- lowering the chemical and structural inhomogeneity, characteristic for fillers from two-phase titanium alloys;
- increasing the energy intensity of fracture of welded joints on high-temperature titanium alloys due to reduction of the number of defects in the weld structure;
- increasing the values of mechanical properties of welded joints from VT8 alloy, compared to joints made with application of standard fillers.

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EFFECT OF HIGH-TEMPERATURE THERMAL CYCLING ON DEPOSITED METAL OF THE TYPE OF HEAT-RESISTANT DIE STEELS

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The effect of high-temperature cyclic loads on thermal stability, structure and microscopic chemical heterogeneity of deposited metal of the type of heat-resistant die steels was investigated. It was shown that, despite the fact that no diffusion of main alloying elements was detected during the tests, structure of the deposited metal experienced changes leading to its weakening.

Keywords: *arc cladding, flux-cored wire, deposited metal, forming rolls, dies, thermal cycling, thermal stability, structure*

One of the main types of wear of working surfaces of forming rolls, dies and other tools used for hot deformation of metals is thermal fatigue, i.e. formation of a network of fire cracks caused by high-temperature cyclic loads [1–4]. The thermal fatigue cracks form on the surfaces of parts after some (relatively small) quantity of thermal cycles. They result from the effect of cyclic thermal stresses induced by constraint changes in size of isolated regions of a part in periodic fluctuations of temperatures [5–8].

A combination of cyclic temperatures and elasto-plastic deformations is a characteristic feature of anisothermic cyclic fatigue. The type of anisothermic cyclic fracture, at which the maximal temperature of a thermal cycle corresponds to compression in a cycle of elasto-plastic deformation, was called the thermal fatigue [5, 6]. The quantity of the heating–cooling cycles to formation of cracks usually serves as a characteristic of resistance of materials to thermal fatigue [2, 3].

Depending on the test procedure that meets service conditions of parts to this or other extent, the quantity of thermal cycles leading to formation of the thermal fatigue cracks for the majority of materials does not exceed several hundreds or thousands of the heating–cooling cycles [2–3].

In addition to thermal stresses, when investigating thermal stability of the deposited metal it is necessary

Table 1. Chemical composition and hardness of deposited metal

Flux-cored wire grade	Content of elements, wt.%							Hardness *HRC*
	C	Mn	Si	Cr	W	Mo	V	
PP-Np-30Kh4V2M2FS	0.35	0.72	1.1	3.97	2.52	1.88	0.44	50
PP-Np-35V9Kh3GSF	0.34	0.6	1.0	3.0	9.3	–	0.71	54

to take into account also the structural changes that may occur in it as a result of high-temperature cyclic effects. Irreversible changes in structure and properties of the deposited metal during operation determine in many respects the serviceability and reliability of the clad tools used for hot deformation of metals and alloys. The purpose of this study was to investigate structural transformations taking place in the deposited metal of the type of heat-resistant die steels as a result of its thermal stability tests.

Experimental flux-cored wires were used for cladding of billets preheated to 300 °C. After cladding the billets were subjected to slow cooling. Actual composition of the deposited metal and its hardness are given in Table 1. Specimens measuring 40 × 40 × 40 mm were made from the clad billets to determine thermal stability of the deposited metal.

Investigations of thermal stability were carried out by using a modular rig for testing of different properties of the deposited metal [9] by the following procedure: heating of the polished surface of a clad specimen to 680–700 °C, and rapid water quenching to 70–90 °C. Thermal stability was evaluated from the quantity of heating–cooling cycles to formation of fire cracks.

Results of the thermal stability tests of the deposited metal, as well as thermal stability values for widely applied die steel 5KhNM quenched and tempered to hardness *HRC* 50 are given in Table 2. Figure 1 shows surface of the clad specimens after the thermal stability tests.

Table 2. Results of thermal stability tests of deposited metal

Type of deposited metal	Formation of cracks		
	First cracks	Crack network	Developed crack network
30Kh4V2M2FS	45	80	120
35V9Kh3GSF	30	70	100
Steel 5KhNM	15	50	70

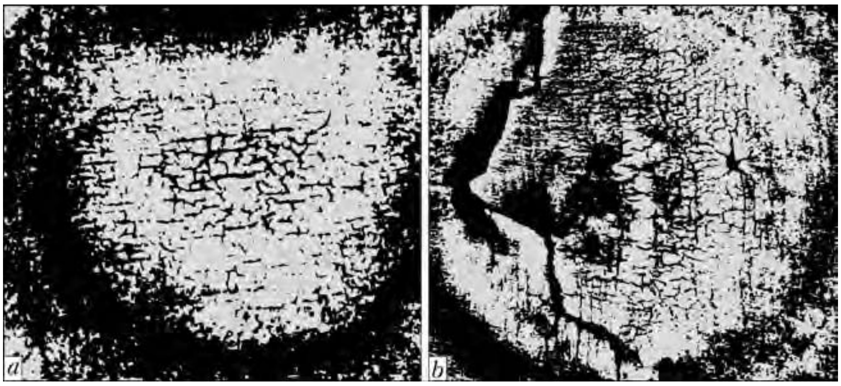

Figure 1. Appearance of specimens after thermal stability tests of deposited metal: *a* — 30Kh4V2M2FS; *b* — 35V9Kh3GSF

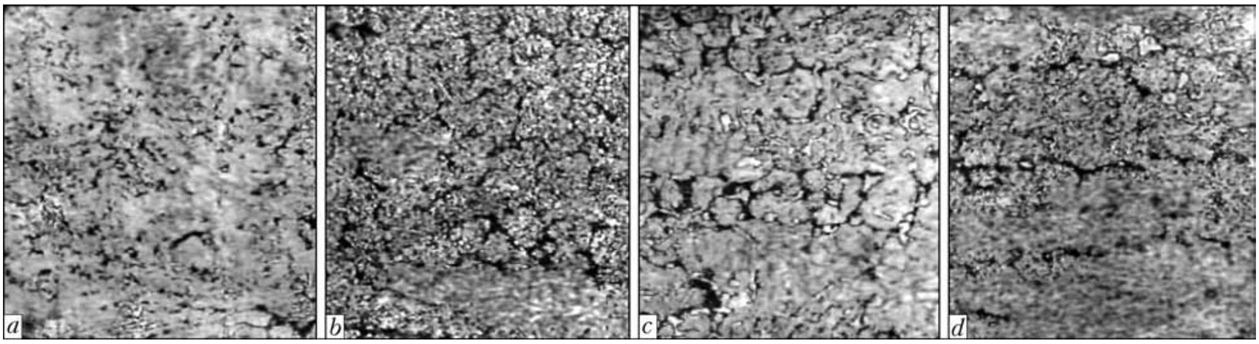

Figure 2. Microstructures (×400) of deposited metal 30Kh4V2M2FS (*a*, *b*) and 35V9Kh3GSF (*c*, *d*) before (*a*, *c*) and after (*b*, *d*) thermal stability tests

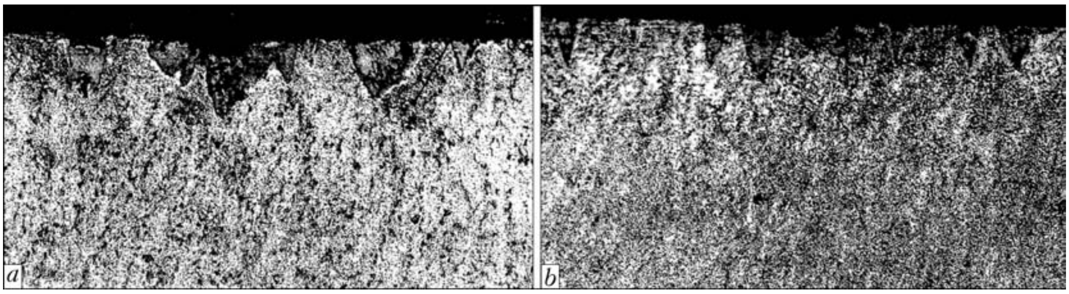

Figure 3. Microstructures (×100) of deposited metals 30Kh4V2M2FS (*a*) and 35V9Kh3GSF (*b*) in thermal cycling zone

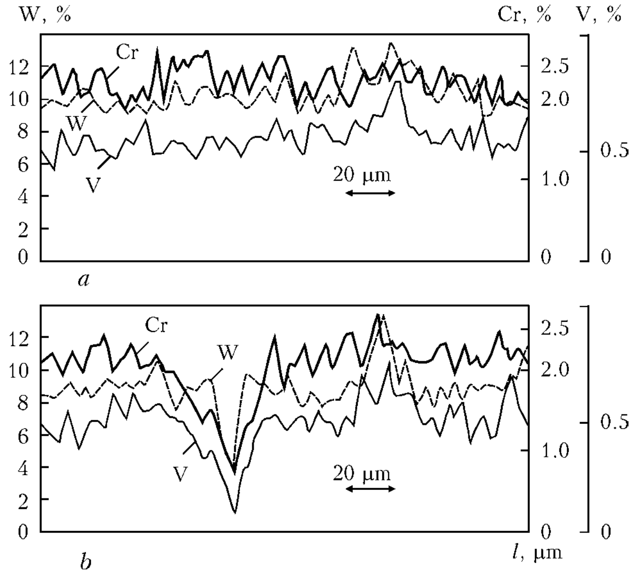

Figure 4. Distribution of alloying elements in deposited metal 35V9Kh3GSF before (*a*) and after (*b*) thermal stability tests

The best thermal stability values were exhibited by the deposited metal of the type of Cr–W–Mo steel, having a comparatively low content of tungsten.

Microstructure of the deposited metal was examined before and after the thermal stability tests. Up to 200 heating–cooling cycles were applied to provide a more complete development of fire cracks. Microstructure of the as-clad metal was examined in the last deposited layer, while after the thermal stability tests the examinations were carried out within the thermal cycling zone (location of fire cracks) at a distance of about 10–20 μm from the surface of the deposited layer.

Microstructure of both types of the deposited metal before and after the tests is shown in Figure 2, and that within the fire cracks zone at low magnification — in Figure 3.

Metal 30Kh4V2M2FS in the as-clad condition had fine-acicular martensitic-bainitic structure with hardness *HV* 5140–6060 MPa. Precipitates of retained austenite and an insignificant amount of eutectic were fixed along the polygonisation boundaries (see Figure 2, *a*). Cracks (see Figure 3) and structural changes evidencing coagulation and spheroidisation of carbides (Figure 2, *b*), as well as decomposition of martensite and partial decomposition of eutectic along the polygonisation boundaries, which led to decrease in hardness to *HV* 3830–4010 MPa, were detected after thermal cycling in the wear zone.

Approximately the same picture was fixed for deposited metal 35V9Kh3GSF. The martensitic structure with microhardness *HV* 5140 MPa was fixed in the matrix, while precipitates of retained austenite and an insignificant amount of eutectic were detected along the polygonisation boundaries (see Figure 2, *c*) after cladding. Decomposition of the martensite component (*HV* 3090 MPa) was fixed after the thermal stability tests, small regions of retained austenite being preserved (see Figure 2, *d*).

As shown by the examinations of microstructure, multiple heating and cooling cycles (thermal cycling) resulted in structural changes taking place in surface layer of the deposited metal, leading to its weakening. Also, this was proved by the results of X-ray diffraction analysis of phase composition. For instance, the content of the α-phase in metal of the 35V9Kh3GSF type after thermal cycling increased from 84 to 87 % because of formation of the ferrite component. Compressive stress of the second kind grew from –0.27 to –0.44 GPa.

X-ray spectral microanalysis of distribution of main alloying elements in structure of the clad specimens before and after the thermal stability tests at a depth of down to 20 μm from the cladding surface in parallel to it in the automatic mode with an interval of 2–99 μm along the fire crack network front was carried out by using analyser CAMEBAX SX-50. Figure 4 shows results of examinations of the 35V9Kh3GSF type deposited metal. Distribution of the main alloying elements in the deposited metal was practically uniform (Figure 4, *a*) and remained almost unchanged after the thermal stability tests, except for one point — dramatic decrease in the content of alloying elements was fixed in the thermal fatigue crack zone (Figure 4, *b*), which probably was caused by their oxidation.

Approximately identical character of distribution of alloying elements (before and after the tests) was noted in the 30Kh4V2M2FS type deposited metal.

It is likely that the temperature-time parameters of the chosen procedure for testing the deposited metal to thermal stability do not lead to diffusion of the main alloying elements in the investigated types of the deposited metal.

Therefore, though no diffusion of the main alloying elements was fixed in surface layer of the deposited metal of the die tool steel type, the changes in structure leading to its weakening were detected after multiple heating and cooling cycles.

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