*Welding International*
Vol. 22, No. 4, April 2008, 256–260
Selected from *Svarochnoe Proizvodstvo 2007* ***60*** *(7) 3–8*

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# Kinetics of the process of electroslag surfacing and the tructure of deposited metal based on nickel aluminide

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At present, the demand for surfacing materials, characterised by a higher creep strength in comparison with nickel and cobalt superalloys, is very strong [1]. The prospect of producing new, more effective and cheaper types of deposited metal is associated with the solution of the problem of stabilisation of the structure of these materials and the decrease of the extent of softening formed as a result of thermal-force loading at temperatures above 1000°C. One of the possible mechanisms of the formation of the mechanical properties of the surfacing alloys, working at these temperatures, is the hardening in the formation of the composite, heterogeneous structure of the metal, characteristic of the advanced creep-resisting casting alloys based on nickel aluminide, produced by the methods of high-gradient directional solidification [2].

The technology of electroslag surfacing is highly suitable for the deposition of wear-resisting and creep-resisting (up to 1100–1150°C) alloys based on alloyed aluminide γ'-$Ni_3Al$, characterised by high chemical heterogeneity of the deposited metal and the susceptibility to hot cracking under the effect of the hard thermal-deformation cycle of welding.[3] One of the efficient variants of producing high-quality directionally solidified metal is the technology of electroslag welding with a composite wire in this section with a current-supplying solidification mould, developed by the authors, using a hollow electrode and the two-circuit power supply to provide direct current to the slag pool.[4, 5]

The aim of the present work is the investigation of the special features of the heat and mass transfer in the slag in electroslag surfacing with a composite wire, and also examination of the phase composition, morphology and structure of the creep-resisting alloy based on γ'-$Ni_3Al$.

The investigations were carried out both on the basis of the direct experiments and by the simulation of electrophysical processes in the slag, the process of melting out physical–chemical interaction of different ingredients of the composite wire in the metal. The structure, micro-morphology and elemental composition of the weld meta where investigated by optical (digital microscope Olympus BX61) and electron microscopy (scanning mass spectrometer with the auto-emission cathode JEOL JSM6700F). The content and distribution of the alloying elements in the structural components were determined in scanning the sections in the local (1–3 $nm^3$) surface volume of the metal at a depth of up to 2 nm in the regime of application of the signals of secondary electrons. The phase composition of the metal was determined by x-ray diffraction analysis in copper radiation in DRON-3M diffractometer. The deformation resistance of the deposited metal was estimated on the basis of the high temperature hardness in TSh-2 equipment with a hard-alloy ball with a diameter of 5 mm at a load of 7.35 kN and a holding time of 10 s.

The two-layer shell of the composite wire was produced using nickel (NP-2, GOST 2170) and aluminium (A97, GOST 7871) strips, and the filler was in the fall of the wire made of commercial purity titanium, tungsten, molybdenum and Np-Kh20N20 nichrome, and also the charge consisting of a mixture of metallic powders of aluminium, nickel, zirconium and graphite GSP.

The experimental specimens were deposited and the process of electroslag surfacing investigated using a small welding system with a hollow non-consumable graphite electrode, with a spherical cavity at the end (Figure 1*a*). In electric arc melting of the ANF-6 flux in the solidification mould, the surface of the slag was blown with argon. The wire with the diameter of 4 mm was supplied into the slag through the hollow electrode with the speed of 0.5 cm/s. The height of the metal, deposited on the experimental specimens of 40Vohh steel, was 10 mm. This method of electroslag surfacing makes it possible to deposit on the ends of the component is a layer of metal with a thickness of 2–3 mm with unlimited height in the displacement of the component (or the blank) in the direction downloads along the solidification mould (Figure 1*a*) with the surfacing speed. The content of the alloying elements in the deposited metal (%): 0.5–0.8 C; 2.5–3.0 W; 2.5–3.0 Mo; 1.0–1.5 Zr; 3.5–4.5 Cr; 1.0–1.5 Ta; 4.0–6.0 Fe; 0.0 35–0.04 B; 0.15–0.20 Ti; 10.5–11.0 Al; Ni–balance.

The experimental results show that the stable electroslag process, and u and a high quality formation of the deposited metal lined showed and the ratio of the cans from the hollow electrode and the section of the solidification mould equal to 0.8–1.2. Consequently, it is possible to produce a high temperature region

ISSN 0950-7116 print/ ISSN 1754-2138 online

DOI: 10.1080/09507110802141933
http://www.informaworld.com

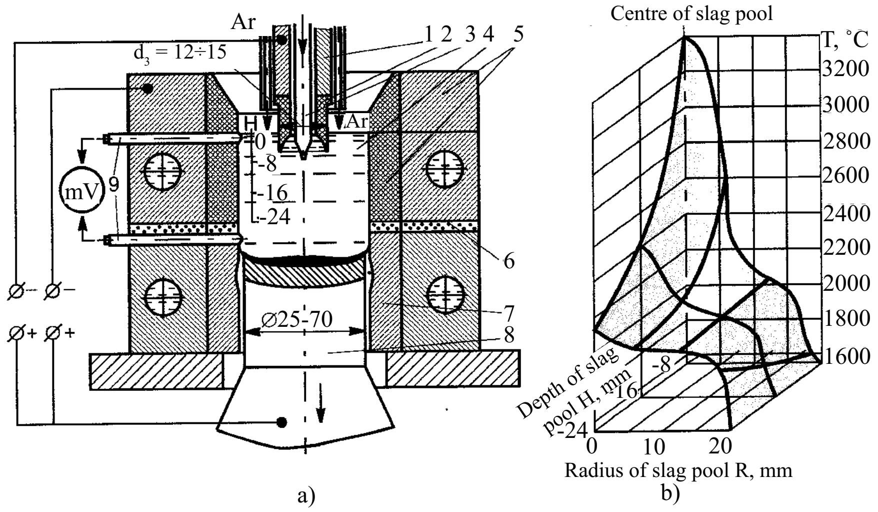


Figure 1. The diagram of electroslag surfacing in a solidification mould (*a*) and the thermal field in the slag pool (*b*): *1*) the current supply to the hollow electrode *2*; *3*) the composite wire; *4*) of the slag pool; *5*) separate graphite and copper current-supplying sections; *6*) insulator; *7*) the replaceable shaping section; *8*) the component to be deposited; *9*) the sensors for the control of the level of the slag and metallic pool.



with the current density of 550–650 A/mm$^2$ defined by the 3000°C isotherm in the slag when using a hollow electrode (Figure 1*b*). The presence in the slag of the concentrated heat source with the maximum temperature of up to 35°C in the spherical cavity of the electrode makes it possible to melt rapidly and efficiently as the composite wire and other surfacing materials, containing metallic components with different physical–mechanical properties. In the interaction of the electromagnetic and thermal fields from two heat sources, a toroidal rapidly moving high temperature flow appears in the slag pool. The effect of the flow on the hydrodynamic conditions in the slag increases (in comparison with the commercial process of electroslag surfacing) the holding time of the droplet of alloyed metal and increases the probability of the movement of the slag–metal system to the equilibrium condition in which the metallurgical processes take place to the very end.

The melt of the weld pool also moves under the effect of the forces of surface tension between the slag and the metal. This supports the redistribution of the droplet in the volume of the pool and results in the formation, in subsequent dissolution, of a deposited metal with the improved welding and technological properties.

The time-dependent interpretation of the process of surfacing is shown by the cyclogram in Figure 2a. As a result of preliminary treatment of the deposited surface with the rotating superheated slag, the end the volume of the component is characterised by the formation of a directional heat flow (Figure 2b) which not only supports the uniform spreading of the metallic melt but also determines the formation of the fusion zone without any defects. The high quality of the deposited metal, without any welding defects in the form of pores, nonmetallic inclusions, hot and cold cracks, etc, is achieved as a result of the efficient metallurgical treatment of the metal with the superheated basic slag and also by the effect of directional solidification. The formation of the surface of deposited metal is assured by the metered supply of heat into the world pool in the final stage of electroslag surfacing in the presence of pulsations of current from the section of the solidification mould.

Analysis of the equilibrium diagrams of the Ni–Al system and of the process of melting of the filler material shows that in the stage of the nation of the composite wire into the superheated slag in interaction of aluminium and nickel layers in the composite wire the most probable thermodynamic process is the formation of the aluminide melt γ'-$Ni_3Al$. In heating the shell of the wire,

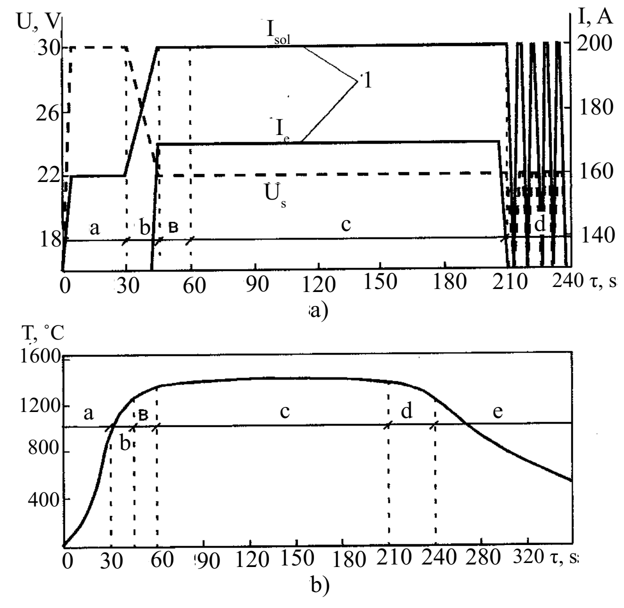


Figure 2. The cyclogram of the process of electroslag surfacing of the cylindrical end with a diameter of 30 mm (a) and the thermal cycle of surfacing in the vicinity of the conventional fusion line (b) ($U_s$ – the voltage in the slag pool, *a* – process, *b* – unstable electroslag process, *c* – the start of rotation of the slag pool, *d* – the supply of wire into the slag; e) the formation of the deposited metal; f) cooling of the metal after surfacing): *1*) the variation of current from the current-supplying section of the solidification mould $I_m$ and the hollow electrode $I_e$.

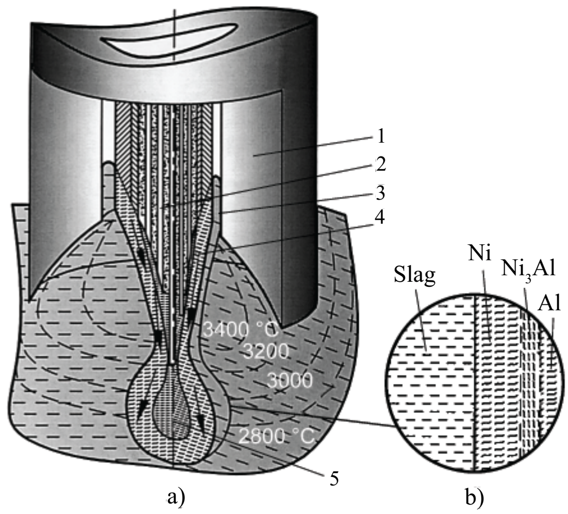


Figure 3. The diagram of the melting of the end of the composite wire (a) and the interaction of the layers of the shell (b): *1*) the hollow graphite electrodes; *2*) the composite wire; *3*) the superheated slag in the gap between the electrode and the wire; *4*) the γ'-$Ni_3Al$ melt; *5*) of the droplet of the melt of the filler of the wire, coated with nickel aluminide.

the aluminium layer of the shell melts at a higher rate leading to the development of the processes of adsorption of nickel in liquid aluminium and in the initiation of a chemical reaction between these metals. The diffusion nature of the formation of the intermetallic compound in this case is unlikely to be observed because of the short-term (up to 0.1 s) holding time of the contacting phases in the high temperature range of the slag pool (Figure 3). In the next stage of the process of melting in the conditions of comparable values of the surface tension of the liquid aluminide and at the interface between the liquid aluminide and the slag, the melt of the filler of the wire is wetted, followed by dissolution in the aluminide.

The examination of the structure and composition of the slag, solidified after surfacing, shows that the chemical elements, present in the ANF-6 flux, are distributed not uniformly along the height of the slag pool (Figure 4). The chemical heterogeneity of the slag is influenced by the distribution of temperature and the volume of the slag after completion of the process of electroslag surfacing. Because of the higher temperature of the slag in the surface volume of the pool, the content of the calcium fluoride with the lower boiling point in the $Al_2O_3$–$CaF_2$ system decreases and this is confirmed by the data in reference 6. In this case, the ratio of oxygen and aluminium correspondingly increases. The increase of the carbon content in the slag is explained by the erosion of the graphite coating of the current-supplying section of the solidification mould and the hollow electrode. It should be mentioned that in the volumes are adjacent to the interfacial boundary, the content of carbon and aluminium in the slag and the metal is identical in accordance with the law of heterogeneous equilibrium (Figure 4b, 5a).

Other alloying elements in the slag were not detected, indicating the sufficiently higher degree of dissolution of these elements in the metal of the weld pool. One of the probable reasons for this low-activity mass transfer between the droplet of the liquid metal, formed in melting of the wire, and the slag, is the screening effect of liquid aluminide γ'-$Ni_3Al$. The shell of the wire contains, for a certain period of time, the alloyed melt of the filler of the wire, easily oxidised with tantalum, zirconium and titanium.

The results of metallographic examination show that the directionally solidified (as a result of electroslag surfacing) metal has a complicated hetero phase structure. The structure of the metal (Figure 6) consists mainly of relatively large (linear size 10–40 μm, volume content 65–70%) primary dendrites of alloyed aluminide γ'-$Ni_3Al$. They contain the γ-solid solution based on nickel

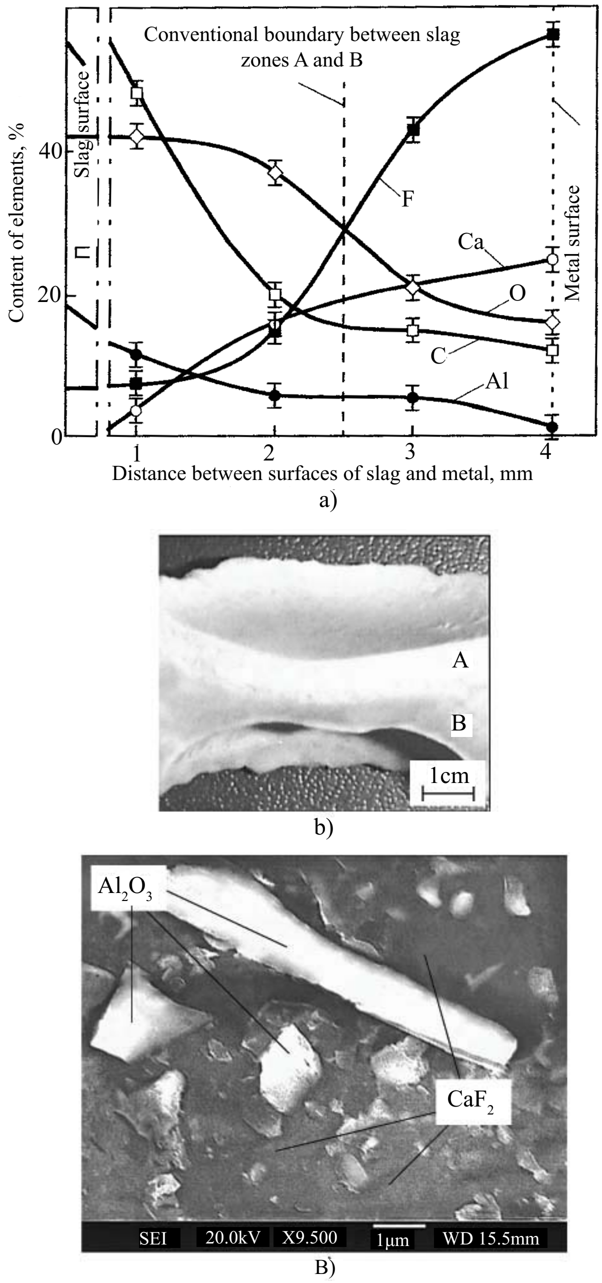


Figure 4. The distribution of alloying elements along the height of the slag pool (a), the macrosection of the solidified slag pool (b) and the microstructure of the slag (c, × 9500).

characterised by the disordered structure, and also alloyed with chromium, tungsten, molybdenum, tantalum, titanium and ion; there are also dispersed (0.2–0.5 μm) secondary $\gamma'_{sec}$ -phases; intermetallic compounds CrNiMoTiZr (χ-phase); refractory carbides $Ta_2C$, WC, $Mo_2C$ and a small amount of nonequilibrium inclusions of the β-NiAl-phase, which has not reacted as a result of the peritectic reaction L + β-NiAl ↔ γ'-$Ni_3Al$. The interdendritic spaces (Figure 5a) contain irregular aluminides $\gamma'_{eu}$ of the eutectic origin with precipitates of the χ-phase (Figure 5a, region *7*). The carbide eutectic and the $\gamma'_{eu}$ phase (region 6), consisting of the $Cr_7C_3$ and $Mo_2C$ carbides are uniformly distributed between the primary crystals of γ'. The total content of the γ'-$Ni_3Al$ phases of different origin in the deposited metal is 85–90%.

In electron probing of the surface of the alloys of the experimental specimens in the local (3 μm in Figure 5b and 30 μm in Figure 7) sections of the dendrites it was found that their composition is characterised by relatively high chemical micro-heterogeneity. This influences the

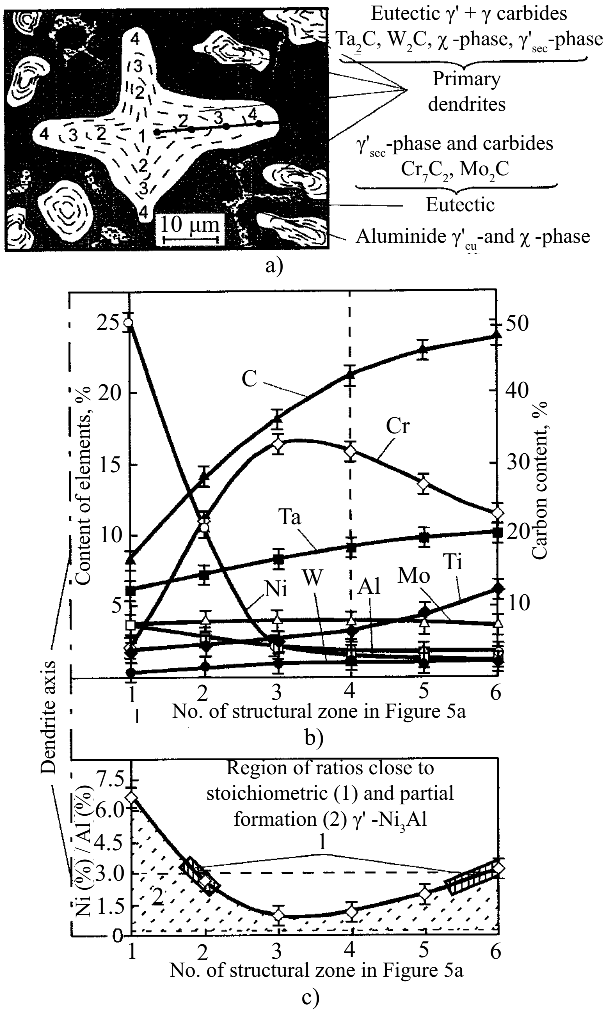


Figure 5. The distribution of the phases in the structure of the deposited metal (the area of analysis of the chemical composition of the metal in the local micro volumes indicated by the points) (a), the content of the elements in the cross-section of the primary dendrites γ'-$Ni_3Al$ (b) and nickel and aluminium in the cross-section of the dendrite of γ'-$Ni_3Al$ (c).

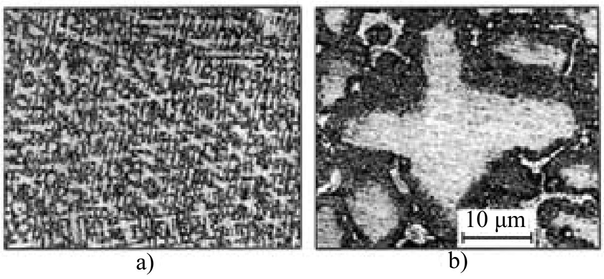


Figure 6. The microstructure of the deposited metal: *a*) the general appearance (× 100); *b*) dendrite γ'-$Ni_{23}Al$ and the surrounding phases (× 1000).

ratio of the content of nickel and aluminium, which determines the formation of the aluminide γ'. This ratio is closest to the stoichiometric value (Figure 5c) in the regions of primary crystals in the immediate vicinity of nickel-supersaturated axial volumes, and also in spaces between them, with the concentration of the $\gamma'_{sec}$ -phase. It has been established that the liquation of nickel, chromium and carbon in the alloyed is especially intensive. This indicates the preferential precipitation of the layers of the γ-solid solution in the axle volumes of the dendrites and the more active carbide formation in the remote areas of the structure of the deposited metal. Having the size of 4–8 μm, the intermetallic compounds of the χ-phase, characterised by low solubility at high temperatures, with the content of these phases in the alloyed of up to 15–18%, uniformly distributed with a high density (the distance between the particles 10–15 μm) both in the primary crystals and in the eutectic γ'-phase.

It is evident that the higher creep strength of the investigated deposited metal maybe explained by the combined effect of structural hardening of two types leading to the formation of the so-called natural composite.

The first type of hardening is determined by the presence of the stable composite structure, consisting

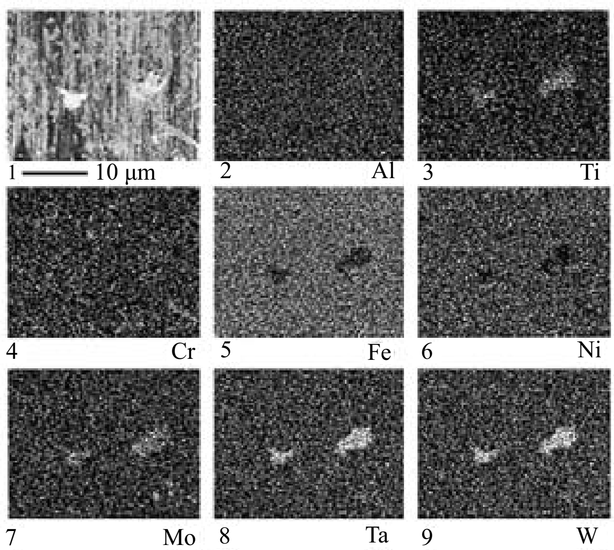


Figure 7. The microstructure of the local section of the primary dendrite of γ'-$Ni_3Al$ (1) and the distribution of the alloying elements in the dendrite (2–3).

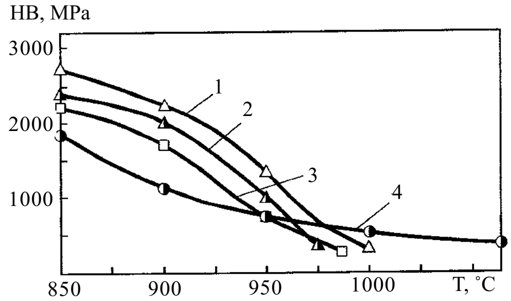


Figure 8. The dependence of the hardness of the deposited metal at high temperature on the test temperature: 1) 160Kh28K60V8N Stellite; 2) Hastelloy-C; 3) 250Kh22N66M4B2Ts; 4) deposited metal based on alloy γ'-$Ni_3Al$.

of the strong frame of the $\gamma'_{sec}$ -phase and the carbide eutectic combined with the ductile matrix in the form of a dendritic solid solution, alloyed with refractory elements, representing the eutectic based on γ' + γ. The second type of hardening is characterised by the presence in the alloy of a relatively high fraction of the thermal dynamically stable micro-particles of the χ-phase with a stable size, morphology and distribution.

The comparative analysis of the results of tests of the creep-resisting deposited metal of different structural types (Figure 8) shows that the alloy based on γ'-$Ni_3Al$, produced by electroslag surfacing, is characterised by higher resistance to plastic deformation in the temperature range 950–1100°C.

The application of the new material in the industry makes it possible to increase the efficiency of the deposited heavily loaded components of machines and tools subjected to the long-term effect of heat and forces at temperatures of up to 1100°C.

## Conclusions

In the electroslag surfacing with the ANF-6 flux using the two-circuit power supply for the slag pool using direct current with the comparable values of the cavern from the nonconsumable electrode, the slag is characterised by the formation of the thermal–kinetic conditions for the uniform melting of the similar ingredients of the composite wire and a relatively complete transfer of the alloying elements, including easily oxidised aluminium, tantalum, titanium and zirconium, from the wire into the weld pool. This results in the production of the high quality deposited metal based on γ'-$Ni_3Al$.

The higher high temperature properties of the metal, deposited by electroslag surfacing, and based on γ'-$Ni_3Al$, in comparison with the surfacing alloys based on nickel and cobalt, obtained as a result of the formation of the heterophase composite structure, determined by the redistribution of the alloying elements in the volume of the dendrites of γ'-$Ni_3Al$ and by the formation of the regions of concentrational heterogeneity in the precipitation of the microparticles of intermetallic compounds $\gamma'_{sec}$ and χ-phases, and also mono carbides of refractory metals.

## References

1 Skachkov, O.A., Promising creep-resisting and high temperature alloys based on intermetallic compounds NiAl and $Ni_3Al$, *Stal'*, 2002, (2) 74–77.

2 Povarova, K.B., et al., The comparative analysis of the principles of formation of creep-resisting on nickel superalloys and alloys are based on intermetallic $Ni_3Al$ (γ'-phase), *Perspektivnye Materialy*, 2005, (2), 10–18.

3 Sokolov, G.N., et al., Electroslag surfacing of the heat-resisting alloy based on $Ni_3Al$ on steel in order to harden the tools for hot deformation of steels, *Voprosy Materialovedeniya*, 2004, (2), 87–98.

4 Sokolov, G.N., et al., Special features of the process of electroslag surfacing with a composite bar in a small section solidification mould, Avt Svarka, 2004, 10, 26–30.

5 Tsurikhin, S.N. et al., Powder wire for the surfacing of alloys are based on nickel aluminide, *Svar Proiz*, 2006, 1, 17–22.

6 Moisov, L.L., et al., Thermodynamic activity of the components in the ANF-6 flux, *Svar Proiz*, 1983, 3, 10–11.