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INFLUENCE OF WELDING THERMAL CYCLES ON THE STRUCTURE AND HARDNESS OF THE METAL IN THE HAZ OVERHEATING AREA IN WELDED JOINTS OF MEDIUM-CARBON ALLOY STEELS OF HIGH HARDNESS

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ABSTRACT

During welding, two characteristic areas are formed in the heat-affected zone of welded joints of medium-carbon alloy steels with hardened (high-temperature area) and tempered (low-temperature area) metal. Since the metal of the high-temperature area of the HAZ is heated above the temperature A_{c1} (approximately 730 °C), the initial structure in it is transformed into austenite, which upon cooling decomposes with the formation of other structures, from ferritic to martensitic. Accordingly, the mechanical properties of the metal also change. The formation of a particular structure in the cooled metal depends on the chemical composition of the material and the degree of its supercooling. This paper presents data on the influence of welding thermal cycles on the structure and mechanical properties of the metal in the HAZ overheating area in welded joints of medium-carbon alloy steels of different chemical composition.

KEYWORDS: medium-carbon alloy steels, high hardness, welding thermal cycle, metal structure, mechanical properties, welded joints

INTRODUCTION

Throughout the world, heat-strengthened medium-carbon alloy steels of high hardness (*HV* — over 5000 MPa) and strength (σ_t — more than 1400 MPa) are widely used in the manufacture of metal structures for special machines and individual, particularly loaded assemblies of mining and processing equipment. Such steels acquire high hardness and strength, combined with the necessary toughness properties by alloying with manganese, silicon, chromium, molybdenum, nickel, microalloying with boron, titanium, aluminium, vanadium, etc., as well as by heat treatment, which involves quenching of steel and then low-temperature tempering [1–8].

Most products that use high-hardness steels are welded. Individual parts and assemblies in such products are joined together using arc welding processes. This process involves heating of a rolled steel to temperatures exceeding A_{c1} temperature (approximately 730 °C) in some HAZ areas and reach 1300 °C in the area in direct contact with the weld (high-temperature areas of the HAZ in welded joints).

It should be noted that a high-temperature HAZ area includes areas of overheating (temperature ranges from 1100–1500 °C), normalization (temperature ranges from 930–1100 °C) and partial recrystallization (temperature ranges from 720–930 °C). When these areas are heated in the metal, the primary structure transforms into austenite. During cooling, austenite decomposes forming other structural components. The type of a formed structure depends on the chemical composition of steels and the degree of supercooling. Accordingly, mechanical properties (hardness, strength, ductility, and impact toughness) of the metal with the newly formed structures change [9–11]. Taking this fact into account, the aim of this paper is to present the results of laboratory studies on the influence of welding thermal cycles on the structure and mechanical properties of the metal in the HAZ overheating area in welded joints of different chemical composition of medium-carbon alloy steels.

RESEARCH METHODS

The studies were carried out on medium-carbon alloy steels, the maximum requirements for the concentration of alloying elements and chemical composition of which are given in Table 1.

The influence of welding thermal cycles on the structural transformations of the metal in the HAZ overheating area was studied using model specimens that were heated and cooled through the thermal cycles typical of arc welding processes.

The welding thermal cycle was recorded using a chromel-alumel thermocouple with a diameter of 0.5 mm.

To simulate the welding thermal cycles, the research complex Gleeble 3800 equipped with a high-speed dilatometer was used, which allowed detecting the temperature interval, in which structural and phase transformations in the metal start and end.

Table 1. Requirements for the chemical composition of the studied steels and mass fraction of alloying elements in them, wt.%

Steel grade		C	Si	Mn	Cr	Ni
1	Requirements	0.29–0.36	1.2–1.5	0.60–1.00	1.50–2.00	2.00–2.40
	Actual	0.32	1.2	0.70	1.80	2.20
2	Requirements	≤0.32	≤0.4	≤1.20	≤1.00	≤1.80
	Actual	0.23	0.25	0.84	0.50	0.97

Table 1 (Cont.)

Steel grade		Mo	B	V	Ti	S	P
1	Requirements	0.45–0.55	–	0.18–0.25	0.005–0.025	≤0.003	≤0.012
	Actual	0.50	–	0.20	0.024	0.008	0.011
2	Requirements	≤0.70	≤0.005	–	–	≤0.010	≤0.015
	Actual	0.33	0.002	–	–	0.004	0.013

Rigidly fixed specimens were studied, that were continuously heated and cooled in a manner similar to the thermal cycles typical of arc welding processes. The specimens were heated by a current passing through the specimen at a rate of 210 °C/s (heating time 6 s) to a temperature of 1250 °C. The cooling intensity of the specimens was adjusted so that in the temperature range of 600–500 °C, the cooling rate ($W_{6/5}$) varied from 2.5 to 30.0 °C/s. More details of this procedure and the requirements for model specimens are described in [12]. The final identification of the final structure formed as a result of the thermal cycle effect on the metal was revealed on the basis of metallographic examinations. The ratio of the phases formed as a result of transformations was determined by the segment method.

Metallographic examinations were performed using the Neophot-32 microscope; the microhardness of individual structural components and the integrated hardness of the metal were measured in the LECO M-400 hardness tester at loads of 100 g ($HV_{0.1}$) and 10 kg (HV_{10}), respectively. The specimens were prepared for studies according to the standard method using diamond pastes of different dispersion, and the microstructure was revealed by chemical etching in a 4 % alcohol solution of nitric acid.

The microhardness (HV), strength ($\sigma_{0.2}$ and σ_t), ductility (δ_5) and impact toughness (KCU_{20}) of the HAZ metal were evaluated by the results of testing standard specimens made from model specimens heated by the current passing through the specimen. The specimens were continuously heated and cooled through the thermal cycles of arc welding processes. The model specimens of 12×12×120 mm, from which standard specimens for tensile and impact toughness tests were made, were heated using the MRS-75 equipment. The cooling rate of the specimens was regulated by blowing them with air at different intensities.

RESEARCH RESULTS AND DISCUSSION

Metallographic examinations have established that the structure of the base metal of steel 1 was identified as martensite, which has a microhardness $HV_{0.1}$ = 4680–5020 MPa (Figure 1, *a*).

The transformation of supercooled austenite in the metal in the HAZ overheating area of steel grade 1, regardless of its cooling rate, occurs exclusively in the martensitic area. The cooling rate of the metal affects the structure parameters. As the cooling rate grows, the structure becomes finer. This is evidenced by the fact that the size of martensite packets in the metal in the HAZ overheating area decreases from approximately 40 μm at $W_{6/5}$ = 2.5 °C/s to 12 μm at $W_{6/5}$ = 30 °C/s. The cooling rate of the metal in the HAZ overheating area also affects its microhardness (Table 2). Thus, at $W_{6/5}$ = 2.5 °C/s, it is in the range of 4510–4600 MPa, and at $W_{6/5}$ = 30 °C/s it is approximately 5510 MPa.

The structure of the base metal of steel 2 represents a mixture of bainite and martensite with a pronounced rolled texture (Figure 2, *a*). The hardness of the base metal is $HV_{0.1}$ = 4770 MPa.

Examinations of the metal structure of steel 2 specimens, which were continuously heated and cooled through the welding thermal cycles, revealed the following. At a cooling rate of $W_{6/5}$ = 1 °C/s, the structure of the simulated HAZ metal is bainitic-martensitic (B–M) with a microhardness $HV_{0.1}$ = 3210–3860 MPa (bainitic component) and $HV_{0.1}$ approximately ≈ 4730 MPa (martensitic component) (Figure 2, *b*). The size of martensite packets (D_p) is in the range of 120–240 μm.

At higher cooling rates ($W_{6/5}$ > 3 °C/s), an exclusively martensitic structure is formed in the metal in the HAZ overheating area of steel 2 (Figure 2, *c*, *d*). Its microhardness increases from 5090 to 5490 MPa as the metal cooling intensity grows. At the same time,

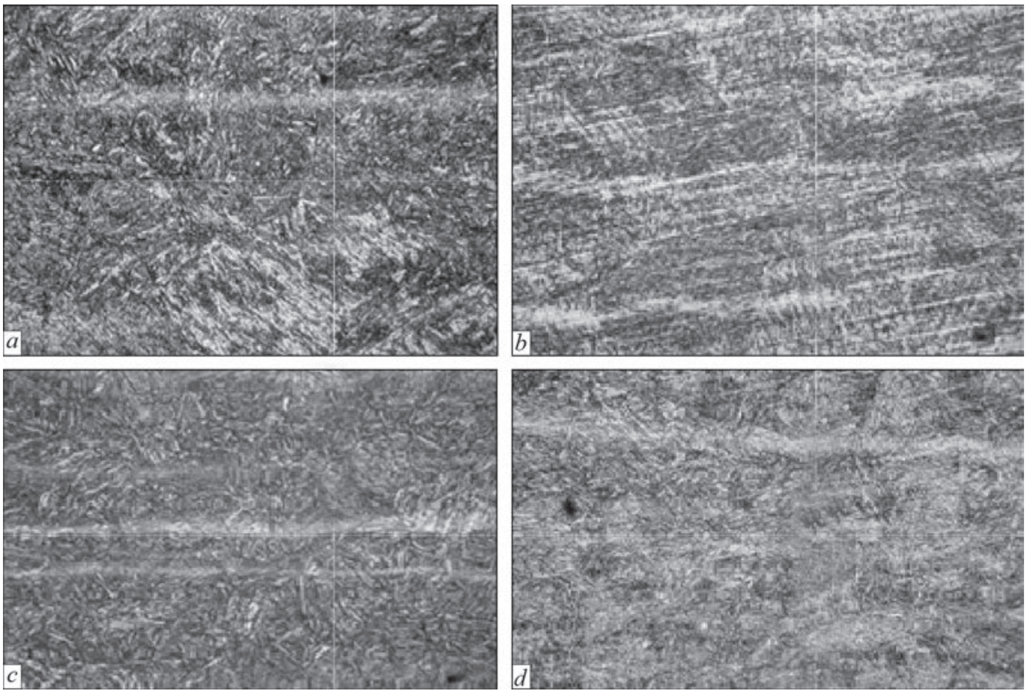

Figure 1. Structure of the base metal (*a*) and metal in the HAZ overheating area (*b–d*) of steel 1: *b* — 2.5; *c* — 10.0; *d* — 30 °C/s

Table 2. Microhardness of the base metal and metal in the HAZ overheating area of steel 1

$W_{6/5}$ °C/s	Base metal	2.5	5.0	10.0	15.0	30.0
Structure	M	M	M	M	M	M
$HV_{0.1}$, MPa	4680–5020	4200–4950	5100–5150	5050–5350	5150–5350	5150–5350

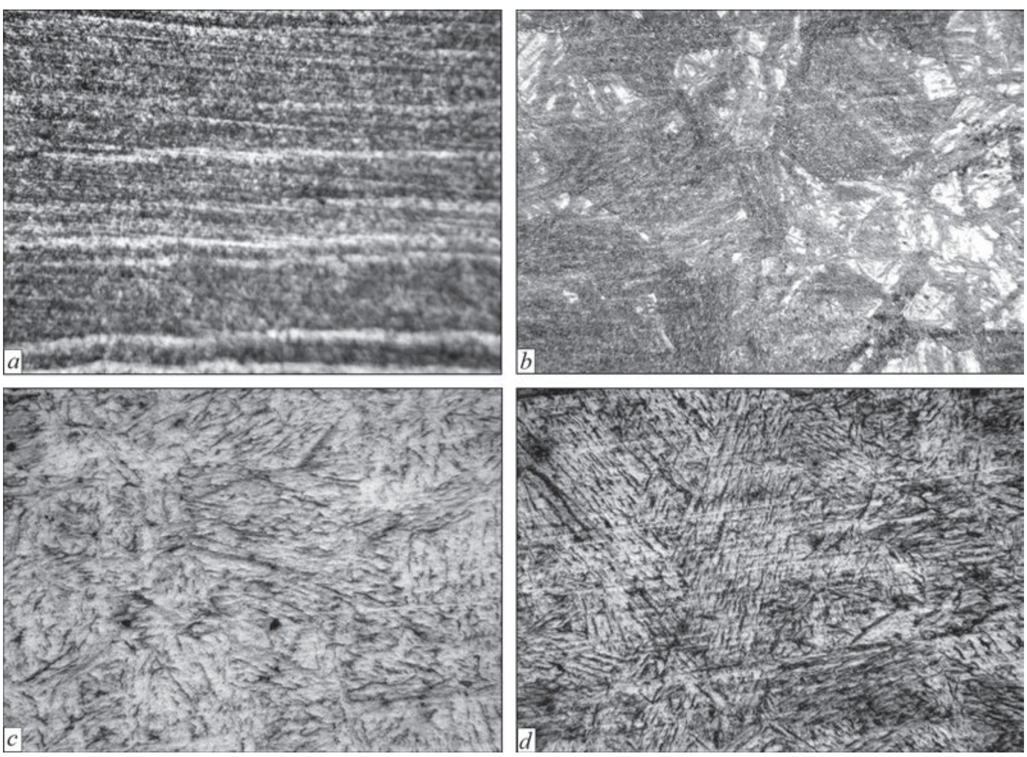

Figure 2. Structure of the base metal (*a*) and metal in the HAZ overheating area of steel 1 cooled at the following rates: *b* — 1.0; *c* — 10.0; *d* — 30 °C/s

Table 3. Microhardness of the base metal and metal in the HAZ overheating area of steel 2

$W_{6/5}$, °C/s	Base metal	1	3	5	10	20
Structure	M	B+M	M	M	M	M
$HV_{0.1}$, MPa	4700–4900	2950–3850 (B) 4150–4550 (M)	4200–4950	5100–5150	5150–5350	5150–5350

Table 4. Mechanical properties of the metal in the HAZ overheating area of the studied medium-carbon alloy steels

Steel grade	$W_{6/5}$, °C/s	HV	$\sigma_{0.2}$	σ_t	δ_5	φ	KCU, J/cm^2
		MPa			%		
1	0	5400	1460	1780	11.1	58.6	80.0
	5	4370	1262	1490	12.7	55.0	62.1
	10	4920	1395	1615	12.1	53.6	58.0
	15	5200	1445	1705	11.2	48.3	54.6
	20	5500	1502	1805	10.6	47.3	48.7
	30	5710	1607	1896	10.4	46.8	44.3
2	0	5100	1432	1670	7.6	55.0	127.0
	5	4200	1158	1327	8.5	45.0	72.0
	10	4930	1409	1637	7.2	28.8	56.0
	20	5150	1435	1692	7.0	25.9	52.0

martensite packets are also refined. As the cooling rate grows, their sizes decrease from D_p = 100–150 μm at $W_{6/5}$ = 3 °C/s to D_p = 50–70 μm at $W_{6/5}$ = 20 °C/s. The microhardness values characteristic of the metal of the studied steels and the cooling conditions of the specimens are given in Table 3.

The results of studies on the influence of the cooling rate of the HAZ overheating area on the mechanical properties of the metal are given in Table 4. They show that, despite the fact that the studied steels contain different amounts of alloying elements, their concentration in steel 1 is higher, and due to heat treatment, they acquire almost the same hardness, approximately HV 4850–4860 MPa. Nevertheless, the strength and ductility of these steels is somewhat different. Steel 1 has the highest values. As for the impact toughness of steels, it can be noted that steel 2 will have a better ability to resist dynamic loads.

As noted above, structural changes occurring in the metal under the influence of welding thermal cycles also cause certain changes in the mechanical properties of the overheated HAZ metal in welded joints of the studied steels.

As for the metal strength indices, despite the differences in the absolute values of σ_{02} and σ_t, which are higher in steel 1, the same tendency is observed for both steels in terms of the influence of metal cooling conditions on these indices. At a cooling rate $W_{6/5}$ < 5.0 °C/s, the strength of the HAZ metal in relation to the base metal decreases by 15–20 %. In the range of cooling rates $10.0 \leq W_{6/5} \leq 15.0$ °C/s, this difference becomes much smaller and at $W_{6/5} \geq 20.0$ °C/s reaches the strength of the base metal.

Despite the fact that the HAZ metal strength of the studied steels is lower in steel 2, its ductile properties (δ_5), regardless of the metal cooling rate, are worse than in steel 1. This is probably predetermined by different conditions of heat treatment of steels. Taking into account that the concentration of alloying elements in steel 2 is lower than in steel 1, it is obvious, that to ensure high hardness of this steel, its heat treatment conditions were more rigid.

As for the impact toughness of steel, in the initial state it is significantly, almost 1.5 times higher than that of less alloyed steel 2. However, as a result of high-temperature heating during the welding thermal cycle, the KCU values of the metal in the HAZ overheating area almost level and tend to decrease monotonically as the metal cooling intensity grows.

CONCLUSIONS

The results of studies on the influence of welding thermal cycles on the mechanical properties of the metal in the HAZ overheating area in welded joints of different chemical composition of medium-carbon alloy high hardness steels (HB 500) showed the following.

1. As a result of heat treatment of medium-carbon alloy steels of high hardness (HB 500) according to conditions typical of arc welding process, a martensitic structure is formed in the metal in the HAZ overheating area, the dispersion of which grows with an increase in the metal cooling rate.

2. The high hardness of the metal, which is acquired due to heat treatment of steel during rolled production, can be reduced as a result of its heating through the thermal cycles typical of arc welding. It has the most significant manifestation in the metal cooled at $W_{6/5} \leq 5.0$ °C/s. The lower the concentration of alloying and microalloying elements in steel, the lower the metal hardness.

3. At a cooling rate $W_{6/5} \leq 5.0$ °C/s, the strength of the HAZ metal in relation to the base metal decreases by 15–20 %. In the range of cooling rates $10.0 \leq W_{6/5} \leq 15.0$ °C/s, this difference becomes much smaller and at $W_{6/5} \geq 20.0$ °C/s reaches the strength of the base metal.

4. The impact toughness of less alloyed steel is almost 1.5 times higher than that of steel containing a higher concentration of alloying and microalloying elements. However, as a result of high-temperature heating during the welding thermal cycle, the *KCU* values of the metal in the HAZ overheating area almost level and tend to decrease monotonically as the metal cooling rate grows.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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