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Relationship between Structure and Crack Resistance of Welded Joints Made without Heating and Subsequent Heat Treatment

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To estimate the crack resistance of welded joints in the brittle-viscous transition region, performed by two variants of transverse hill welding differ in heat input, the impact strength in the certain temperature range and the nature of fracture during shock bending are studied, as well as the temperature of the transition to a brittle state and the structure of the welded joint zones are determined. As found, in the heat affected zone of a welded joint made with less heat input, a higher impact strength in the brittle-viscous transition region is achieved, which is due to the formation of a favourable granular bainite structure in this zone.

Key words: heat-resistant steel, impact strength, transverse hill welding, crack resistance, bainite.

Для оцінки тріщиностійкості зварних з'єднань в області крихко-в'язкого переходу, виконаних за двома варіантами зварювання поперечною гіркою, що відрізняються тепловкладенням, досліджено ударну в'язкість в певному інтервалі температур, характер руйнування за ударного перегину, визначено температуру переходу в крихкий стан, вивчено структуру зон зварного з'єднання. Встановлено, що в зоні термічного впливу зварного з'єднання, виконаного з меншим тепловкладенням, досягається більш висока ударна в'язкість в області крихко-в'язкого переходу, що зумовле-

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но формуванням у цій зоні сприятливої структури зернистого бейніту.

Ключові слова: теплотривка сталь, ударний перегин, зварювання поперечною гіркою, тріщиностійкість, бейніт.

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1. INTRODUCTION

The reliability of welded joints of chromium-molybdenum-vanadium steels during operation is determined by a combination of strength, ductility and crack resistance [1–3]. The study of crack resistance is of particular importance for finding the best technological options for repair welding, both in the manufacture of castings and in the course of a turnaround time during the operation of massive cast parts. The structure formation during welding significantly affects the crack resistance characteristics of welded joints [4–6].

However, the question of the effect of structure on the level of crack resistance characteristics depending on the parameters of the welding process has not been studied enough. To determine the critical temperature of brittleness, above which the absence of brittle cracks is guaranteed, a number of criteria have been proposed [4, 7–9]: by impact strength, (International Institute of Welding), 0.5 of the maximum value obtained when determining the dependence of toughness on temperature, according to the results of studying the viscous component in a kink (0, 50, 100%) according to GOST 4543, by the magnitude of the crack development work.

Therefore, for the practice of assessing the quality of welded joints, it is advisable to study the relationship between the structure of welded joints made according to various technological options and crack resistance with the selection and determination of quantitative quality criteria in the field of brittle-viscous transition, which is the purpose of this work.

2. EXPERIMENTAL DETAILS

Welded joints of steel 15Kh1M1FL are carried out according to two welding options with a cross hill welding (CHW) without preliminary and concurrent heating and subsequent tempering, with a different amount of heat input.

The size of the welded joint: plate length—250 mm, width—200 mm, thickness—110 mm. In the middle part of the plate along a length of 250 mm, a sampling of 60 mm wide and 70 mm deep is performed. Steel is used after heat treatment: double normalization of 1000–1030°C and 970–1000°C and tempering 720–750°C. Welding is carried out with electrodes of type Eh-09Kh1MF of the TML-3U grade with a diameter of 4 mm at a direct current of reverse polarity. The weld conditions are different by current strength: 160–170 A—the first option, 200–210 A—the second option.

When determining the crack resistance of welded joints, and the relationship between crack resistance and structure, we considered the impact strength of specimens with a sharp Charpy notch, its dependence on temperature, the nature of fracture of specimens, their hardness and the forming structures. The scheme for cutting samples for impact bending tests is shown in Fig. 1.

Impact bending tests are carried out according to GOST 9454-78 in the temperature range from –60°C to 100°C. The hardness of HV5 is measured according to GOST 2999-75.

The microstructure of the samples is studied by optical microscopy. Microsections are etched using two reagents: to detect the microstructure, in a 4% alcohol solution of HNO_3; to identify grain boundaries in heat affected zone (HAZ) and weld metal—in a supersaturated aqueous solution of picric acid with the addition of surfactants. The grain size is determined by comparing with the standard score scale GOST 5639-82 and the method of random secants [10] with the calculation of average nominal diameters (ND).

The chemical composition of the welded joint is shown in Table 1.

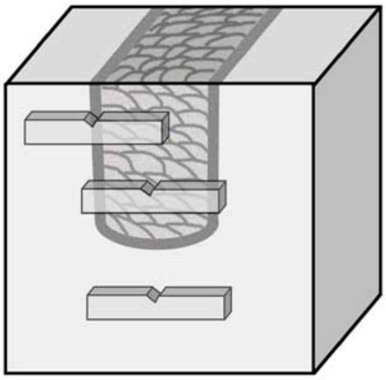


Fig. 1. Scheme of cutting samples from a welded joint.

TABLE 1. The chemical composition of the elements of the welded joint.

Location	Element content, %									
	C	Si	Mn	P	S	Cr	Mo	V	Ni	Cu
Base metal	0.16	0.43	0.89	0.010	0.010	1.38	1.02	0.33	0.17	0.11
The seam	0.08	0.20	0.83	0.011	0.003	0.99	0.55	0.28	0.07	0.10

3. RESULTS AND DISCUSSION

Based on the obtained characteristics, we constructed a diagram (Fig. 2) and established the following temperature characteristics of the brittle-viscous transition of the base metal of the welded joint: $T_0 = 0°C$, $T_{50} = +60°C$, $T_{100} = +100°C$, which corresponds to typical data for castings 15Kh1M1FL.

To determine the resistance to crack propagation according to the brittle-viscous transition diagram, we calculated the value of the stress intensity factor at the crack tip (K_{1c}) at 20°C of the welded joint metal according to the following relationship [11]:

$$K_{1c} = 0.8\sqrt{\sigma_{0.2} KCV(T_{100})}\left(\frac{T}{T_{100}}\right)^{3.8}, \qquad (1)$$

The K_{1c} value of 75 $\mathrm{MPa{\cdot}m^{1/2}}$ is obtained, which is in good agreement with our results of determining this characteristic on specimens of steel 15Kh1M1FL with induced crack, tested according to GOST 25.506-85.

In relation to the lowest working temperature of parts made of steel 15Kh1M1FL—250°C, an assessment of the temperature stock of viscosity $T_v \geq T_{\text{work}} - T_{50}$ is made and a value of 190°C is obtained [12].

Figure 3 shows a comparison of the temperature curves of the toughness of the metal of HAZ and the weld with the base metal of the welded joint.

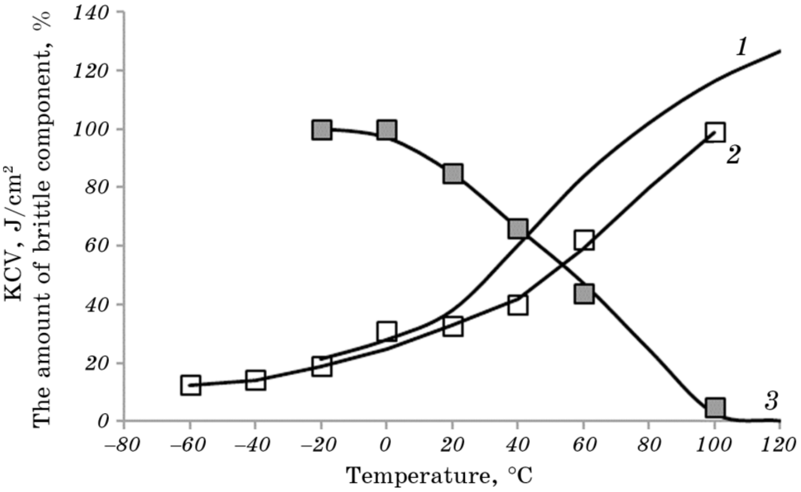
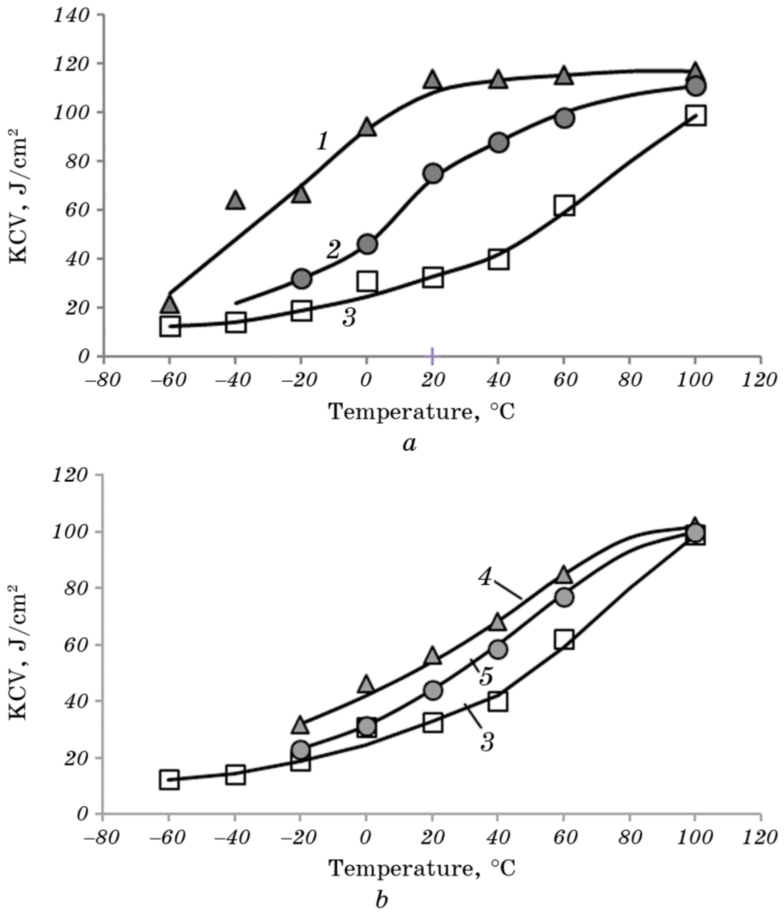


Fig. 2. Diagram of the transition of 15Kh1M1FL steel from a brittle to a viscous state. The toughness of the casting metal according to the literature (*1*), the base metal of our welded joint (*2*) and the brittle component in the fracture (*3*) depending on temperature.

The highest level of toughness in the brittle-viscous transition range is characteristic for HAZ, and the lowest—for the base metal. The brittle-viscous transition interval is shifted towards negative temperatures as follows: base metal, seam, HAZ. View of the fractures of the samples of the base metal and the notched samples in HAZ, differing in value by impact strength at 20°C twice (Fig. 4).

The nature of the fracture during testing of specimens with notching in HAZ is typical for the viscous state of the metal, when the initiation of cracks begins at the surface of the tear at the corners of the 'deformation triangle' [5]. In this case, the region of destruction of the samples is located in the zone of thermal influence.

The fracture of the samples cut from the weld metal and the notched



a

b

Fig. 3. Temperature dependence of the impact strength of the HAZ metal (*a*), weld (*b*) and the base metal of the welded joint (*3*), made in two ways: the first (*1*, *4*), the second (*2*, *5*).

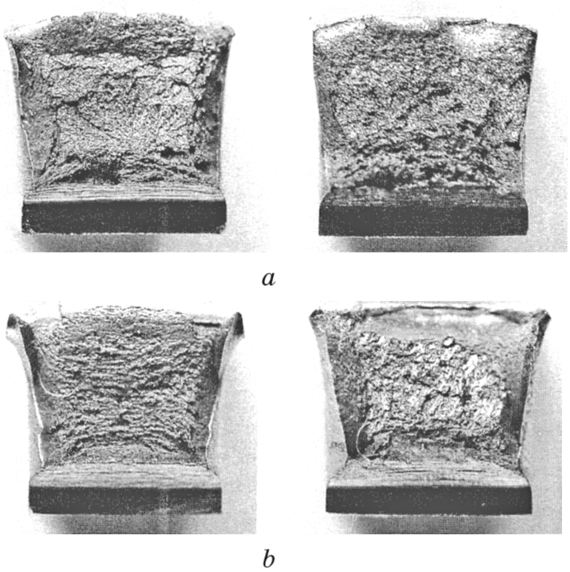


Fig. 4. Fractures: the base metal (*a*), a notching in the HAZ (*b*), ×3.5.

samples in HAZ is characterized by the morphological diversity of the relief of the fracture surface, in which brittle and viscous sections are adjacent, which complicates the quantitative assessment of the viscous component in the fracture and the study of the temperature dependence with the determination of T_0, T_{50} and T_{100}. In this regard, for a comparative assessment of the options for welded joints, the temperature corresponding to the impact strength of 60 J/cm^2 is adopted as a criterion. According to the temperature curve of the base metal, this value corresponds to T_{50} (Fig. 2).

The evaluation results for the proposed criterion are presented below (Table 2).

Based on the proposed quantitative assessment, the advantages of the first variant are clearly visible in the brittle-viscous transition interval. The temperature curves of the brittle-viscous transition diagram of castings of steel 15Kh1M1FL correspond to a structure consisting of upper and lower tempering bainite and ferrite, the ratio of

TABLE 2. Temperature criterion for assessing crack resistance.

Weld zone	Temperature corresponding to K_{CV} = 60 J/cm^2 of weld metal, °C	
	The first variant	The second variant
HAZ	−35	+10
The seam	+25	+40

which is determined by the chemical composition in microvolumes, which depends on the degree of development and stability of dendritic segregation during the metallurgical cycle of manufacturing castings.

Ferrite is practically absent in the base metal of the studied welded joints, the predominant structure is the upper and lower bainite of tempering of various morphology (Fig. 5). This combination of the bainitic structure is primarily due to microchemical heterogeneity at the location of the axes of the dendrites and interdendritic spaces, the light-etched sections of the structure correspond to the axes of the dendrite, and the dark etched ones correspond to the interdendritic spaces. The carbide phase both in the form of a rash, and unitarily larger sizes and various shapes is located both randomly and directionally. The manifestation of dendriticity in the structure of the base metal negatively affects the value of impact strength and the temperature of transition to a brittle state.

In HAZ, the nature of the microstructures is diverse—there are both structures close in morphology to the base metal, and structures that underwent transformations during welding. In this case, the predominant structure in the regions of the undergoing transformations is granular bainite, the α-solid solution of which is a mixture of residual austenite and the structure formed by martensitic kinetics—upper, lower bainite or martensite [13].

Features of the forming structures are more clearly identified at the welded joint of the second option, characterized by increased heat input. Near the fusion boundaries at a distance of 0.2–0.4 mm, the structure of upper granular and lower bainite and martensite is observed inside the former austenitic grains of a polyhedral shape (Fig. 6, *a*). It is noteworthy that the orientation of the martensite and lower bainite plates is normal and parallel to the crystallographic planes and grain boundaries and subgrains of the former austenitic grain, as well as the

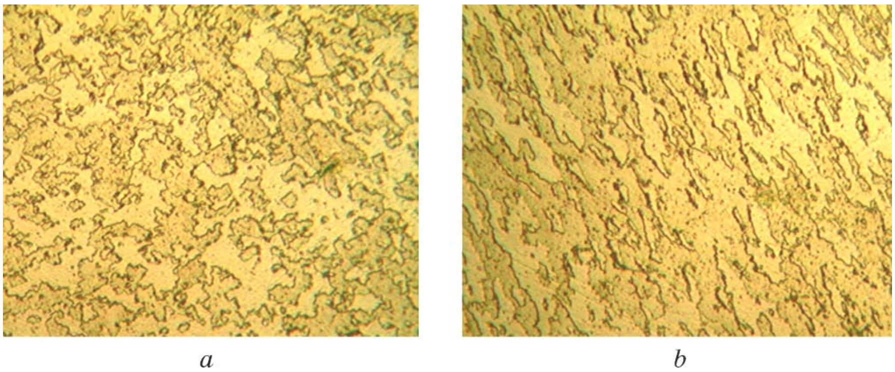

a *b*

Fig. 5. Structure of the base metal of welded joints ×600: upper bainite (*a*), lower bainite (*b*).

formation in separate sections near the fusion boundary of a structure consisting only of upper granular bainite.

Carbide phase condition differs inhomogeneity—large, round and fine carbides are located randomly and oriented both inside the grain, and along the grain boundaries by clusters and discontinuous chains. Figure 6 shows structures characteristic of temperatures significantly exceeding the upper critical point that differ in the size of the former austenitic grain and the state of the carbide phase along grain boundaries: grain size 4–5 points, large accumulations of rounded carbides at the boundaries, grain size 5–6 points, small individual and large carbides along the boundaries in the form of continuous chains, grain size 6–7 points, barely noticeable separate dispersed carbides along the grain boundaries. The revealed differences in the structure are probably related to the inheritance of the chemical composition of dendrites, which indicates the role of the initial state of the metal in the transformations during welding.

As the distance from the fusion boundary to a distance of 1–2.5 mm, the grain size in HAZ decreases and the morphology of granular bainite changes, the sizes of carbides and their density increase.

Of particular interest is the study of structural sections of the base metal in the initial stage of recrystallization, which practically did not undergo transformation (Fig. 6, *b*). The α-solid solution of this structure is characterized by elongated subgrains and portions of the light phase, at the place of which accumulations of carbides are observed, which is in accordance with the description of structures at the initial stages of recrystallization in the temperature range of the lower critical point on heating [14].

When comparing the structures of the welded joint made according to two options, it is found that the largest differences in the structure

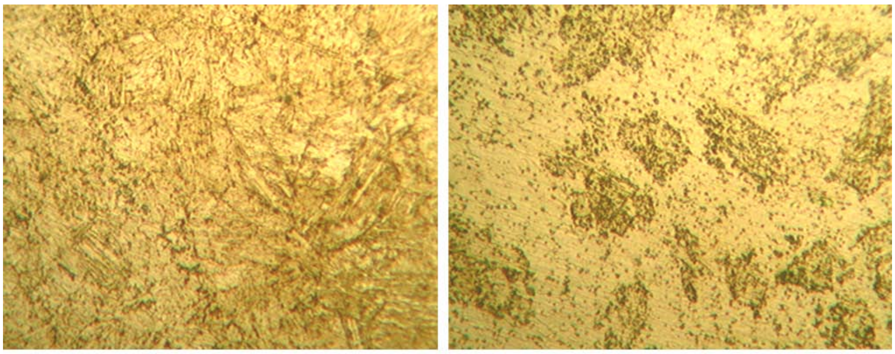

a *b*

Fig. 6. HAZ structure near the fusion boundaries (*a*), metal structure in the initial stage of recrystallization (transition zone) (*b*).

are observed near the fusion boundary at a distance of 0.2–0.4 mm from the boundary, whereas identical types of structures are obtained at a distance of 1–3 mm. Whereas for the first variant near the fusion boundary, the predominant structure is granular bainite, then for the second variant, along with the upper granular bainite, the structures of martensit and lower bainite are formed.

From the data of the structure study it follows that under conditions of thermodynamic cycles that depend on the heat input during the layer-by-layer filling of the weld groove, various competing processes develop: transformations in the structure associated with a significant change in the critical parameters of thermokinetic and isothermal structure formation—critical points and velocities during heating and cooling of austenite, grain growth temperature, temperature of isotherms with their structural decomposition [14, 15]; deformation with subsequent recrystallization and polygonization, the change in the parameters of which is associated with an increase in the diffusion rate under the influence of emerging stresses, a decrease in the temperature of recrystallization, and a change in the critical degree of deformation during recrystallization and polygonization [16].

The predominance of a process causes structural changes in HAZ. Moreover, the nature of the development of processes is inevitably associated with the initial state of the metal—the chemical composition and structure.

Despite the revealed variety of HAZ structures, the toughness in the range of brittle-viscous transition of HAZ metal of the welded joints of both variants is higher than the toughness of the base metal by two to three and a half times. Although the destruction of specimens during impact bending testing develops in HAZ region, the phenomenon of ‘brittleness of recrystallization’ [14] is not detected and the impact strength is not dramatically reduced.

The fusion region in welded joints is characterized by a smooth transition of the weld metal structure into the base metal without a clearly defined boundary. For the second variant of a welded joint in the fusion region, small sections with a width of the order of 50 μm of a decarburized layer on the base metal side can be formed (Fig. 6, *a*).

The microstructure of the weld is heterogeneous and consists of upper bainite—granular and oriented, and subgrain ferrite, carbides of various shapes and sizes, are unevenly distributed. The differences in the carbide distribution density observed in the structure are clearly visible in Fig. 7. In the weld metal of the welded joint of the first variant, a structure is formed with a predominance of upper granular bainite.

The heterogeneity of the weld metal structure is due to the thermal cycling of the heat input and the dendrite formation feature, which determines the nature of the decomposition of austenite upon rapid cooling or by an isotherm under stress and strain.

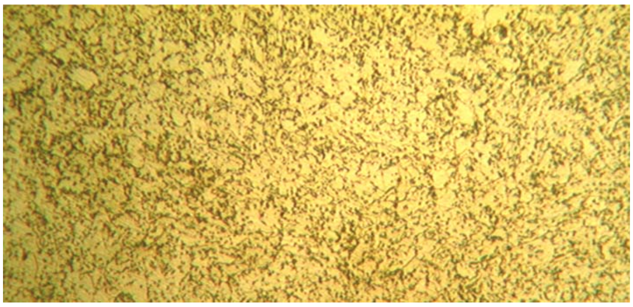


Fig. 7. Microstructure of the weld, ×600.

For a weld metal with the above structures, the toughness is about one and a half times higher compared to the toughness of the base metal.

4. CONCLUSIONS

1. It is proposed to carry out a temperature determination above which the absence of brittle cracks in the heat affected zone of welded joints is guaranteed by the impact strength of 60 J/cm^2 on samples with a sharp V-shaped notch, which corresponds to the brittle-viscous transition temperature of the base metal at 50% viscous component content in kink.
2. The heat affected zone of the welded joint is characterized by higher crack resistance than the base metal and weld metal, which is due to the structural feature formed during the cross hill welding.
3. The crack resistance of the heat affected zone varies depending on the heat input of the cross hill welding process: a higher level is obtained with lower heat input, when a higher degree of uniformity of the granular bainite structure is ensured and formation of a mixed granular bainite and martensite-bainitic structure is avoided.

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