemes 1 + 1 and 1/2 + 1 (Figure 4, *a*, *b*) in welding without heating, and 1 + 1 in welding with heating (Figure 4, *c*) is less effective.

Efficiency of reheating, influencing the technological strength, can be judged based on the results of measurements of hardness in hardening area in the first bead by the example of 1 + 2 scheme, i.e. in the initial state the maximum value of hardness made *HV* 460, after deposition of one bead — *HV* 430, after deposition of the second bead — *HV* 360.

Increase of welding current in performance of temper beads also had positive effect on rise of cracking resistance due to larger heat input into the welded joint (see test results in welding on 1/2 + 2 scheme with I_w = 130 A in comparison with the same variant performed on 100 A current, which was used in all experiments (Figure 4, *b*). However, as it was mentioned above, it is reasonable to limit growth of current.

Quantitative rise of cracking resistance can be evaluated by relationship of σ_{cr} values for one of the technological variants to σ_{cr} of initial variant – welding with single bead. Thus, for example, (see Figure 4, *a*) in welding on 1 + 2, 1 + 2 + 2 and 1 + 2 + + 5 schemes the delayed fracture resistance increased approximately 2.3 and 4.7 times, respectively.

As can be seen from Figure 5, reheating in welding without preheating on schemes 1 + 2 + 2 and 1 + 2 + 5 allows reaching cracking resistance, close to welding with heating to 220 and 250 °C order. Reheating on scheme 1 + 2 creates an effect close to welding with heating around 150 °C. The effect becomes more significant when using preheating.

It was experimentally determined that efficiency of tempering influence depends on welding modes and level of overlapping of the first and deposited beads. As an example, Figure 6 shows the schemes illustrating distribution of the maximum temperatures in the near-weld zone in deposition of a new bead on the earlier performed. The test material was martensite steel 0.1C9CrMoVNb of 14 mm thickness, depo-

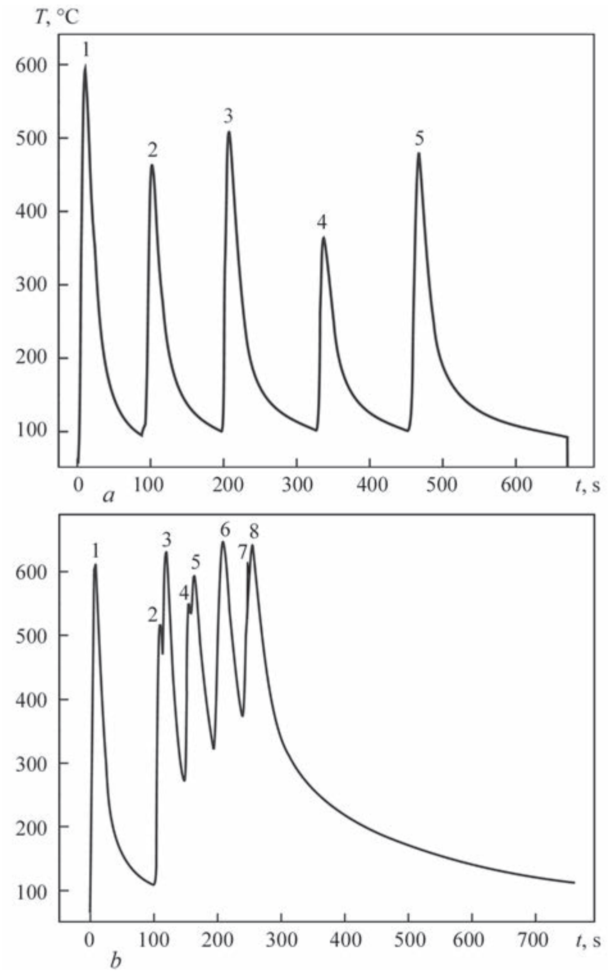

Figure 3. Thermal cycles in place of TC welding to sample in performance of test joints on 1 + 2 + 2 beads scheme (*a*) and on 1 + 2 + 5 beads scheme using principle of «transverse hill» welding (*b*)

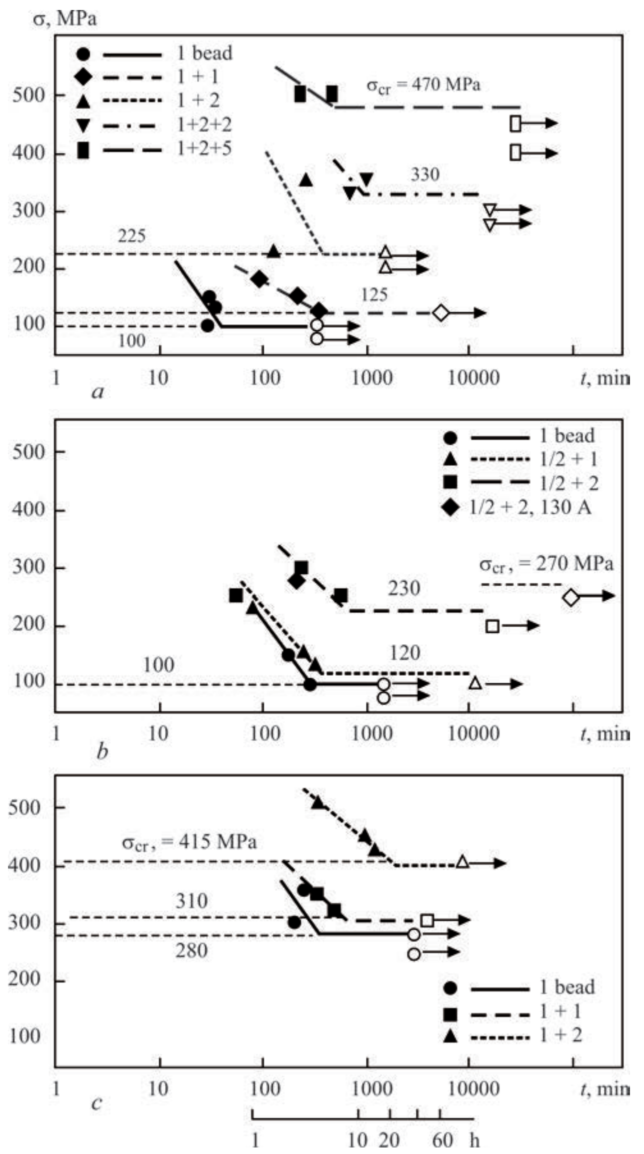

Figure 4. Results of tests: *a* — welding without heating with simple bead; *b* — welding without heating with grinding of the first bead for 1/2 of its thickness; *c* — welding with 200 °C preheating (dark and light marks — joints with and without fractures)

sition of beads was carried out using MAW with electrodes of similar alloying system of 3.2 mm diameter at two modes with 200 °C heating. There were used the results of determination of maximum heating temperatures at different depth from steel surface in deposition of the single bead as well as real dimensions of bead and hardening area, measured in cross-sections. In this case, record of thermal cycles was carried out simultaneous with two TC, passed through from below into the holes, drilled across the plate thickness to different distance from assumed fusion line and located with displacement one from another. Bead-on-plate deposition was carried out along the line of TC location. As it is shown on Figure 6, *a*, *b*, deposition of the second bead on the first creates a new hardening area of metal (in HAZ 2) being heated over A_{c1}–A_{c3} interval temperature. Temperatures below A_{c1} promote partial tempering of metal, hardened in per-

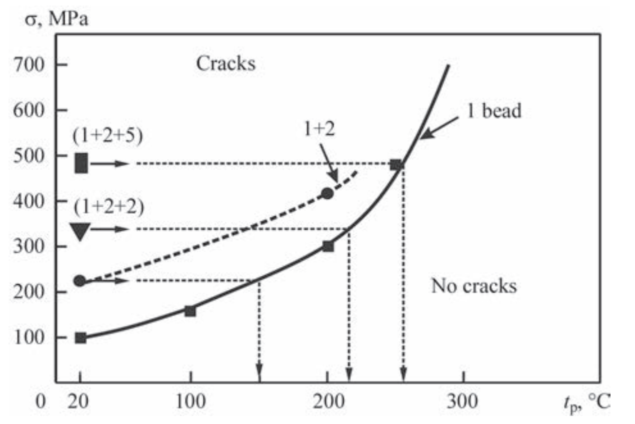

Figure 5. Comparison of the test results in welding with reheating without preheating (t_p = 20 °C) and welding with preheating (t_p — temperature of preheating)

formance of the first bead. Such a situation will take place in deposition of the second bead in the zenith of the first (on scheme 1 + 1). In this case tempering will affect the biggest part of hardened metal in HAZ 1 in the first bead. When grinding the first bead to half thickness (scheme 1/2 + 1, Figure 6, *c*) area of hardening of the second bead will «make layers» on the bigger part of hardened metal from the first bead (HAZ 1). Lower part of hardened metal in HAZ 1 will be subjected to tempering. Probably, this is the reason why insufficient tempering effect had small influence on σ_{cr} increase on Figure 4, *b*. Similar situation with overlaying of the second and first hardening areas can take place in welding with simple bead, but at deposition of the second bead at higher current (Figure 6, *d*). In this case, a favorable factor, from point of view of heat effect on hardened metal, is input of larger amount of heat into the welding zone.

Also it was interesting to evaluate the effect of reheating on amount of diffusion hydrogen remaining in the metal. The pencil probes [11], deposited with TML-5 electrodes (alloying of 06Kh1M type) in a condition after long-term storage without baking, were used in the experiments carried for this purpose. The probes after deposition were cooled in water for registration of initial concentration of diffusion hydrogen, then their reheating using gas flame and alcohol analysis were carried out. Temperature was controlled by pyrometer. In high-temperature heating (500 °C and more) immediately after reaching the necessary temperature the metal was cooled in water, in heating to 300 °C it was cooled in air to 100 °C and then in water. At combined cycles the initial probe was heated to higher temperature, firstly cooled in air to approximately 100 °C, then in water, after that the probe was heated to the next temperature with the same gradual cooling (air/water). At 200 °C longer furnace heating was also carried out for simulation of the conditions of postweld cooling down. Using TC, fastened in the middle of thickness of the pencil probe, there was car-

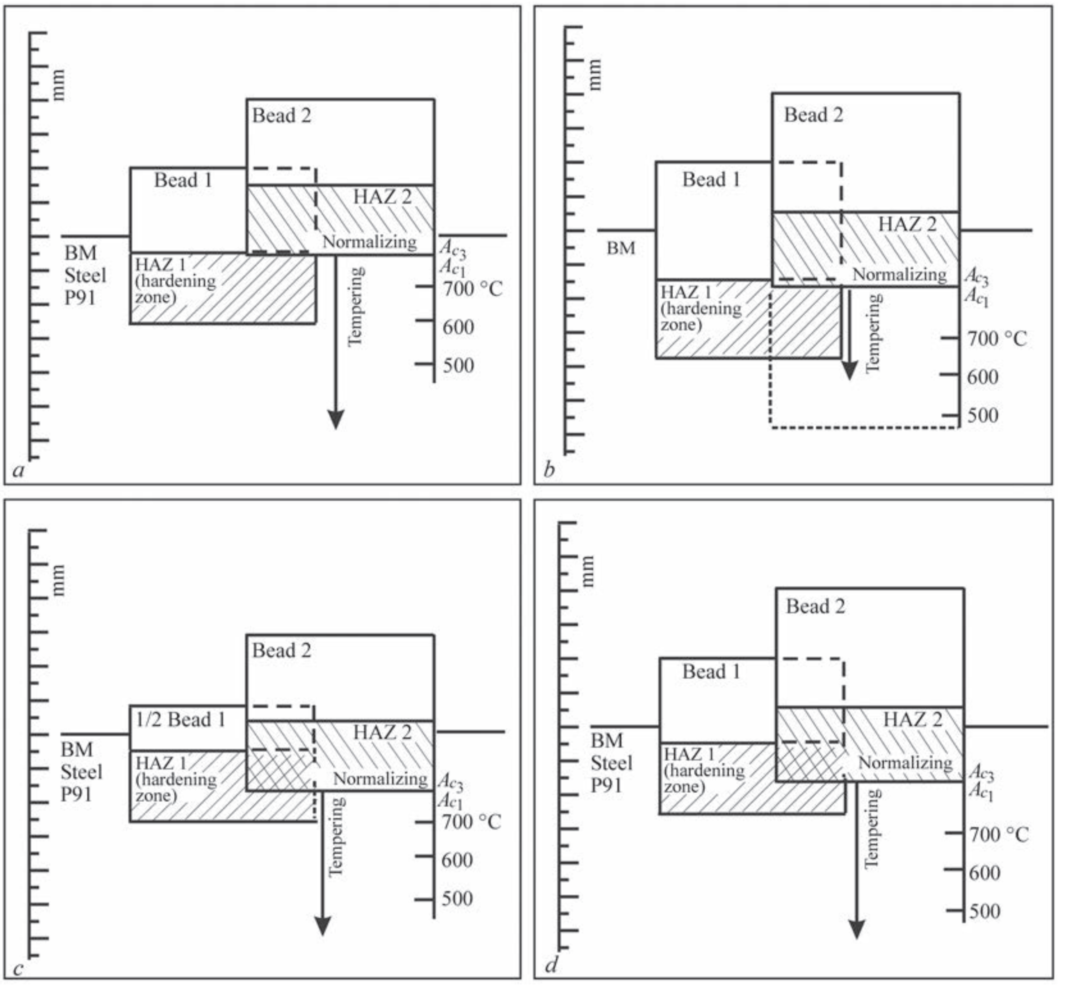

Figure 6. Distribution of temperatures in near-weld zone in performance of two beads (*a*, *b* — conventional welding: *a* — I_w = 100 A, q/v = 8.3 kJ/cm; *b* — I_w = 160 A, q/v = 11.38 kJ/cm; *c* — welding with first bead grinding, I_w = 100 A; *d* — welding with simple bead, first bead is made on current I_w = 100 A; second — 160 A)

ried out an evaluation of time of gas heating to 1000, 500, 300, 200 and 100 °C temperatures, which made, respectively, 15; 5.5; 2.9; 2 and 1.3 s. Duration of probe cooling in smooth air in 300–100, 200–100 °C intervals made 300 and 200 s. At the same time HAZ of Implant samples demonstrates quicker drop of the temperature in the indicated intervals, on average 2.3 and 3 times more, nevertheless the durations of heating to 500 °C were close. Considering the available differences in the thermal cycles with real welded samples, it can be assumed that the experimental approach allows only tracing the tendency of change of diffusion hydrogen content in the reheatings.

Effect of reheating on emission of diffusion hydrogen $[H]_{dif}$, cm^3/100 g Me) from deposited metal (pencil probes)

initial state (after deposition)	7.55–5.37
1000 °C	~0.2
700 °C	~0.2
500 °C	~0.7
300 °C	0.96
200 °C	2.26
500 °C + 300 °C	~0.2
300 °C + 200 °C	0.26
200 °C, 20 min	0

The results showed that at short-term high-temperature effect the concentration of diffusion hydrogen reduces by order and more. Heating to 200–300 °C results in 2–3 times decrease of $[H]_{dif}$. At combined cycles the concentration $[H]_{dif}$ also reduces for more than order. Cooling down is the most efficient; similar effect will, probably, take place in welding with preheating.

Summing up the set forth material, it is noted that cold cracks are the consequence of critical combination of three factors in their specific quantitative expression (Figure 7, *a*): welding stresses, in MPa, created by shrinkage, are determined with the help of special procedures, under Implant test conditions they are set by tension force of the sample in the joint; condition of hardening structure can be evaluated by hardness value, hydrogen factor is usually evaluated on amount of diffusion hydrogen in the probes of the deposited metal or in the samples of the welded joint. Weakening of effect of one or several of them results in appearance of «reserve» in cracking resistance (that, as an example, on scheme of Figure 7, *b* is symbolized by white sector as a result of weakening of a negative role of the structural factor). High tem-

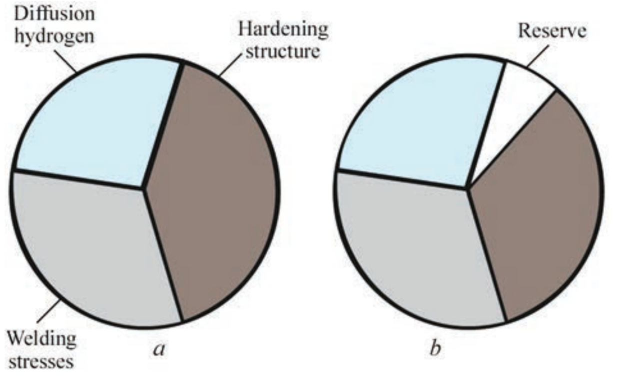

Figure 7. Factors, promoting delayed fracture of welded joints (*a* — critical state; *b* — state with reserve of cracking resistance)

pering of welded joints can be assumed an extreme measure for reaching high crack resistance that leads to relaxation of the residual stresses, maximum decrease of hydrogen content and transfer of hardened metal in a state close to equilibrium one, being characterized with improved ductility. As it is shown in present work, reheating of metal in the area of earlier performed passes develops a positive effect under conditions of multipass welding. The consequence is improvement of structural state of metal and, probably, reduction to some level of diffusion hydrogen concentration in the hardening zone in the area of earlier performed passes as a result of its diffusion redistribution and scattering.

Conclusions

1. By the example of tests on Implant method using the samples of hardening heat-resistant 25Kh2NMFA steel it is shown that under conditions of manual arc welding with coated electrodes welding reheating allows significantly increasing the delayed fracture resistance of the hardened metal in the area of earlier made passes. Effect is revealed in welding without preheating as well as with heating.

It was experimentally demonstrated that the critical stresses promoting crack formation depending on number of cycles of repeated thermal effect at deposition of new layers of tempering beads can be increased approximately 2–4 times. At that welding without preheating can provide cracking resistance equivalent to resistance in welding with heating to 150–250 °C.

2. The results of carried experiments allow assuming that welding reheating in multipass welding simultaneously effects two factors influencing delayed fracture, namely structural, creating partial tempering of hardened layers in the area of earlier performed passes, and hydrogen, promoting reduction of diffusion hydrogen concentration in them.

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