STRUCTURE AND PROPERTIES OF WELDED JOINTS OF 15Kh1M1FL STEEL AT REPAIR OF CASTING DEFECTS BY TRANSVERSE HILL METHOD

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Welding up casting defects in power equipment components from thermally stable steels involves the risk of brittle fracture as a result of increased volumetric stress state. Studying the influence of technological measures for controlling the thermodeformational welding cycle in order to obtain a favourable structure and properties in welded joints, is of interest. In this work the influence of transverse «hill» welding without preheating or heat treatment on mechanical properties and structure of various zones of welded joints from 15Kh1M1FL steel was studied, and these values were compared with the properties of welded joints after welding with preheating by the standard technology. It is established that after transverse «hill» welding upper granular bainite structure forms in the high-temperature zone of HAZ metal and in the weld metal, which is characterized by an optimum set of mechanical properties, namely a combination of high strength with high enough impact toughness values. It is shown that cold cracking resistance after transverse «hill» welding without preheating is higher than after welding by the standard technology. 12 Ref., 6 Figures.

Keywords: *steel, welding, preheating, heat treatment, granular bainite, subgranular structure, properties*

In welding up casting defects in large-sized thick-walled structures of power equipment from low-alloyed thermally stable steels the main risk is quenching structure formation in the high-temperature zone of HAZ metal, that does not eliminate cold cracking. Specific difficulties arise in repair of defects in massive structures from 15Kh1M1FL steel (for instance, turbine casing of about 100 t weight).

At solidification the deposit metal stays within rigid contours formed at defect cutting-out, that impairs the conditions for its plastic flow. The situation is further complicated when the volume of cut-out areas for welding-up reaches 1000 cm^3 and more. Lowering of deformational ability of solidified metal leads to increase of volumetric stress state and creates the conditions for brittle fracture of structures in service. To lower the stressed state of metal in the area of defect welding-up, in keeping with the normative documents, it is necessary to ensure performance of additional technological operations (local preheating and concurrent heating and postweld high tempering).

On the other hand, a number of studies [1–4] give investigation results confirming the impracticality and even risk of conducting high preheating in welding of hardening steels. At present technological solutions for welding large-sized structures from hardening steels without preheating or heat treatment, ensuring technological strength, have been studied and are recommended.

Analysis of currently available welding processes showed that the most acceptable one for repair welding of hardening steels without preheating is the transverse «hill» welding (THW) [4, 5], which ensures self-preheating and self-heat treatment from welding heat. The method is based on controlling the heat input by deposited metal layers filling the groove that, in its turn, allows influencing the thermodeformational cycle through periodical heat impact and formation of a certain type of structures. Work [4] specifies the technology of repair of large-sized massive structures by THW from readily weldable steels without preheating or heat treatment. This method is not well enough studied in the case of thermally stable hardening steels.

This work is devoted to substantiation of THW applicability in repair of defects without preheating of massive structures from 15Kh1M1FL steel.

Material and experimental procedure. Structure and property studies were performed on cast billets from 15Kh1M1FL steel of 120 mm diameter and 300 mm length, heat-treated in standard technology mode (normalizing at 970–1000 °C, tempering at 720–750 °C). In the billet middle part longitudinal recesses of 60 mm depth, 50 mm width and 270 mm length were mechanically cut out for welding-up. Welding-up was performed by electric-arc process with 4 mm electrodes of E-09Kh1M1F type of TML-ZU grade in the following mode: I_w = 160–170 A, U_a = 26 V. Here one batch of the billets was welded according to standard technology — by step-back welding (SBW) with preheating up to 200–250 °C, the other batch was TH-welded without preheating by layer-by-layer filling of the groove.

In THW-up recesses angle of billet inclination relative to the horizontal plane in the range of 25–30° was ensured [6]. HAZ metal temperature was measured with thermocouples, which were caulked-in in different points of the welded joint at 1, 2, 3, 4 and 7 mm distance from the groove edge. The readings were recorded in EPP-09M3 instrument. It is established that the width of metal interlayer heated above 850 °C is in the range of 1 mm. At 2–3 mm distance from the fusion line, heating temperature reached 630–660 °C.

After welding part of the billets were tempered together with the casing parts at 720–750 °C with 3 h soaking.

Macroanalysis and hardness measurement were performed on 13–14 mm thick templates cut out in the transverse direction relative to weld axis. *HV*5 hardness was measured on three levels by weld height (10, 25 and 40 mm). After that samples were cut out of the templates to determine mechanical properties in different joint zones. Impact toughness was determined on standard samples with notches in the base metal, in the HAZ high-temperature zone and in the weld metal at the following temperatures: *KCU* — from –20 up to 350 °C, *KCV* — from –60 up to 100 °C.

Microstructure was studied by the method of optical and electron microscopy. In order to detect grain boundaries in the HAZ and deposited metal, microsection etching was performed in oversaturated water solution of picric acid with SA addition. Grain size was determined by method of random secants.

Investigation results. Macroanalysis showed that HAZ width was equal to 2.5–3.8 mm, no macrodefects were found, and weld metal was highly sound.

Nature of hardness variation by zones on all the levels is practically the same. Figure 1 shows the graphs of its average value variation on one level of 25 mm. It is established that after application of both welding techniques without tempering hardness of weld metal and high-temperature zone of HAZ metal is higher than that of the base metal.

So, in the joint made by SBW with preheating, the highest hardness (*HV* 370) is noted in weld metal near the fusion line (Figure 1, *a*). After THW hardness of all the zones is lower by approximately *HV* 50.

Comparison of obtained hardness values with hardness data and their respective structural diagrams of anisothermal decomposition of austenite in 15Kh1MFL steel [6] shows that at cooling in higher hardness zones under the conditions of SBW with preheating first austenite transformation into lower bainite takes place, and then martensite forms with preservation of residual austenite (about 12 %). At THW without preheating upper bainite (up to 70 %) with martensite and residual austenite forms that is not contradictory to works [7, 8].

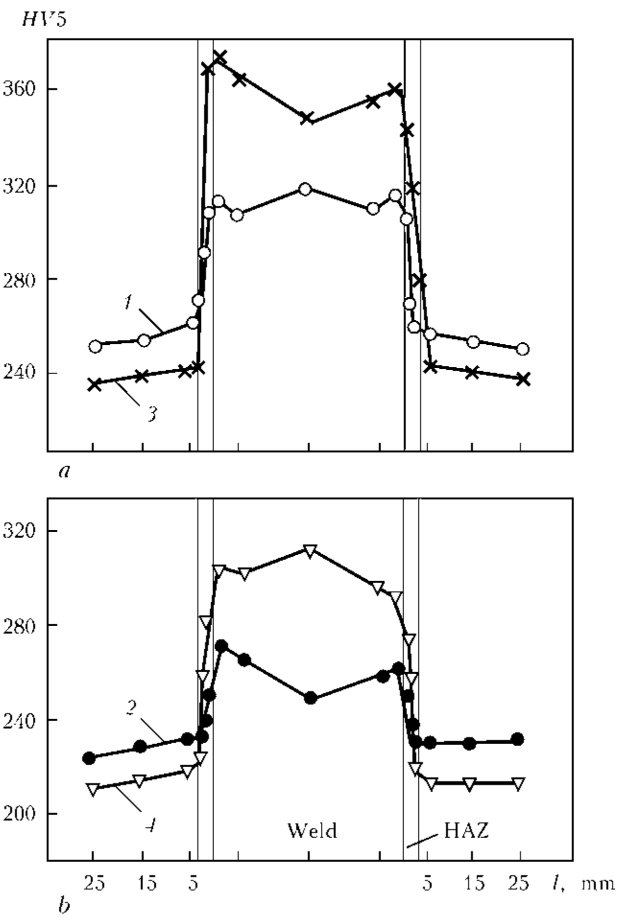

Figure 1. Variation of hardness in 15Kh1MFL steel welded joints: *a* — without postweld heat treatment; *b* — with postweld heat treatment; *1*, *2* — THW without preheating; *3*, *4* — SBW with preheating

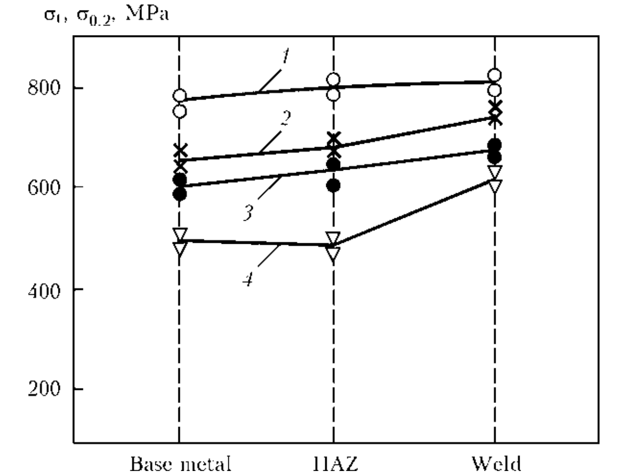

Figure 2. Change of strength properties of different zones in 15Kh1M1FL steel welded joints after THW: *1*, *3* — σ_t and $\sigma_{0.2}$ without postweld heat treatment; *2*, *4* — σ_t and $\sigma_{0.2}$ with high tempering after welding, respectively

Naturally, increase of self-preheating effect in THW promotes lowering of cooling rate, that leads to formation of upper bainite additionally prone to self-tempering, and lowers the risk of formation of structures leading to embrittlement of metal of this zone.

High tempering lowers the hardness of all zones of the welded joint (see Figure 1). However, it remains higher in the HAZ and in the weld metal near the fusion boundary (particularly after SBW). This is related to thermodeformational impact on grain morphology and structure in the HAZ and delayed decomposition of non-equilibrium structure. In the weld metal near the fusion line preservation of increased hardness after tempering can be also due to microchemical inhomogeneity, resulting from diffusion processes on the weld pool liquid metal–base metal boundary. Liquid metal volumes near the molten edge are more saturated with alloying elements, carbon and impurities, that delays solid solution decomposition and increases the number of precipitating carbide and intermetallic phases, thus increasing the hardness.

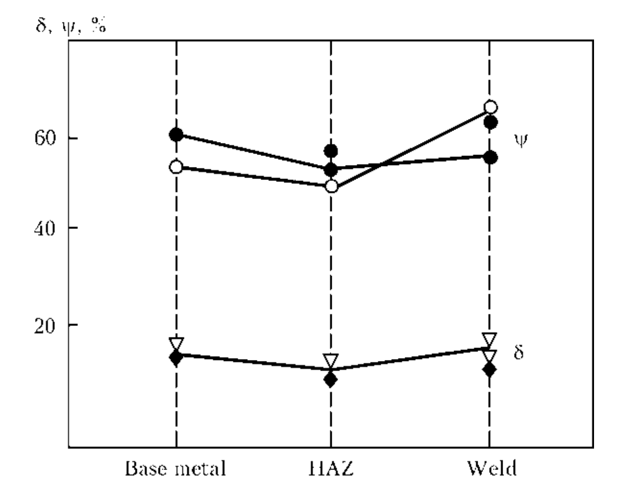

Figure 3. Variation of plastic properties in different zones of 15Kh1M1FL steel welded joints after THW without heat treatment (*light symbols*) and with high tempering (*dark*)

It is established that THW ensures high values of strength in all the zones (Figure 2) that satisfies the requirements of the norms for metal of thick-walled cast structures from 15Kh1M1FL steel. Level of σ_t values is practically the same, despite hardness increase in the HAZ and weld metal; $\sigma_{0.2}$ level in the HAZ and weld metal rises somewhat, compared to base metal. After tempering σ_t and $\sigma_{0.2}$ values decrease in all the zones, but $\sigma_{0.2}$ in weld metal remains higher.

After THW relative elongation δ is practically the same (18–20 %) in all the zones, both in the case without tempering, and with postweld tempering (Figure 3). Reduction in area ψ has high values for all the zones (more than 50 %), the highest ψ values are found in weld metal after welding without tempering (68 %).

Results of impact toughness *KCU* testing showed that abrupt lowering of its values occurs in all the zones at 20 °C (both without tempering, and with tempering after welding).

Comparative analysis of changes in mechanical properties, found in high-temperature zone of HAZ metal after both the welding methods (both with and without tempering), shows (Figure 4) that after THW without preheating strength

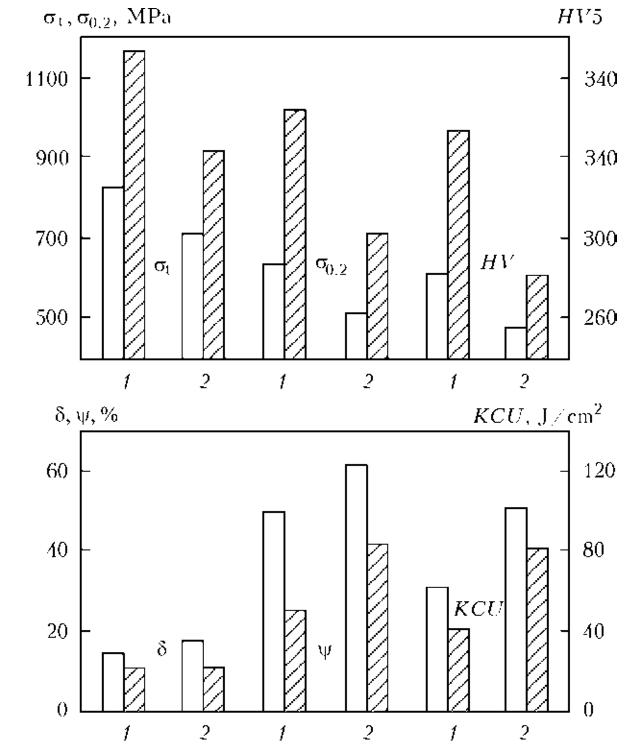

Figure 4. Mechanical properties of high-temperature zone of HAZ metal after welding of 15Kh1M1FL steel by different methods: *light diagrams* — THW without preheating; *hatched* — SBW with preheating up to 200 °C; *1* — without postweld heat treatment; *2* — with postweld high tempering

properties are lower, and ductile characteristics and *KCU* are higher than after SBW with preheating.

Brittle fracture susceptibility in high-temperature zone of HAZ metal was evaluated at determination of impact toughness of samples with a sharp notch (*KCV*). It follows from Figure 5 that after THW *KCV* values are higher at all testing temperatures. Here for both welding methods at testing from −60 up to 20 °C *KCV* is higher in the case, if no postweld tempering was performed that is attributable to disperse phase precipitation and restructuring of dislocation structure of the grains, associated with the processes of recovery and polygonization. The same in both welding methods lowering of *KCV* at temperature below −20 °C is noted that points to the fact that critical brittleness temperature does not depend on performance of additional technological operations (preheating and postweld tempering).

Microanalysis showed that in THW without preheating a structure consisting of upper granular bainite forms in the HAZ and weld metal (Figure 6, *a*). A weakly manifested transition to the structure of HAZ high-temperature zone is noted. At 1.5–2.0 mm distance from the boundary (Figure 6, *b*), HAZ metal microstructure consists of fine grains of hypoeutectoid ferrite and granular bainite. In the HAZ zone at about 3 mm distance from the fusion line (Figure 6, *c*) incomplete phase recrystallization proceeded in the metal. Here coarse formations of excess ferrite did not undergo any phase recrystallization in welding. They, however, are fragmented into individual fine subgrains that is due to the processes of dynamic recrystallization and polygonization («in situ»). The above processes proceed under the conditions of plastic deformations and high heating temperatures, accompanying the entire thermal cycle of layer-by-layer filling of the groove in welding. The width of plastic deformation zone is 2 to 3 times greater than that of

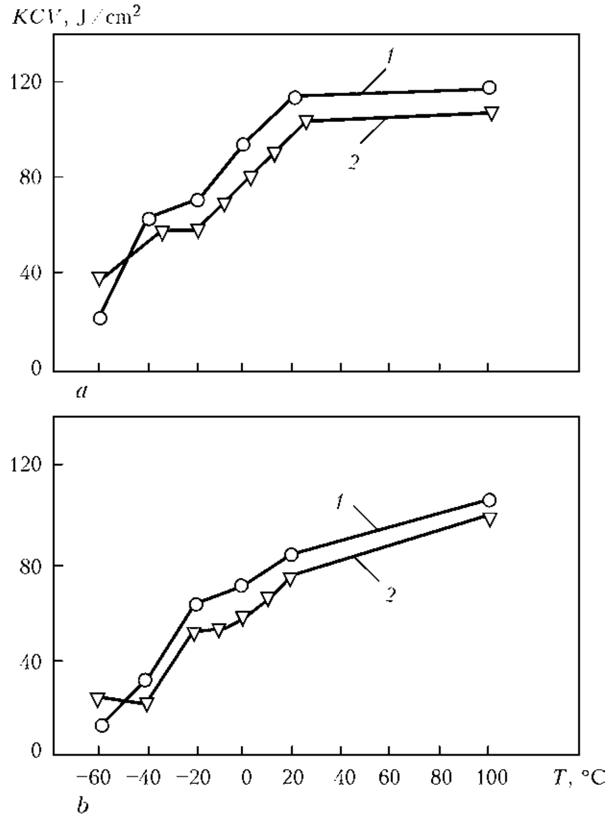

Figure 5. Influence of test temperature on *KCV* impact toughness of metal in HAZ high-temperature zone after welding of 15Kh1M1FL steel by THW without preheating (*1*) and by SBW with preheating up to 200 °C (*2*): *a* — without postweld heat treatment; *b* — with postweld high tempering

the HAZ. Distribution of plastic deformation over the welded joint cross-section occurs non-uniformly.

In welded joints of thick-walled structures from low-alloyed steels plastic deformation can reach 4 to 5 % and more [1, 9, 10]. Under such conditions polygonization and recrystallization occur simultaneously, competing with each other [11, 12], and thus creating a ramified network of sub-boundaries in the deformed grains. When studying the grain structure in welded joints made by THW, it was found that near the fusion zone some grains have serrated boundaries and

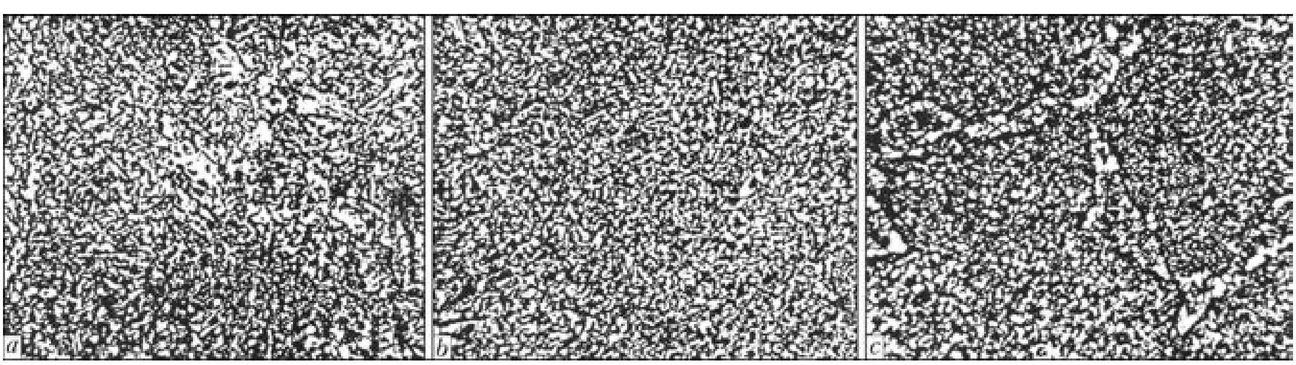

Figure 6. Microstructure (×500) of 15Kh1M1FL steel welded joint made by THW without preheating and postweld heat treatment: *a* — fusion zone; *b* — HAZ at approximately 2 mm distance from the fusion line; *c* — same, about 3 mm

deformed shape that results from plastic deformation, and in the HAZ high-temperature zone and in the weld the metal is fine-grained. So, in the HAZ $\overline{D}_{cond} \approx 0.0192$ mm (7–8 grain size number), and in weld metal $\overline{D}_{cond} \approx 0.0186$ mm (number 8–9). However, grain structure is heterogeneous, finer grains, corresponding approximately to number 13, are located along the boundaries of the main grains and inside them, that is a confirmation of the start of development of dynamic recrystallization processes. Fine-grained structure with a ramified network of subgrains ensures a high set of mechanical properties in the HAZ high-temperature zone and increases brittle fracture resistance.

Conclusions

1. In welded joints of 15Kh1M1FL steel made by THW and SBW, hardness is higher in the HAZ high-temperature zone and weld metal than in the base metal. Postweld tempering reduces the difference in hardness. However, a complete equalizing of its values does not occur, that is related to the processes of thermodeformational strengthening in the HAZ and weld and slowing down of non-equilibrium structure decomposition.

2. THW ensuring self-heating and self-heat treatment leads to formation of upper granular bainite structure in the HAZ and weld metal, which provides an optimum combination of mechanical properties and improves brittle fracture resistance.

3. *KCV* impact toughness of HAZ high-temperature zone after both the welding methods is higher in welded joints not subjected to high tempering, in the test temperature range from −60 up to 20 °C. At test temperature increase up to 100 °C, this difference is leveled off. Both the welding methods are characterized by the same value of critical temperature (−20 °C), which does not change after high tempering. Therefore, the position of cold shortness threshold depends predominantly on grain morphology formation under the conditions of thermodeformational welding cycle.

4. THW of 15Kh1M1FL steel without preheating ensures high values of mechanical properties of the joints, satisfying the requirements specified in the normative-technical documentation, that forms the basis for commercial application of this process in welding-up defects in casings of turbines and steam fittings.

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