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INFLUENCE OF LOW-TEMPERATURE TEMPERING ON STRUCTURE AND PROPERTIES OF WELDED JOINTS OF HIGH-STRENGTH STEEL 30Kh2N2MF

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The results of investigations of influence of low-temperature tempering on structural changes, physical and mechanical properties of HAZ metal and crack resistance of welded joints of high-strength medium-carbon alloy steel 30Kh2N2MF are given. It is shown that the use of a low-temperature tempering is absolutely necessary during welding of products by low-alloy materials, which significantly increases the crack resistance of welded joints. During welding of joints by high-alloy materials in the hardened HAZ metal a relatively more ductile and less stressed structure is formed, in which the maximum level of stresses is lower than that which can be achieved after thermal tempering of a welded joint with a low-alloy weld. Therefore, the level of crack resistance of welded joints is sufficiently high in any case and in this situation there is no need to use low-temperature tempering. This is an unnecessary technological operation that does not significantly affect the reliability during operation of products, but only makes their cost higher. 13 Ref., 4 Tables, 6 Figures.

Keywords: high-strength steel, welded joints, low-temperature tempering, structure, properties, crack resistance

Thermal tempering of critical products of high-strength alloy steels, which are preliminary subjected to hardening, is a recognized technological operation. During tempering, in the metal diffusion processes of carbon redistribution in the structure and degassing of the hardened metal take place, which significantly increases its ability to microplastic deformation under the action of external load [1–3]. This contributes to a significant increase in crack resistance of critical products during operation, which is the main purpose of applying thermal tempering.

The similar positive changes during thermal tempering occur also in the structure of a hardened metal of HAZ and welded joints [4–6]. In addition, during degassing the level of hydrogen in the metal of welded joint, with which it is saturated during welding, is significantly reduced. Typically, in manufacture of metal structures from high-strength alloy steels, during welding of which low-alloy materials were used, low-temperature tempering is performed. After welding, not later than in 24 hours, they are subjected to tempering at a temperature of 200–250 °C for at least 3 h.

However, rationality of perfoming thermal tempering of joints, during welding of which high-alloy materials were used, remains a controversial issue today. First, as a result of carbon diffusion heat treatment of welded joints with a high-alloy weld can lead to the formation of brittle interlayers in the fusion zone [4–6]. Secondly, in a hardened HAZ metal of a welded joint with a high-alloy weld, as a result of the action of physical and metallurgical processes, already during welding proper a more ductile and less stressed structure is formed [7, 8]. And in the third, high-alloy metal has a high ability to dissolve hydrogen [9]. Therefore, during cooling of welded joint, its diffusion from a high-alloy deposited metal into the HAZ will proceed much more slowly as compared to a low-alloy one. This causes a significantly lower content of hydrogen in the HAZ metal of joints during welding by a high-alloy material and still there is no need in a further reduction of its content. In addition, it should also be taken in account that thermal tempering of welded metal structures is a high-cost technological operation, it requires the use of complex equipment and significant power consumption. Sometimes the material costs on thermal tempering amount up to 50 % of the cost of manufacturing a welded metal structure.

Taken the abovementioned into account, it can be assumed with a high degree of probability that it is most likely impractical to perform low-temperature tempering (LTT) of metal structures, in the welding of which high-alloy materials were used. But to prove this conclusion, it was necessary to conduct special comparative studies of changes in the parameters of the structure of a hardened HAZ metal and crack re-

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sistance of welded welds of high-strength steel with low- and high-alloy joints before and after LTT. This was the purpose of the investigations, the results of which are given below.

Procedure of investigations. As the object of investigations, model specimens and welded joints of high-strength medium-carbon alloy steel of type 30Kh2N2MDF were used. On the model specimens, the influence of LTT on the change of physical and mechanical properties of a hardened HAZ metal was determined. At the same time steel of grade 30Kh2N2M0F of the following composition, wt.% was used: 0.36 C, 1.32 Si, 0.81 Mn, 1.65 Cr, 2.34 Ni, 0.50 Mo, 0.21 V. And during comparative investigations of changes in the structure of a hardened HAZ metal the welded joints were used, which after welding were not subjected to LTT. At the same time, steel of grade 30Kh2N2MDF was used having the composition similar to the abovementioned, but the carbon content in it was closer to the lower limit of alloying (0.31 % of C). In all cases, LTT, in case of its using, was performed during 3 h at a temperature of 230 °C within 15–20 h after simulation of thermodeformation cycle on the model specimens or after welding of joints.

The simulation of thermodeformation cycles of arc welding with the use of model specimens was performed in the installation MSR-75 [10]. At the same time, model specimens of two types were used – with a cross-section of 12×12 mm and 20×10 mm. The first specimens were used to determine strength ($\sigma_{0.2}$, σ_t), ductility (δ_5, ψ) and impact toughness (KCU_{+20}) and the second to determine critical stress intensity factor (K_{1C}) of a hardened HAZ metal. According to the accepted method of simulation, the maximum heating temperature of the model specimens was 1250 °C, the heating rate was 180–200 °C/s (heating time was 6–7 s). After heating, the specimens were immediately cooled at the rates from 4 to 20 °C/s ($w_{6/5}$), which are the most typical for the conditions of arc welding of multilayer joints. In the central part of the specimens, an area of metal of 40 mm width was formed homogeneous as to its structure. Then, from the model specimens, special specimens were made for testing on static tension and impact bending in accordance with GOST 1497 and GOST 9454, or static bending in accordance with GOST 25-506.

To determine the factor $K_{1C,}$ sequence of experiments was as follows. After simulating thermodeformation cycle of arc welding, a notch was prepared in the central part of the model specimens, from the top of which fatigue cracks of 3 mm depth were grown. After that, the specimens were tested under static bending load. During the tests, the value of critical load during propagation of the main crack was determined and the index of critical stress intensity factor K_{1C} was calculated according to the method of fracture mechanics [11].

The specimens of butt welded joints were prepared as follows. They were 10 or 20 mm thick and had a V-shaped groove, which was welded in a mechanized way in a mixture of shielding gases (82 % Ag + 18 % CO_2) by two materials. During welding of some specimens, the wire Sv-10GSMT was used, and other were welded using the wire Sv-08Kh20N9G7T. In both cases, the diameter of the wires was 1.2 mm. Welding modes were the same, namely: welding current was 160–180 A, arc voltage was 26–28 V, welding speed was 12–15 m/h (input energy was 8–10 kJ/cm). In case of welding using low-alloy wire, in order to avoid the probability of cold cracks formation in the HAZ metal of joints, preliminary heating of the metal to a temperature of 250 °C was used. When using high-alloy wire, the specimens were welded without a preheating. The temperature of the metal during multilayer welding of the specimens did not exceed 30–50 °C, to achieve which the specimens were cooled in air after applying each layer of the weld.

Crack resistance of welded joints was determined during their tests on resistance to the formation of fatigue cracks under cyclic bending loading in the installation UMP-02 in accordance with generally accepted methods [12]. The cycle stress under loading of welded joints was 60 MPa with a frequency of 14 Hz. As the evaluation criterion during tests, a critical number of load cycles was accepted, during which in the welded joint a fatigue crack with a length of 2–3 mm is formed.

To study structural changes in the metal of welded joints, standard methods of optical and electronic metallography were used. For optical metallography, the microscope Neophot-32 and the durometer M-400 were used. Parameters of a fine structure and dislocations density in a hardened HAZ metal were investigated in the transmission electron microscope (TEM) JEM-200CX of the JEOL Company. Subsequently, using experimentally detected structural parameters by the method of analytical evaluation, local inner stresses ($\tau_{l.in}$) were calculated [13].

Results of investigations and their analysis. At the first stage of investigations, the effect of LTT on the change of physical and mechanical properties of a hardened HAZ metal during testing of model specimens was determined. The determined indices of mechanical properties and fracture toughness of a hardened HAZ metal depending on its cooling rate are summarized in Table 1 and Table 2.

Comparing the obtained results of the tests given in Table 1, it is seen that after LTT the indices of temporary strength of HAZ metal are decreased to 10 %

Table 1. Effect of LTT on mechanical properties of HAZ metal of steel 30Kh2N2MF

Presence of LTT	$w_{6/5}$, °C/s	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	KCU_{+20}, J/cm^2
No/Yes	Steel	1460	1780	11.1	48.6	80
	5	1262/1250	1490/1420	12.7/12.8	55.0/55.0	62.1/64.3
	15	1445/1430	1705/1580	11.2/12.1	48.3/50.3	54.6/58.0
	20	1502/1480	1805/1640	10.6/11.8	47.3/49.8	48.7/52.9

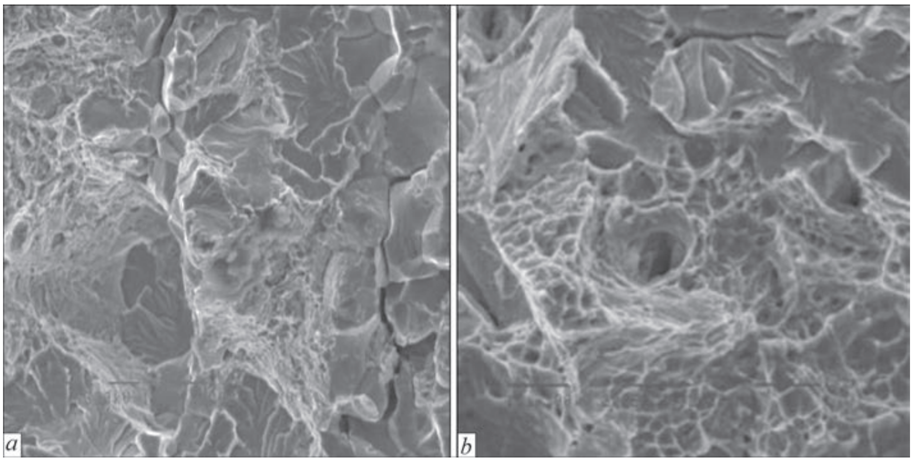

Figure 1. Typical surface of fracture of HAZ metal of steel 30Kh2N2MF ($w_{6/5}$ = 12.0 °C/s) in the area of main crack propagation without (*a*) and at the presence of LTT (*b*): *a* — ×1010; *b* — ×2020

(from 1490–1805 to 1420–1640 MPa), and the yield strength of the metal almost does not change and is at the level of 1250–1480 MPa. In this case, the values of ductility of a hardened metal at a static load δ_5 and ψ and the fracture impact toughness KCU_{+20} at an increased cooling rate is gradually increased by approximately 5.3 and 11.3 % and 8.6 %. The indices of critical factor of crack propagation K_{1C} are increased more significantly from 14 to 61 %, depending on the cooling rate (Table 2). After LTT, they are equalized in value regardless of the metal cooling rate during welding and are in the range from 96.8 to 100.9 MPa√m. In this case, the share of a viscous component on the surface of the specimens fractures increases significantly, more than 2 times, the fracture of which in both cases is characterized by a predominantly brittle intragranular type (Figure 1), and in case of absence of LTT — by the presence of intergranular brittleness with secondary cracks along the grain boundaries (Figure 1, *a*).

The carried out tests showed that during LTT of welded joints a hardened HAZ metal improves its ductile properties. This should be reflected also in an increased crack resistance of welded joints, which was determined in the second stage of investigations. For the tests under cyclic bending loading, the specimens of welded joints of steel 30Kh2N2MF were selected, during welding of which the wires Sv-10GSMT and Sv-08Kh20N9G7T were used. To testing butt welded joints with a thickness of 20 mm with a V-shaped groove were subjected, the welding of which was performed with a full penetration (welding of the weld root on the reverse side). The conditions of welding and testing of specimens are given above. The generalized results of test are presented in Figure 2.

Table 2. Effect of LTT on resistance of HAZ metal of steel 30Kh2N2MF to brittle fracture

Presence of LTT	Critical stress intensity factor K_{1C}, MPa√m		
	$w_{6/5}$ = 4.0 °C/s	12.0	20.0
No	87.8	69.7	60.0
Yes	100.9	100.1	96.8

As is seen, LTT facilitates the increase in crack resistance of welded joints of steel 30Kh2N2MF with both low-alloy as well as high-alloy weld. But the initial level of crack resistance and the degree of impact of LTT differs significantly depending on alloying of the deposited metal. During welding by a low-alloy

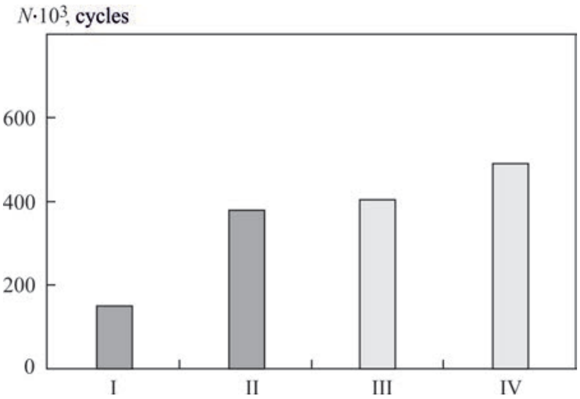

Figure 2. Resistance to the formation of fatigue cracks of butt joints of steel 30Kh2N2MF during welding by the wire Sv-10GSMT (I, II) and Sv-08Kh20N9G7T (III, IV) without (I, III) and at the presence of LTT (II, IV)

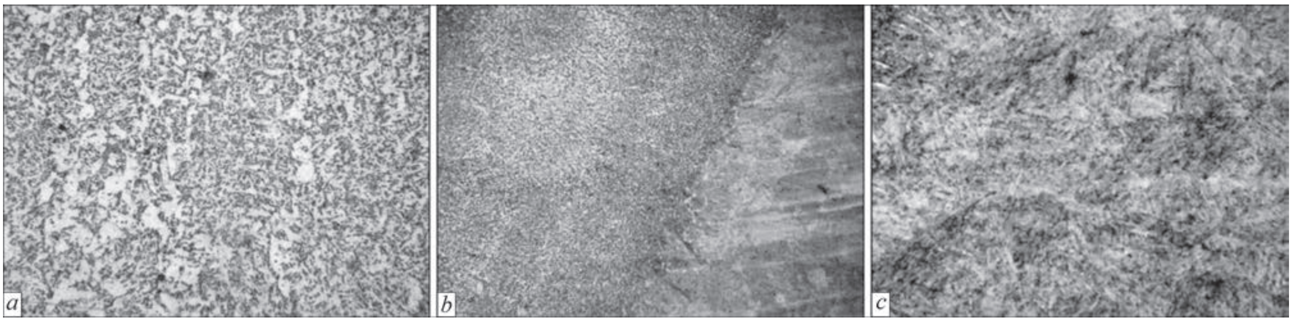

Figure 3. Microstructure of metal of joint of steel 30Kh2N2MF during welding by the wire Sv-10GSMT: *a* — central area of weld metal (×500); *b* — fusion zone (×200); *c* — near-weld area of HAZ at a distance of up to 700 μm from the fusion line (×500)

wire Sv-10GSMT, the resistance of welded joints to the formation of fatigue cracks without the use of LTT is almost 2.73 times lower than during welding with the wire Sv-08Kh20N9G7T. A comparative number of load cycles before the formation of fatigue cracks is 150 and 410 thousand cycles, respectively. It should be noted that welding of steel specimens with a low-alloy wire was performed using preheating to a temperature of 250 °C, and by a high-alloy wire without preheating. At the same time, the cooling rate in the HAZ metal was 3−5 and 20−25 °C/s, respectively. Therefore, in the HAZ metal of welded joint with a high-alloy wire, the conditions for the formation of a hardening structure were more rigid.

After LTT, the resistance of welded joints to fatigue cracking with a low-alloy weld is more than 2.5 times imcreased (from 150 to 380 thou cycles) and that of joints with a high-alloy weld is only 19.5 % (from 410 to 490 thou cycles). It should be noted that after LTT, the number of load cycles before the formation of a fatigue crack for a low-alloy weld does not exceed the level of high-alloy welds, even if they are welded without a preliminary heating and LTT. It is obvious that the established changes in the levels of crack resistance occurred as a result of positive changes in the metal structure of the welded material firstly, and secondly, directly while performing of LTT. Investigations in this direction was the goal of the third stage of research works.

The generalized results of investigations of influence of LTT on the change of a structural condition of the weld and near-weld area of HAZ of welded joints of steel 30Kh2N2MF are given in Table 3 and Table 4, and Figures 3−6 show the characteristic structures of the welded joints metal.

The examinations of the microstructure of the metal of welded joints with a low-alloy weld by the methods

Table 3. Structural parameters of metal of welded joints of steel 30Kh2N2MF during welding by the wire Sv-10GSMT

Area	Presence of LTT	Structural parameters					
		V_a, %	D_{gr} (for weld h_{cr}), μm	$HV_{0.1}$, MPa	h_l, μm	ρ, cm^{-2}	$\tau_{l.in}$, MPa
Weld	No	B$_{gr}$, 100	40−150	2450−2640	–	–	–
	Yes	B$_{gr}$, 100	60−160	2450−2640	–	–	–
HAZ	No	M, 100	20−50	5140−5720	0.4−0.8	$9\cdot10^{10}$−$1.6\cdot10^{11}$	1867−2988
	Yes	M, 100	20−50	4880−5420	0.4−0.8	$8\cdot10^{10}$−$1\cdot10^{11}$	1474−1867

Table 4. Structural parameters of metal of welded joints of steel 30Kh2N2MF during welding by the wire Sv-08Kh20N9G7T

Area	Presence of LTT	Structural parameters					
		V_a, %	D_{gr} (for weld h_{cr}), μm	$HV_{0.1}$, MPa	h_l, μm	ρ, cm^{-2}	$\tau_{l.in}$, MPa
Weld	No	A + F, 97 + 3	7−30	2210−2300	–	–	–
	Yes	A + F, 97 + 3	7−30	2210−2300	–	–	–
HAZ	No	B$_l$, 2−5	25−55	4210	0.4−0.6	5−$6\cdot10^{10}$	924−1109
		M, 95−98		4880−5090		8−$9\cdot10^{10}$	1474−1600
	Yes	B$_l$, 2−5	25−60	4210	0.4−0.6	4−$5\cdot10^{10}$	739−924
		M, 95−98		4420−4880		7−$8\cdot10^{10}$	1294−1474

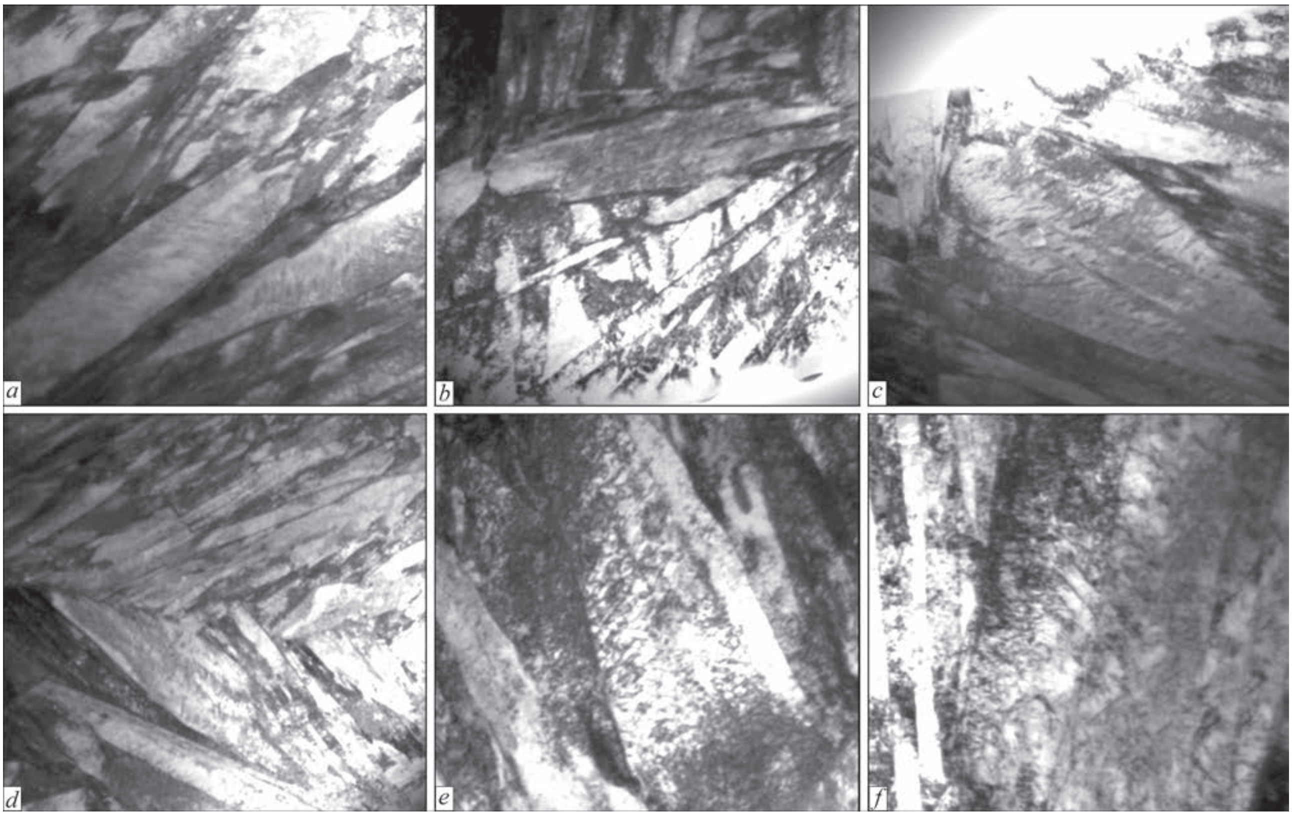

Figure 4. Fine structure of metal of near-weld area of HAZ of welded joints of steel 30Kh2N2MF (wire Sv-10GSMT) without (*a–c*) and at the presence of LTT (*d–f*): *a* — ×22000, *b* — ×25000, *c* — ×35000 — hardening martensite; *d* — ×22000, *e* ×52000, *f* — ×35000 — martensite tempering

of optical metallography showed that in the weld metal the structure of granular bainite (B_{gr}) with a crystallite size h_{cr} = 40–150 μm is formed and a microhardness of *HV*0.1 = 2450–2640 MPa (Figure 3, *a*). The structure of the metal around the near-weld area of the HAZ (coarse grain area) at a distance of 700 μm from the fusion line (FL) is represented exclusively by martensite with a grain size D_{gr} = 20–50 μm and a microhardness of 5140–5720 MPa (Figure 3, *c*). More detailed examinations applying the TEM method revealed that there is a hardening martensite (Figure 4, *a*, *b*) and partially a tempering martensite (Figure 4, *c*), with a size of laths h_l = 0.4–0.8 μm, dislocations density ρ in which is from $9\cdot10^{10}$ to $1.6\cdot10^{11}$ cm^{-2}.

After LTT, the phase composition, dimensions of crystallites in the weld metal and grains in the HAZ metal almost do not change. Microhardness of structural components in the weld metal also do not change. But, unlike the weld, in the near-weld area of the HAZ, the microhardness of martensite decreases by approximately 9 % — down to 4880–5420 MPa, and the density of dislocations in it decreases to $8\cdot10^{10}$–$1\cdot10^{11}$ cm^{-2} at a more uniform distribution (Figure 4, *d–f*). Moreover, the maximum level of local structural stresses ($\tau_{l.in}$), which is calculated as compared to the theoretical strength of the metal, is reduced to 40 % — from 2988 to 1867 MPa. Such reduction in the level of local stresses significantly contributes to the ability of hardened metal to microplastic deformation and its resistance to the formation and propagation of cracks under the action of external loads increases significantly. Therefore, during welding of joints of steel 30Kh2N2MF by a low-alloy wire Sv-10GSMT, the application of low-temperature tempering is absolutely necessary.

In the joints of steel 30Kh2N2MF, which were welded by a high-alloy wire Sv-08Kh20N9G7T, in the central part of the weld metal an austenitic-ferritic structure (A + F) is formed, in which the volume fraction of ferrite does not exceed 3 %. The size of the crystallites is 7–30 μm, microhardness of the structural components is in the range of 2210–2300 MPa (Figure 5, *a*). Near the fusion line, the size of the crystallites and microhardness are increased to 6–50 mm and 2450–2640 MPa, respectively (Figure 5, *b*).

The structure of the metal around the near-weld area of the HAZ, the depth of which is up to 300 μm, is mainly martensitic (95–98 %) with a small volume of bainite (2–5 %), the grain size is 25–55 μm (Figure 5, *c*). Without low tempering of welded joints, the microhardness of bainite is 4210 MPa and martensite is 4880–5090 MPa. Morphologically, this is a lower bainite (Figure 6, *a*) and a lath dislocation tempering martensite with a size of laths of 0.4–0.6 μm

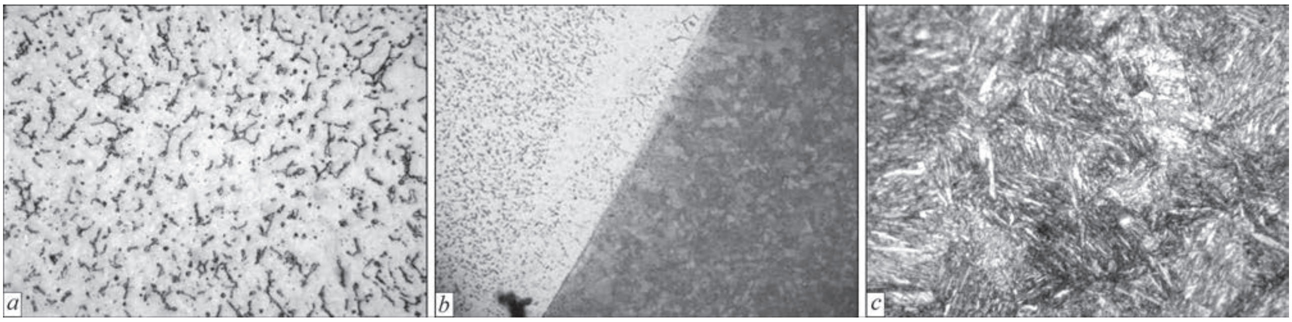

Figure 5. Microstructure of metal of joint of steel 30Kh2N2MF during welding by the wire Sv-08Kh20N9G7T: *a* — central area of weld metal (×500); *b* — fusion zone (×200); *c* — near-weld area of HAZ at a distance of up to 300 μm from the fusion line (×1000)

(Figure 6, *b*, *c*). The density of dislocations in the structural component of bainite, without the use of a low tempering, is $(5-6)\cdot10^{10}$cm^{-2}, and martensite is $(8-9)\cdot10^{11}$ cm^{-2}.

It should be noted that these values of dislocation density in the components of the structure of a near-weld area of the HAZ of welded joint with a high-alloy weld are much lower than during welding by the wire Sv-10GSMT. These values are lower even than those, which were obtained after LTT of welded joints with a low-alloy weld. This is associated with the peculiarities of the influence of thermodeformation processes in a high-alloy weld metal during cooling of joints on structural-phase transformations in the HAZ metal. In this case, the transformations are shifted to the area of higher temperatures with the formation of an intermediate structure of bainite, and during the formation of martensite the processes of its tempering occur [8].

After LLT the phase composition, sizes of crystallites and microhardness of strucutral components in a high-alloy weld metal and grain sizes in the HAZ metal, as well as in the welded joints with a low-alloy weld also almost do not change. But the changes in the following parameters of the metal structure of the near-weld area of the HAZ are observed. Thus, microhardness of the lower bainite does not change, and the density of dislocations in it decreases to $(4-5)\cdot10^{10}$ cm^{-2} (Figure 6, *d*). Microhardness of the martensite component decreases by 5 % to 4420–4880 MPa, the density of dislocations in it decreases to $(7-8)\cdot10^{11}$ cm^{-2} (Figure 6, *e*, *f*). At the same time, the maximum level of $\tau_{\text{l.in}}$ in bainite and martensite is reduced by 17 % (from 1109 to 924 MPa) and 8 % (from 1600 to 1474 MPa), respectively.

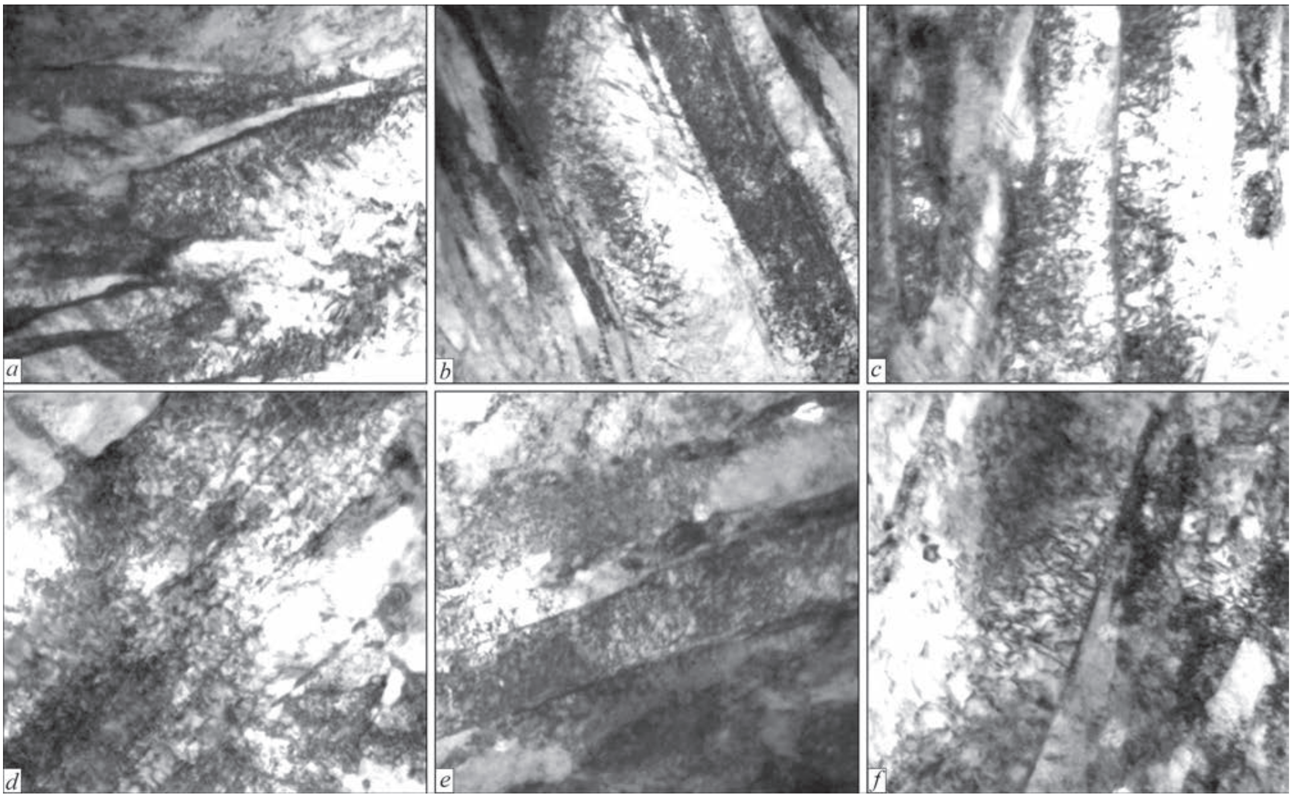

Figure 6. Fine structure of metal of near-weld area of HAZ of welded joints of steel 30Kh2N2MF (wire Sv-08Kh20N9G7T) without (*a*–c) and at the presence of LTT (*d*–*f*): *a* — ×52000, *d* — ×52000 — lower bainite; *b* — ×35000, *c* — ×52000, *d* — ×35000, *e* — ×52000 — tempering martensite

Comparing the obtained data, it is seen that the effect of LTT on the structure of joints welded by the wire Sv-08Kh20N9G7T is not as significant as for the joints with a low-alloy weld (Sv-10GSMT wire). If in the welded joints with a low-alloy weld after tempering the maximum level of structural stresses in the basic component of martensite is reduced to 40 %, then in the joints with a high-alloy weld to only 8 %. Moreover, in the initial state, without LTT, the difference in the levels of structural stresses amounts up to 1.9 times (respectively 2988 and 1600 MPa, see Tables 3 and 4).

The obtained data regarding the changes in the structure parameters correlate well with the results of tests of welded joints on fatigue failure. Therefore, during welding of joints of steel 30Kh2N2MF by high-alloy materials in a hardened HAZ metal, during the welding process proper a more ductile and less stressed structure is formed than that which can be produced after LTT of the welded joint with a low-alloy weld. Therefore, the crack resistance of welded joints of this steel during welding by high-alloy materials is at a high level even without additional heat treatment. LTT for such joints contributes to a slight additional increase in crack resistance, but it is not decisive. Therefore, the use of LTT for the products of a medium-carbon alloy steel 30Kh2N2MF under the conditions of their welding by high-alloy materials will not be significantly critical in terms of providing the reliability of welded joints during operation, and its use is irrational. This conclusion can be applied to all steels of this class. When using steels of other classes for critical products, additional investigations are required.

Conclusions

1. As a result of low-temperature tempering of welded joints of steel 30Kh2N2MF the changes in the parameters of a fine structure in a hardened HAZ metal occur. At the same time, in the HAZ metal of welded joints, the welding of which is performed by low-alloy materials, the processes of self-tempering of martensite run more actively, and the maximum level of local structural stresses is reduced to 40 %. Such a reduction of local stresses significantly contributes to the ability of a hardened metal to microplastic deformation under the action of external load. As a result, the resistance to fatigue formation of joints is more than 2.5 times increased. Therefore, during welding of joints of steel 30Kh2N2MF by a low-alloy wire Sv-10GSMT, the use of low-temperature tempering is absolutely necessary.

2. During welding of joints of steel 30Kh2N2MF by high-alloy materials in a hardened HAZ metal, a relatively more ductile and less stressed tempering martensite structure with a small amount of lower bainite is formed. The maximum stress level in this structure is 17 % lower than that, which can be obtained after LTT of a low-alloy weld. The crack resistance of welded joints during welding by high-alloy materials is at a sufficiently high level and does not require an additional increase. Therefore, there is no need to subject welded metal structures of products of steel 30Kh2N2MF to a low-temperature tempering under the conditions of their welding by high-alloy materials. This is an unnecessary technological operation, which does not significantly affect the reliability of the operation of products, but only makes their cost higher.

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