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FORMATION OF STRUCTURE AND PROPERTIES OF HIGH-ALLOY CORROSION-RESISTANT STEELS IN ELECTROSLAG REMELTING

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Results of investigations of metallographic structure, chemical, phase compositions and physical-mechanical properties of high-alloy corrosion-resistant steels 316L and C20, produced by the electroslag remelting method, are given.

Keywords: *electroslag remelting, high-alloy steels, microstructure, dendrites, polycrystals, mechanical properties*

Reliability and service life of modern machines and mechanisms are greatly defined by the quality of their separate components. Special requirements are specified to the products designed for service under strict and limiting extreme conditions (action of increased and high temperatures, high loads, presence of aggressive media). The fulfillment of these requirements leads to the complication of chemical composition of metals and alloys, to the need in improving quality of the metal of billets. In addition, the method of producing billets should be inexpensive and adaptable [1].

Using traditional methods of producing billets, such as forging, rolling of ingots, centrifugal casting, it is not always possible to produce products of the required quality. Moreover, forging and rolling, because of use of complex and powerful forge-press and rolling equipment, are very expensive methods of producing products. The application of the centrifugal casting in producing billets (long pipe billets in particular) has its advantages, such as high productivity, metal saving to 45–50 %, reduction in a production cycle [2]. However, as to the metal quality the billets of the centrifugal casting are inferior to the forge castings, as the liquation of chemical elements, carbon in particular, is observed both in their length and across the thickness [1].

In this connection the electroslag remelting has undoubted advantage, the use of which makes it possible to produce metal of a high density, physical and chemical homogeneity, isotropy of properties, uniform distribution of non-metallic inclusions characterized by a high purity and fine-dispersed structure. All the above-mentioned is very important, if the ready product is under the extreme service conditions, where its stable high physical and mechanical properties are required.

The present work presents the results of investigations of metallographic structure and properties of ingots from high-alloy corrosion-resistant steels 316L

and C20 of foreign production after electroslag remelting (ESR).

The works were carried in industrial monobifilar electroslag furnace EShP-2.5 using a short movable mould. The program of investigations included the selection of technological conditions of melting two ingots: hollow ingot of $560 \times 140 \times 1550$ mm size and 2.45 t mass and solid ingot of 560 mm diameter, 2050 mm length and 3.6 t mass. To melt the hollow ingots the square-section electrodes (square side was 120 mm) were used, while the 400 mm diameter electrodes were used for the solid ingots.

The general view of the hollow ingot from high-alloy steel 316L after ESR is given in Figure 1.

After melting the hollow ingot, the specimens were cut out from its head, middle and bottom parts to perform the further investigations. Chemical composition of initial consumable electrodes and melted hollow ingot from steel 316L is given in Table 1.

As is seen from the Table the metal of the corrosion-resistant steel was significantly refined after ESR. Here, the content of harmful impurities, sulphur in particular, was much decreased in the entire length as compared with that of the consumable electrode initial metal. Content of alloying elements was averaged: they were uniformly enough distributed in section and length of the melted hollow ingot.

In examination of macrostructure of transverse sections of specimens cut out from the bottom, middle and head parts of the hollow ingot (Figure 2), the differences in formation of structures in the hollow ingot zones were revealed.

Thus, the macrostructure of specimens cut out from the bottom and middle parts of the hollow ingot (Figure 2, *a* and *b*) after ESR is characterized by homogeneous and dense structure without defects of liquation and shrinkage origin. Three zones are distinguished in the macrostructure of specimens: two finer-grained and dense zones at the external layers of ingot section, and the third zone is inside the section having a lower density of grains. The presence of these zones is connected with a different rate of crystallization in the ingot section. Here, the defects of a

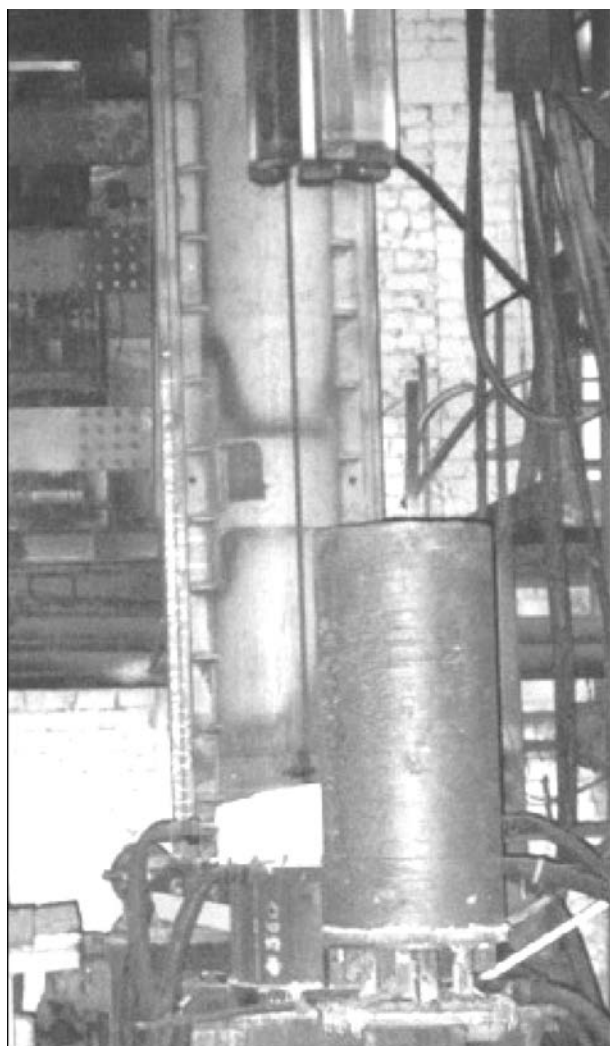


Figure 1. General view of hollow ingot

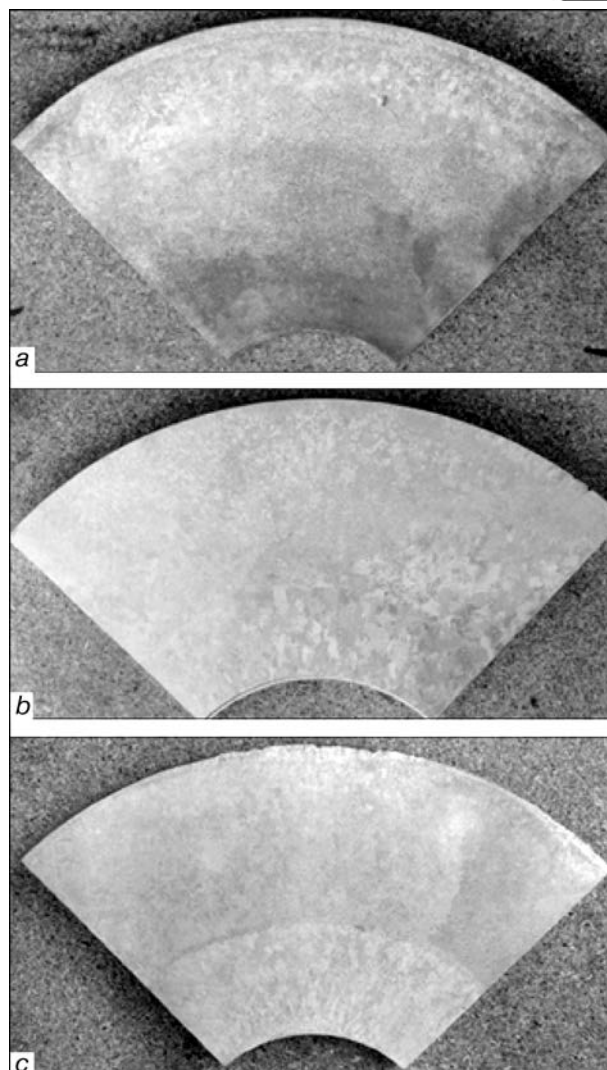


Figure 2. Macrostructure of transverse section of specimens cut out from bottom (a), middle (b) and head (c) parts of hollow ingot

Table 1. Chemical composition (wt.%) of hollow ingot and initial electrodes from steel 316L

Specimen	C	Mn	P	S	Cr	Ni	Mo	Cu
Initial electrode	0.016–0.020	1.83	0.036	0.014–0.016	16.9–17.9	9.56–9.82	2.26	0.41
Ingot parts:								
bottom	0.013–0.014	1.79–1.81	0.026–0.028	0.0011–0.0012	17.0–18.0	9.0–9.4	2.09–2.12	0.37–0.39
middle	0.014–0.015	1.81–1.82	0.027–0.028	0.008–0.009	17.5–18.0	9.7–10.0	2.16–2.18	0.36–0.38
head	0.019–0.022	1.81–1.82	0.030	0.007–0.008	19.5–19.6	10.17–10.40	2.26–2.30	0.32–0.34

Table 1 (cont.)

Specimen	Si	Ti	Al	B	Nb	V	W
Initial electrode	0.55	0.02	0.015	0.0002	0.08	0.092	0.015
Ingot parts:							
bottom	0.51–0.53	0.011–0.012	0.011–0.012	0.00016–0.00018	0.08	0.070–0.077	0.004–0.006
middle	0.42–0.44	0.012–0.013	0.011–0.012	0.00018–0.00020	0.077–0.078	0.075–0.080	0.012–0.014
head	0.47–0.48	0.012–0.013	0.006–0.008	0.00015–0.00017	0.074–0.076	0.07–0.09	0.007–0.009

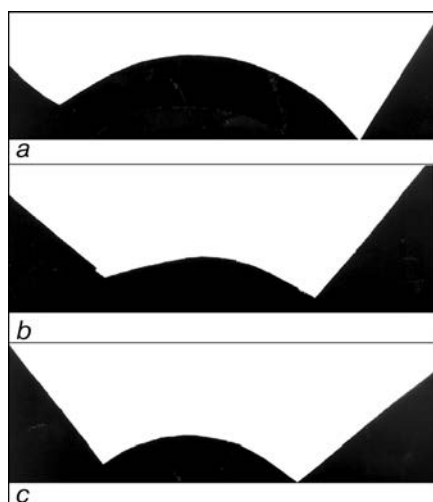


Figure 3. Fragments of sulphur prints of head (a), middle (b) and bottom (c) parts of hollow ingot

shrinkage origin (of porosity type) are not formed inside the ingot.

The macrostructure of the transverse section of the head part of the hollow ingot (Figure 2, c) is characterized by the presence of a fine-grain band formed at the junction of crystallization zones. The formation of this zone of «meeting» crystals is typical of a transcrystalline mechanism of crystallization. The latter takes place when the growth of radial-axial crystals occurs opposite each other from the mould wall and they are abutted approximately at 1/3 of the ingot thickness forming narrow crystalline bands. The appearance of defects of a shrinkage and liquation origin in the zone of «meeting» transcrystallites was not observed. These differences in the macrostructure of zones located in the ingot height are, evidently, due to thermophysical peculiarities of the ESR process.

The examination of the macrostructure of all the parts of the hollow ingot using a sulphur print did not reveal the presence of structure heterogeneity due to a sulphur liquation (Figure 3).

It is seen during comparison of sulphur prints of specimens cut out from a transverse section of hollow ingot and initial electrode from steel 316L (Figure 4) that after ESR the metal is much purer as to the sulphur content, which was spread uniformly in section and length of the ingot (see Table 1).

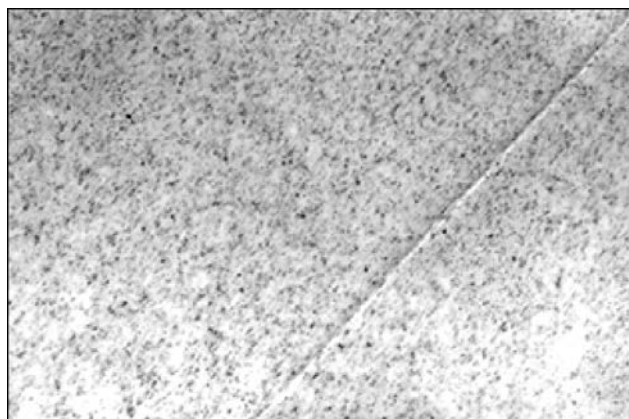


Figure 4. Fragment of sulphur print of 316L steel initial electrode

Table 2. Physical-mechanical properties of metal of transverse specimens of steel 316L hollow ingot

Ingot parts	σ_t , MPa	σ_y , MPa	δ , %	ψ , %
Bottom	480–500	200–210	60–70	66–69
Middle	520–540	230–240	60–65	66–68
Head	530–560	250–260	65–66	56–62

Examinations of macrostructure of a longitudinal section of the hollow ingot revealed some peculiarities connected with the conditions of its crystallization (Figure 5).

In the macrostructure of the longitudinal section of the bottom part of the ingot (Figure 5, a) the dendritic axes, oriented at 45° angle to the edge zones and directed vertically to the central zone, are clearly distinguished. In the macrostructure of the hollow billet middle part (Figure 5, b) the dendritic axes in the zone, adjacent to the 140 mm inner hole of the ingot, are oriented at 45° angle, while in the external part — at 60° angle. They are directed vertically to the central zone. In the macrostructure of a longitudinal section of an ingot head part (Figure 5, c) the dendritic axes have a transcrystalline nature of orientation at 60° angle of inclination in the external zone and 45° in the zone adjacent to the 140 mm diameter inner hole of the ingot. The zone of «meeting» dendrites has a form of a narrow band consisting of columnar polycrystallites. Fragment of scheme of crystallization of a hollow ingot from steel 316L is presented in Figure 6.

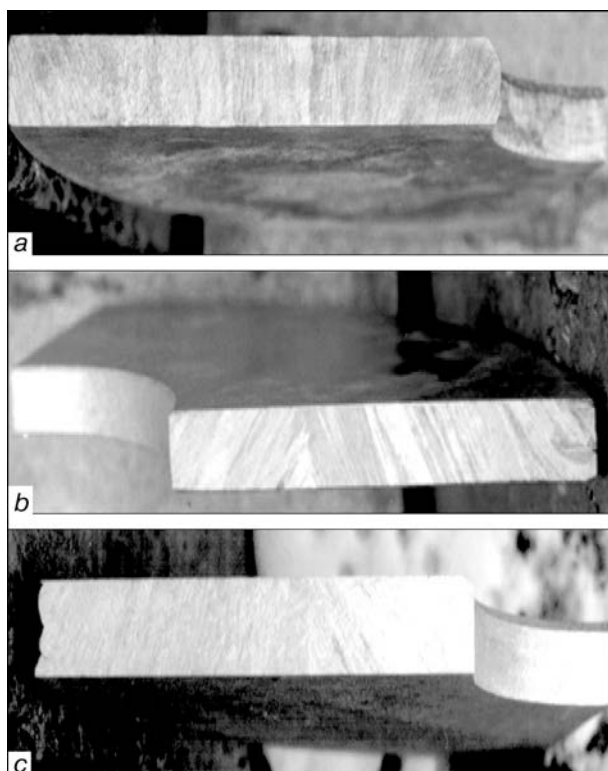


Figure 5. Macrostructure of longitudinal section of specimens cut out from bottom (a), middle (b) and head (c) parts of hollow ingot



Table 3. Content of oxygen and nitrogen in steel 316L, initial electrode and hollow ingot

Specimen	Mass share, %	
	O ₂	N
Initial electrode	0.00959	0.07827
Ingot parts:		
bottom	0.00163	0.01112
middle	0.00184	0.00832
head	0.00278	0.00941

This nature of orientation of dendritic axes of all the hollow ingot parts investigated promotes the formation of a favourable combination of strength and ductile properties of the metal (Table 2).

To examine the microstructure of steel 316L of hollow ingot after ESR the specimens were cut out from different zones of a transverse section of the ingot.

It was not managed to reveal inclusions of oxide and sulphide origin in the steel microstructure using a method of a metallographic analysis, probably, due to a negligible content of sulphur (see Table 1) and oxygen, however nitrides of up to 10 μm size (3–5 pcs in the field of ocular) were revealed. This is associated with a high, as compared with oxygen, nitrogen content, that is correlated with data presented in Table 3. These data were obtained during investigations using a LECO gas analyzer TS-436.

As is seen from Table 3, the content of harmful gases (oxygen and nitrogen) after ESR was decreased greatly and located within the allowable range, which is 0.0021–0.0049 wt.% for oxygen and 0.0050–0.0135 wt.% for nitrogen [3].

Metallographic examinations of etched sections showed that the microstructure of metal of all the specimens is austenitic with an orientation of crystallites typical of polycrystalline materials with a dendritic shape of crystals, characteristic of crystallization of metal under the conditions of the temperature gradient and microliquation of alloying elements (Figure 7).

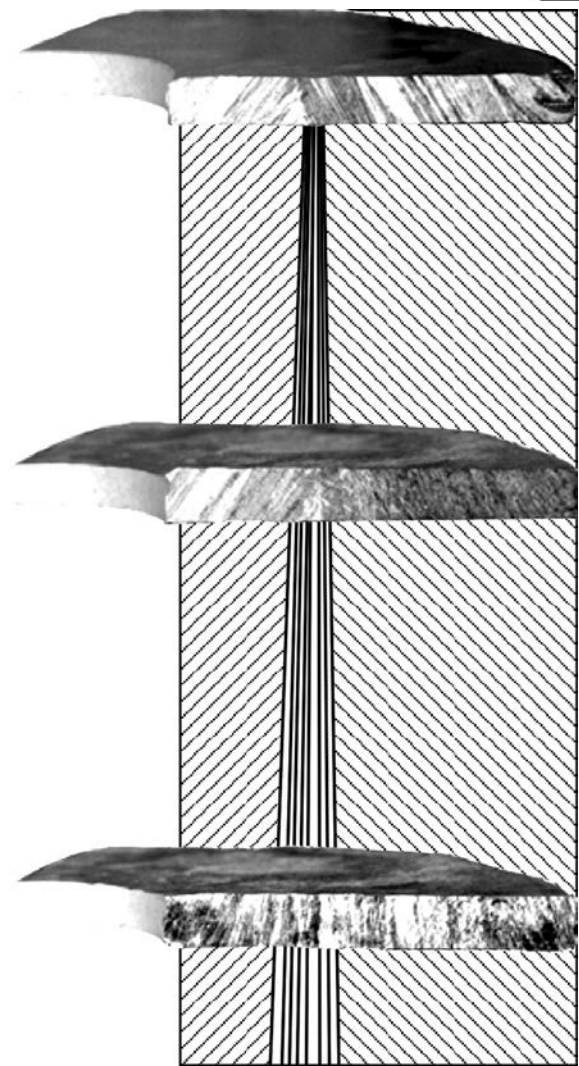


Figure 6. Fragment of scheme of crystallization of hollow ingot from steel 316L (right half of the longitudinal section)

The next stage of experiments was the investigation of formation of structure and properties during ESR in a solid ingot from high-alloy corrosion-resistant steel C20, whose chemical composition is given in Table 4.

Data of the Table show that metal after ESR of high-alloy corrosion-resistant steel C20 became more purified from sulphur as compared with the metal of

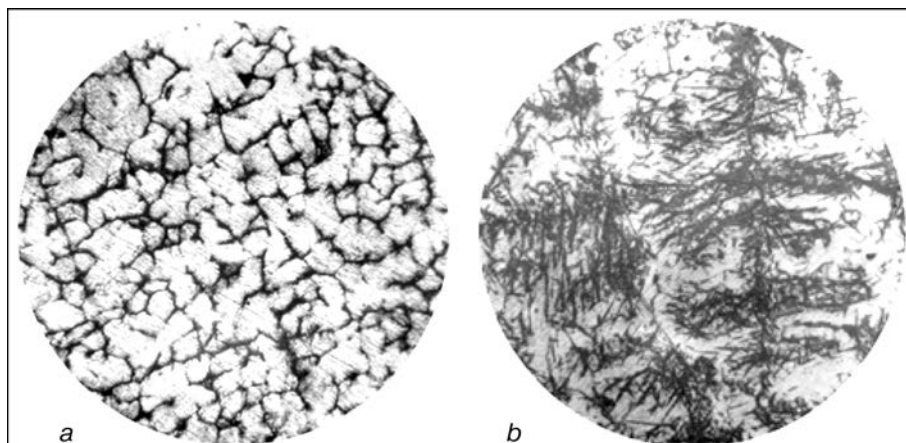


Figure 7. Orientation of crystallites in microstructure of steel 316L of hollow ingot (a) ($\times 100$) and their structure (b) ($\times 500$)



Table 4. Chemical composition (wt.%) of steel C20 solid ingot and initial electrodes

Specimen	C	Mn	P	S	Si	Cr	Ni	Mo
Initial electrode	0.036–0.033	0.82	0.033	0.018	0.52	16.3–16.7	33.0	2.60
Ingot parts:								
head	0.018–0.021	0.77–0.78	0.024–0.025	0.005–0.006	0.52–0.53	15.9–16.4	32.7–32.8	2.48–2.50
middle	0.0152–0.0156	0.77–0.79	0.017–0.018	0.004–0.005	0.48–0.50	15.7–16.0	32.0–32.4	2.17–2.24
bottom	0.014–0.048	0.74–0.77	0.018–0.019	0.0011–0.0012	0.50–0.51	15.5–15.8	31.5–32.2	2.28–2.33

Table 4 (cont.)

Specimen	Cu	Ti	Al	B	Nb	Sn	Ce
Initial electrode	3.28	0.04	0.07	0.0008	0.4	0.02	0.035
Ingot parts:							
head	3.21–3.23	0.037–0.038	0.010–0.015	0.0012–0.0013	0.41–0.42	0.016–0.017	0.038–0.040
middle	3.10–3.16	0.036–0.037	0.020–0.024	0.0007–0.0008	0.40–0.41	0.018–0.019	0.034–0.035
bottom	3.18–3.22	0.034–0.036	0.021–0.023	0.0006–0.0007	0.41–0.42	0.017–0.018	0.036–0.037

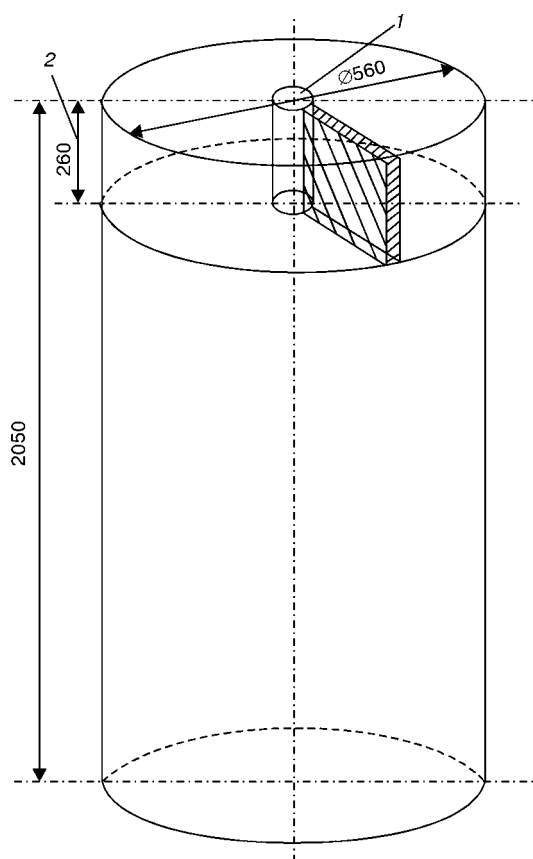


Figure 8. Scheme of cutting specimens out of C20 steel solid ingot: 1 – technological hole of 80 mm diameter; 2 – head part

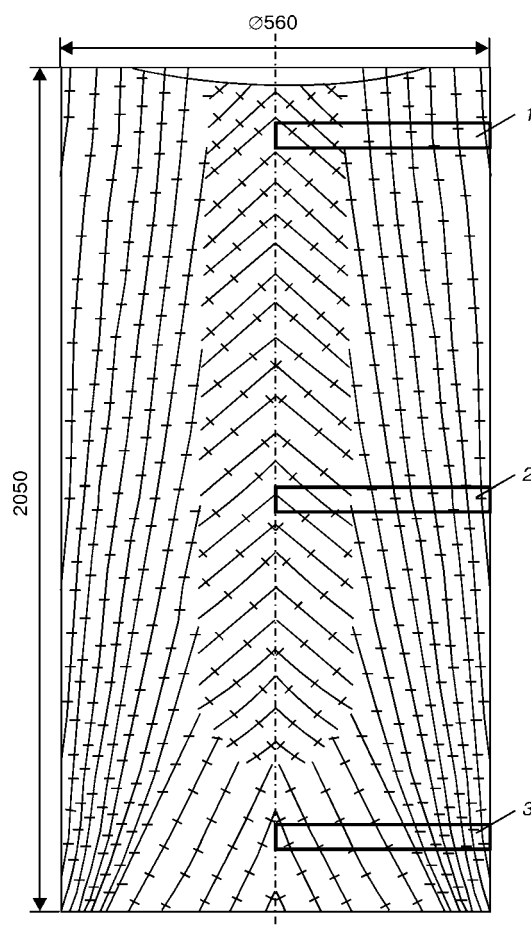


Figure 9. Scheme of crystallization of solid ingot: 1–3 – head, middle and bottom parts of ingot, respectively



an initial electrode and homogeneous in chemical composition both in section and also in the entire length of the ingot.

To perform the metallographic examinations the specimens were cut out from the head, middle and bottom parts of the solid ingot. A scheme of cutting ingots from the ingot head part is given in Figure 8, cutting of specimens from the middle and bottom parts was similar.

During crystallization the formation of microstructure of different zones of metal, subjected to changes from the head to bottom parts of the ingot, is occurred. Scheme of formation of crystallization zones for ingot solidification is given in Figure 9.

Two zones of directed crystallization are distinguished in the macrostructure of a longitudinal section of head and middle parts of the solid ingot (Figure 10): *I* — columnar dendrites located almost parallel to the ingot vertical axis; *II* — inclined dendrites locating in the ingot center and forming 45° angle with its vertical axis.

The macrostructure of a longitudinal section of the specimen of the ingot bottom part has a transcryst-

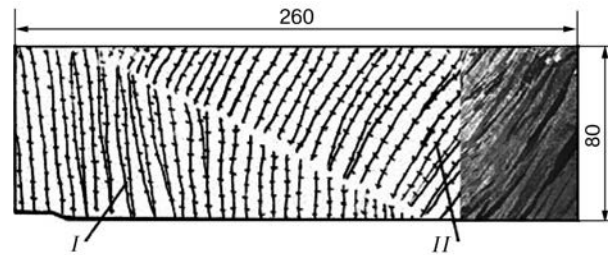


Figure 10. Directed crystallization in structure of longitudinal macrosection of solid ingot

talline nature of orientation of dendrites with 60° angle of inclination, that reflects the stability of thermophysical conditions of metal solidification in this part of the ingot.

The directed successive solidification of metal in the conditions of a constant replenishment of crystallization front with a liquid metal hindered the occurrence of the physical heterogeneity. Owing to this, there were no porosity, shrinkage cavities and liquation zones in the macrostructure of transverse sections of specimens cut out from all the parts of the solid ingot.



Figure 11. Microstructure of C20 steel solid ingot after ESR (×200)



Figure 12. Formations of δ -ferrite in microstructure of steel C20 (×200)

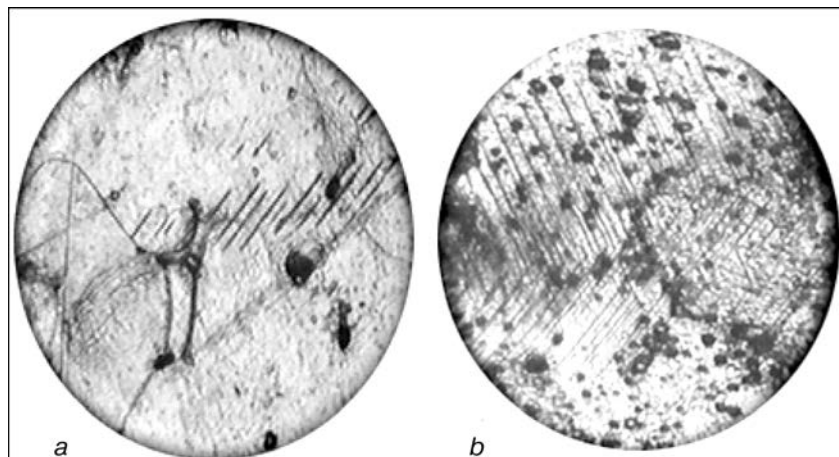


Figure 13. Intermetallic (*a*) (×200) and carbide (*b*) (×500) formations in microstructure of steel C20

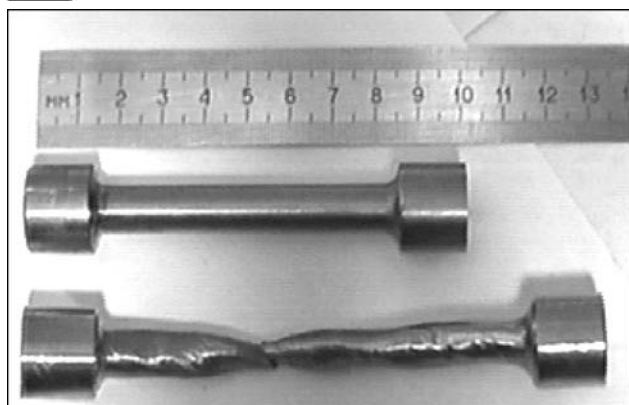


Figure 14. Specimens of steel 316L before and after mechanical tests

The presence of physical and chemical homogeneity of metal of specimens cut out from the longitudinal and transverse section of the ingot is confirmed by examinations of the macrostructure using Bauman's method. Fragment of a sulphur print proves high purity of chemically homogeneous metal.

Investigation of structure of specimens cut out from three zones of steel C20 solid ingot showed that metal has a structure of austenite with inclusions of intermetallic formations with sizes of primary grains which correspond to 6–7 marks of scale of GOST 5639–82 (Figure 11).

The main dendritic axes in microstructure of steel C20 are distinguished by formations of δ -ferrite which, as is seen from Figure 12, look like light formations in a dark fringing on the etched section. The presence of δ -ferrite indicates the high rate of crystallization at high temperatures. The defined zones, being elongated formations of intermetallics and carbides, and also compounds in the form of light small rhombs and spherical points, acicular compounds, oriented by the type of dash lines, separating the grain, are observed inside its grains (Figure 13). The variety of their shapes and orientation is, probably, associated with a high content of alloying elements (see Table 4), and also with crystallographic peculiarities of complex compounds formed by them.

Table 5. Physical-mechanical properties of metal of transverse specimens of steel C20 solid ingots

Ingot part	σ_t , MPa	σ_y , MPa	δ , %	ψ , %
Bottom	440–460	170–180	60.5–75.0	63–65
Middle	480–500	200–220	65.0–70.0	64–66
Head	470–490	190–210	65.0–68.0	63–65

Thus, the examination of microstructure of specimens cut out from the solid ingot showed that it is typical by a directed crystallization of dendritic structure without liquation clusters; even in the cast state the austenitic grains have a form of clearly defined intermetallic compounds of iron with alloying elements included to the chemical composition of steel C20.

Investigations of physical-mechanical properties of steel C20 after ESR were made on specimens of longitudinal section cut out from the head, middle and bottom parts of the ingots (Table 5).

Data given in the Table show the high physical, chemical and structural homogeneity of steel C20 after ESR. Good strength, and especially, ductile properties of the metal were produced owing to a proper selection of technological parameters of remelting (rate of melting, selection of slag and thickness of skull). This is confirmed by the appearance of specimens before and after tensile tests (Figure 14).

Coming from the above-described, the conclusion can be made that the further improving ESR will make it possible to produce the large-sized billets characterized by the high quality of the metal both in the entire length and also in the section of the ingot of any steels of a complex chemical composition.

1. (1981) *Electroslag metal*. Ed. by B.E. Paton, B.I. Medovar. Kyiv: Naukova Dumka.
2. Kurbatov, I.P. (1969) *Artillery materials science*. Moscow: Voenizdat.
3. Volkov, S.E., Volkov, A.E., Zabaluev, Yu.I. et al. (1979) *Non-metallic inclusions and defects in electroslag ingot*. Moscow: Metallurgiya.



SINGLE-STAGE ELECTRON BEAM TECHNOLOGY OF DEPOSITION OF THERMAL BARRIER GRADIENT COATINGS

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Mechanism of formation of gradient structures produced by electron beam evaporation of composite ceramic ingot on the base of zirconium dioxide is considered. Results of investigations of chemical composition, structure and some properties of thermal barrier gradient coatings deposited from the vapour phase on the surface of heat-resistant alloys using a single-stage technology are presented.

Keywords: *electron beam evaporation and deposition (EB-PVD), thermal barrier gradient coatings, gas turbine blades, zirconium dioxide*

Thermal barrier coatings, consisting of a metal bond coat and external ceramic layer on the base of a stabilized zirconium dioxide, are widely used for protection of blades of aircraft and industrial gas turbines. They increase the service life of the turbine blades and also improve the efficiency of operation of the gas turbine engine by the increase in gas temperature [1, 2].

Traditional technological cycle of thermal barrier coating deposition includes several stages and operations, including the deposition of a metal heat- and corrosion-resistant bond coat (by diffusion saturation, electrochemical deposition, spraying using plasma or electron beam methods), heat treatment, compacting and cleaning of surface of this bond coat and deposition of a ceramic layer at the final stage [3–5]. Multistage nature of the technological cycle and a large variety of equipment used for this purpose cannot provide a reliable repetition of coating properties, thus reducing economical efficiency of their application. A plane metal bond coat/ceramics interface, difference in coefficients of a linear expansion of the metal and ceramics, as well as the chemical reactions of oxidizing and corrosion in the contact zone cause damage (separation) of the ceramic layer. It is possible to increase the life of coatings by the creation of a gradient transition layer between the metal (alloy) and ceramics [6].

Processes of evaporation and condensation in vacuum can widen significantly the existing technological means for producing thermal barrier gradient coatings. Fractionation of multicomponent systems in evaporation and subsequent condensation in vacuum, being the physical fundamentals of many technological processes of advanced vacuum metallurgy, refining of metals and alloys in particular, can be useful in producing thermal barrier gradient coatings by vapour deposition.

The methods of deposition of protective gradient coatings are known [7, 8] using electron beam evaporation from one source of mixtures of dissimilar substances (for example, metals and oxides) at different vapour pressures. This makes it possible to create in many cases a gradient transition zone instead of a plane interface between metal and ceramic layers and to attain a good adhesion of coating with a substrate by adding components with a low melting temperature and high pressure of vapour to the composition of mixtures being evaporated.

Below, the specifics of process of electron beam evaporation of multicomponent materials from one source are described and examples of a single-stage deposition of thermal barrier gradient coatings are given.

For this purpose, a composite ingot with a ceramic base (Figure 1) is used, having combinations of inserts (fragments) from metallic and non-metallic materials of a required shape and sizes which are arranged in the ingot volume. During continuous evaporation of this ingot and subsequent condensation the formation of a multilayer gradient coating of a preset composition and structure is provided.

Ceramic base of the ingot defines the purpose of the gradient coating. For example, in thermal barrier coatings the ceramic base of the ingot should be zirconium dioxide with additions of stabilizers or other systems of oxides (for example, on hafnium oxide base) with a low heat conductivity. In heat-resistant and erosion-resistant coatings the ceramic base of the ingot consists of Al_2O_3 , while in hard and wear-resistant coatings it is Al_2O_3 , TiC , TiB_2 .

Procedure of evaporation of the composite ingot is traditional: an ingot is placed into a copper water-cooled crucible and its upper edge is heated smoothly, then it is melted and evaporated completely under the continuous heating. The molten pool surface is maintained at a constant level by a vertical feeding of ingot using a water-cooled rod.



Inserts, arranged in the upper part of the composite ingot, have a shape of tablets or rods and, being first evaporated, form transition layers of a preset composition and structure. They can be manufactured from organic compounds, metals, alloys or ceramics, whose melting temperature is lower and vapour pressure is higher than those of the ingot base (for example, anthracene $C_{14}H_{10}$, Al, Cr, NiAl, (NiCr)Al, Pt, PtAl, (NiPt)Al and so on).

Inserts, arranged in the middle and lower parts of the composite ingot, are manufactured mainly from ceramics or ceramic mixtures (for example, Al_2O_3 , CeO_2 , HfO_2 etc.), whose melting temperature and vapour pressure are close to those of the ingot base. Being evaporated and condensed simultaneously with the ingot material, they form composition, structure and properties of the ceramic layer. Deposition of the upper layer of gradient coating, made from complex multiphase ceramics, is attained by evaporation of an insert-tablet, made from non-metallic materials with a wide range of melting temperature and vapour pressure and located in the lower ingot part to contact the water-cooled surface of the rod. The tablet is evaporated at the last moment and finalizes the gradient coating formation, its composition and condensation conditions predetermine the density and hardness of the coating upper layer.

At the International Center of Electron Beam Technologies at the E.O. Paton Electric Welding Institute of the NAS of Ukraine a single-stage electron beam technology of deposition of gradient thermal barrier coatings in one electron beam installation from one source for one technological cycle has been developed and based on using composite ingot and carousel-type evaporator. This could simplify and reduce significantly the technological cycle: metal bond coat, transition zone and ceramic layer are deposited per one cycle.

At present the International Center of Electron Beam Technologies offers customers two main groups of single-stage thermal barrier gradient coatings for protection of blades made from heat-resistant alloys.

The first group is designed for deposition on air-cooled blades of gas turbine engines made from advanced highly-heat-resistant thermostable alloys of the recent generations, as a rule, with a small thickness of airfoil walls and inner cavity (about 0.5 mm) and small-diameter cooling holes. To reduce the mass to maximum and, consequently, the loads to these blades and minimum narrowing of perforation holes, the coatings for their protection should have a minimum thickness. Coming from this, at the International Center the technology for deposition of thermal barrier gradient coating with a metal bond coat on the base of nickel aluminide, whose thickness does not exceed 15–25 μm , has been developed and passed successful tests, while in traditional thermal barrier coatings the thickness of a metal bond coat is 2–3 times larger.

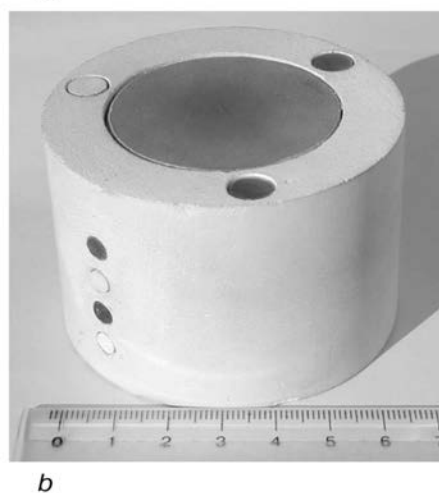
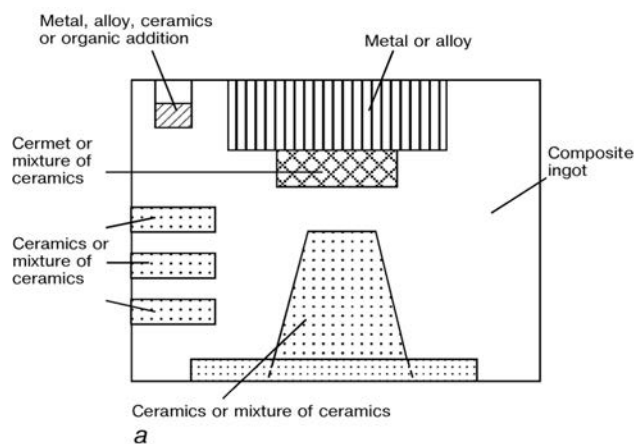


Figure 1. Design (a) and appearance (b) of composite ceramic ingot used for deposition of gradient coatings

The second group of thermal barrier gradient coatings is designed for protection of low-thermostable heat-resistant alloys, whose chemical composition causes the need in use of a metal bond coat of higher thickness to limit the diffusion flows in the coating/heat-resistant alloy combination. These alloys have, as a rule, increased content of titanium, tantalum, hafnium, sulphur and carbon.

It should be noted that all the offered coatings are subjected, after their deposition, to a vacuum treatment at the temperature 1080–1100 $^{\circ}C$ for formation of thin film on $\alpha-Al_2O_3$ base at the metal/ceramics contact interface, so-called TGO, which provides a high adhesion between the metal bond coat and ceramic layer.

As is known, one of the main causes of fracture of thermal barrier coatings in blade service is the following growth of Al_2O_3 -based film at the heat-resistant bond coat surface, which is separated at a certain critical thickness together with a ceramic layer due to occurring stresses [9]. Diffusion of some refractory metal of heat-resistant alloys to the metal bond coat/ceramic layer interface also contributes to this. Therefore, one of the major problems in the development of new coatings, especially with a decreased thickness of the bond coat, is the delay in the Al_2O_3 film growth and diffusion processes in the heat-resistant alloy/bond coat system.

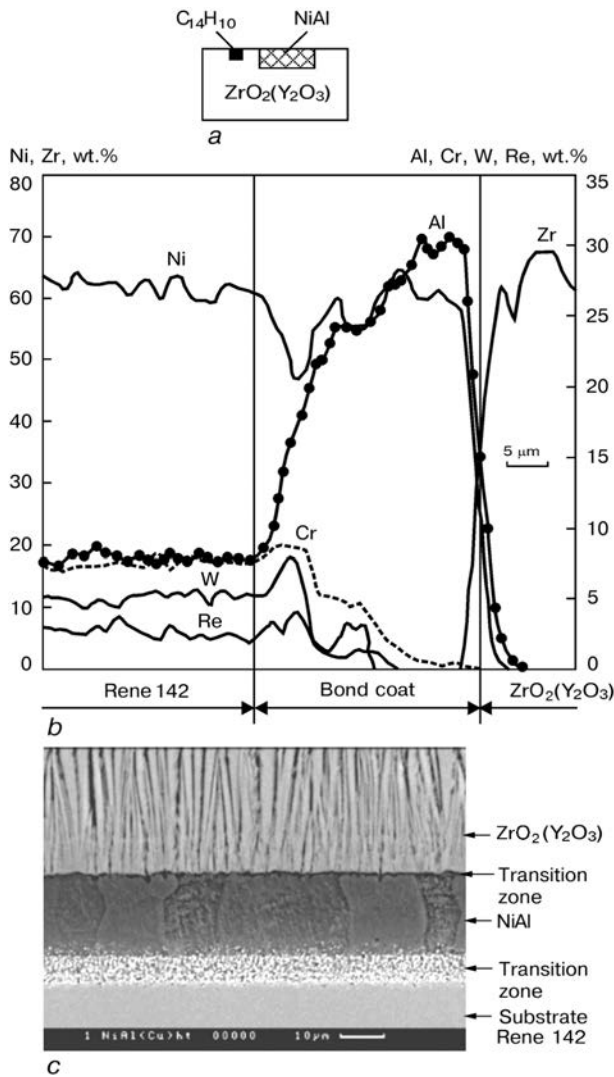


Figure 2. Structure of composite ceramic ingot (a), distribution of chemical elements across coating thickness (b) and microstructure of transverse section (c) of thermal barrier coating $M_xC_y + NiAl/ZrO_2(Y_2O_3)$ on substrate Rene 142 in initial state

Figure 2 presents a structure and composition of a composite ingot used for deposition of thermal barrier gradient coating $M_xC_y + NiAl/ZrO_2(Y_2O_3)$, and also the microstructure of this coating in initial state (after deposition and vacuum heat treatment). The coating was produced by evaporation of 68.5 mm diameter composite ceramic ingot $ZrO_2-7\% Y_2O_3$, containing inserts from pre-sintered $NiAl$ and anthracene $C_{14}H_{10}$ in the form of tablets (Figure 2, a), with a subsequent deposition directly on heat-resistant alloy surface heated to 950 °C. The peculiar feature of this gradient coating consisting of 20–25 μm thick $NiAl$ bond coat and external ceramic layer of 150 μm thickness, is the presence of a thin transition zone enriched with carbides of alloying elements of heat-resistant alloy M_xC_y (first of all, with carbides of tungsten and chromium). This transition zone at the heat-resistant alloy/bond coat interface creates a diffusion barrier delaying the penetration of heat-resistant alloy elements to ceramic layer. Formation of the transition zone occurs due to initial evaporation of insert of anthracene $C_{14}H_{10}$ included into composition of the

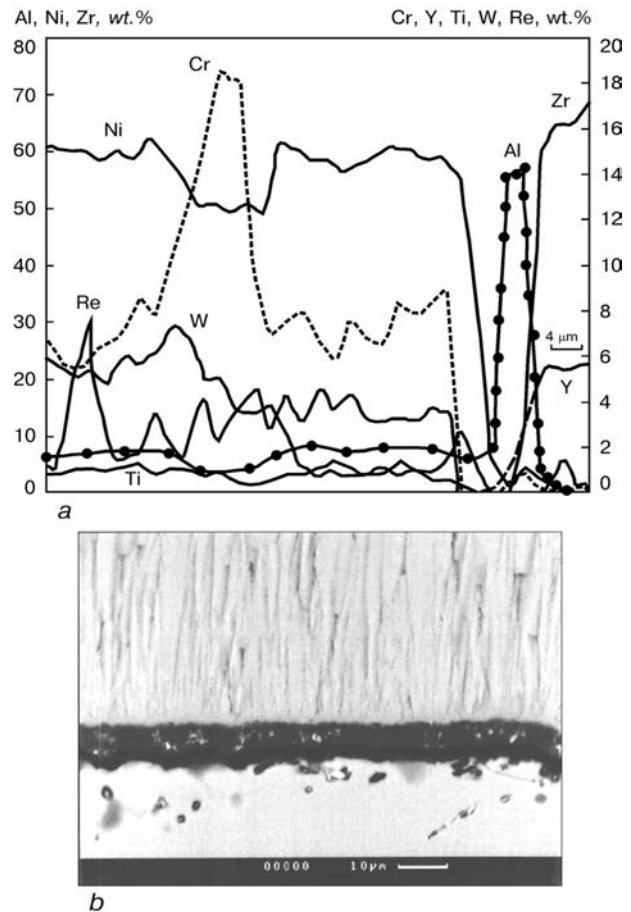


Figure 3. Distribution of chemical elements across coating thickness (a) and microstructure of transverse section (b) of thermal barrier gradient coating $M_xC_y + NiAl/ZrO_2(Y_2O_3)$ on substrate CMSX-4 after 680 thermal cycles

ingot. The cleaning of the heat-resistant alloy surface is also occurred by recovery action of hydrogen atoms formed in hydrocarbon decomposition.

One vacuum cycle of deposition results in formation of a thermal barrier coating, consisting of a gradient bond coat and external ceramic layer, on the surface of the heat-resistant alloy. At subsequent vacuum heat treatment an oxide film (TGO) on $\alpha-Al_2O_3$ base is formed on the bond coat surface, containing up to 30 % Al.

Figure 3, a, b shows the distribution of elements and microstructure of coating $M_xC_y + NiAl/ZrO_2(Y_2O_3)$ after 680 thermal cycles of tests using condition 50 $\leftrightarrow$ 1093 °C with 45 min holding at maximum temperature. Thickness of scale Al_2O_3 at bond coat/ceramics interface does not exceed 8 μm , transition zone, enriched with carbides, hindered the diffusion of tungsten, rhenium and, to a less extent, titanium from the heat-resistant alloy.

Thermocycling tests of similar coatings on advanced alloys, such as CMSX-4 and Rene 5 showed that their life is several times superior to that of other systems of coatings.

The second group of thermal barrier gradient coatings, developed and tested over the recent years at the International Center, includes also coatings deposited on the surface of the traditional bond coat

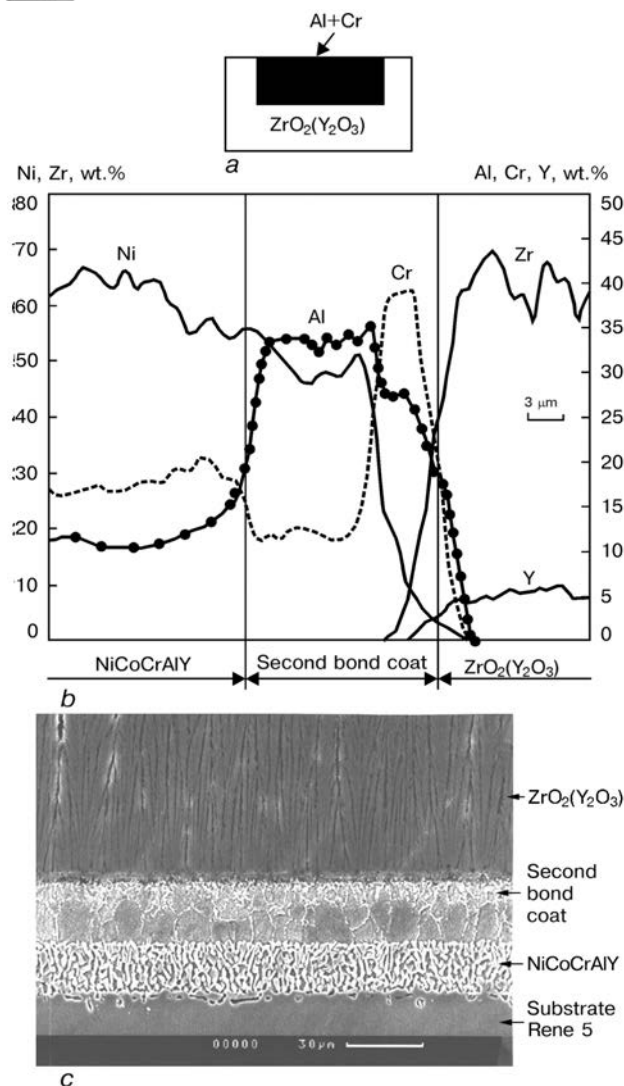


Figure 4. Structure of composite ceramic ingot (a), distribution of chemical elements across the coating thickness (b) and microstructure of transverse section (c) of thermal barrier gradient coating NiCoCrAlY/Al + Cr/ZrO₂(Y₂O₃) on substrate Rene 5 in initial state

NiCoCrAlY (SDP-1 type). This bond coat of a required thickness is deposited for one cycle using the first evaporator of the electron beam installation, then the fixture with products is transferred and arranged over the next evaporator (of carousel type), where the composite ingot is evaporated. As was already noted, the deposition of thicker bond coat NiCoCrAlY is preferable for insufficiently thermostable heat-resistant alloys.

One of variants of the gradient coatings, deposited on bond coat NiCoCrAlY, is the coating containing the Al + Cr transition zone. Structure and composition of the composite ingot used for deposition of thermal barrier gradient coating NiCoCrAlY/Al + Cr/ZrO₂(Y₂O₃), distribution of chemical elements in this coating and its microstructure are given in Figure 4. Aluminium, contained in a tablet (Figure 4, a), has the highest vapour pressure at evaporation temperature as compared with chromium and ZrO₂(Y₂O₃) and, therefore, is evaporated in the first place. Atoms of aluminium meet the surface of the

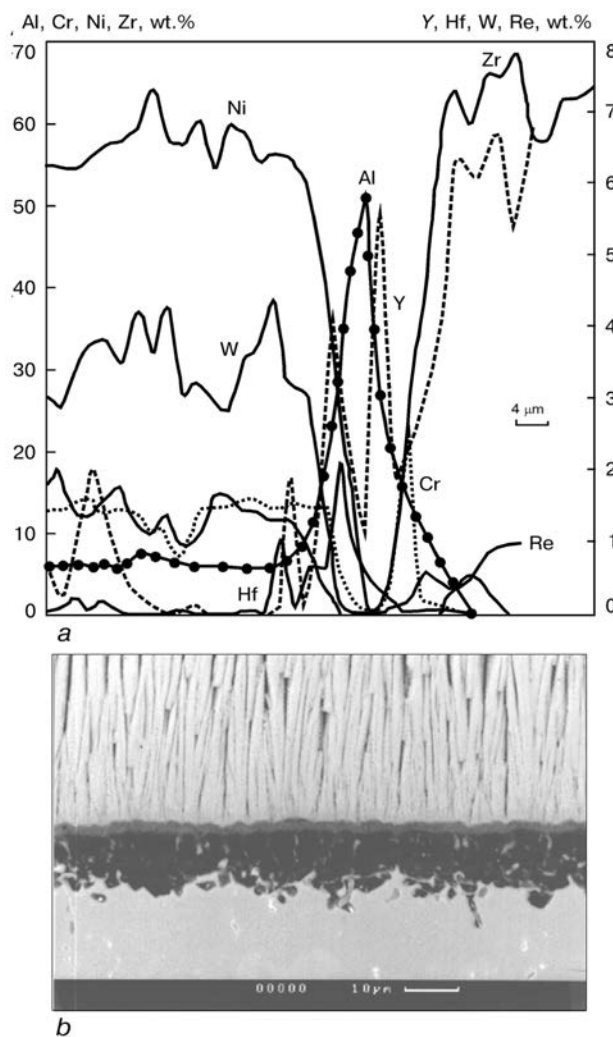


Figure 5. Distribution of chemical elements across the coating thickness (a) and microstructure of transverse section (b) of thermal barrier gradient coating NiCoCrAlY/Al + Cr/ZrO₂(Y₂O₃) on substrate CM-186 after 1000 thermal cycles

bond coat, heated to temperature much exceeding the aluminium melting temperature (660 °C), here their condensation is occurred by vapour-liquid-solid phase mechanism. Condensing liquid phase interacts intensively with the surface of bond coat NiCoCrAlY by changing its chemical composition and forming the second bond coat with a high content of aluminium close by the composition to NiAl. Further, chromium is evaporated from the tablet, forming thin (about 2–3 µm) transition zone on the aluminide surface with up to 40 % Cr, which directly contacts the zirconium dioxide layer deposited after all (Figure 4, b). Chromium and oxide of chromium contained in the transition zone favour the formation of α -Al₂O₃ mainly and create effective diffusion barrier delaying, first of all, the growth of aluminium oxide layer (Figures 4, b and 5, a). Coatings with bond coat NiCoCrAlY are preferable in protection of heat-resistant alloys of Rene 142, CM186LC, PWA 1480 and ZhS32 types.

Figure 6 shows the generalized results of thermocycling tests of traditional and gradient thermal barrier coatings on different heat-resistant alloys. As is seen, the gradient thermal barrier coatings with bond



Results of measurement of thickness of Al_2O_3 -based scale formed in bond coat/ceramic layer transition zone

Thermal barrier coating	Thickness of Al_2O_3 -based scale (μm) depending on number of thermal cycles			
	60	250	500	600
Traditional $\text{NiCoCrAlY}/\text{ZrO}_2(\text{Y}_2\text{O}_3)$	5	10	—	—
Gradient $\text{M}_x\text{C}_y + \text{NiAl}/\text{ZrO}_2(\text{Y}_2\text{O}_3)$	2	6	7	8
Gradient $\text{NiCoCrAlY}/\text{Al} + \text{Cr}/\text{ZrO}_2(\text{Y}_2\text{O}_3)$	4	7	10	—

Note. Thermocycling tests were performed using condition $1150 \leftrightarrow 50^\circ\text{C}$ on specimens from heat-resistant alloy Rene 142.

coat of $\text{M}_x\text{C}_y/\text{NiAl}$ and $\text{NiCoCrAlY}/\text{Al} + \text{Cr}$ type possess the highest life. This is explained by their high thermal stability and heat resistance due to formation of gradient transition zones at the bond coat/heat resistant alloy and bond coat/ceramic layer interface. This is confirmed by a delay in kinetics of growth of Al_2O_3 -based film between the bond coat and ceramic layer during tests (Table).

One of the important trends in the improvement of thermal barrier coatings is the increase in erosion resistance of external ceramic layer and decrease in its penetrability to prevent the penetration of different harmful compounds from atmosphere or fuel combustion products which can provoke the damage (destabilizing) or spalling of the ceramic layer. This is attained by compacting external ceramic layer using deposition on it of the more hard and dense layer of another chemical composition or by heat treatment with use of concentrated power sources (for example, laser).

In this case the need arises in additional technological equipment, that complicates and makes the process of deposition of traditional thermal barrier coatings more expensive. The use of the composite ceramic ingot with a lower insert makes it possible to solve effectively the problem of deposition of gradient thermal barrier coatings with a compact surface of the external ceramic layer using a single-stage technology. Figure 7, *a* shows the scheme of the composite ceramic ingot used for deposition of the gradient thermal barrier coating with a ceramic layer $\text{ZrO}_2(\text{Y}_2\text{O}_3)$ of $150\mu\text{m}$ thickness, here the external layer of about $30\mu\text{m}$ thickness is compacted by a gradient adding of HfO_2 . This is attained by the fact that with moving of the molten pool front to the lower insert and further to the ingot end the insert together with ingot material begins to evaporate and, as a result, the surface of the deposited coating contains the additions of hafnium oxide (Figure 7, *b*), whose amount at the ceramic layer surface reaches 46 %. As is known, hafnium oxide, being refractory, forms a continuous series of solid solutions with ZrO_2 , here the high-temperature mechanical properties, in particular erosion resistance, are higher as compared with traditional

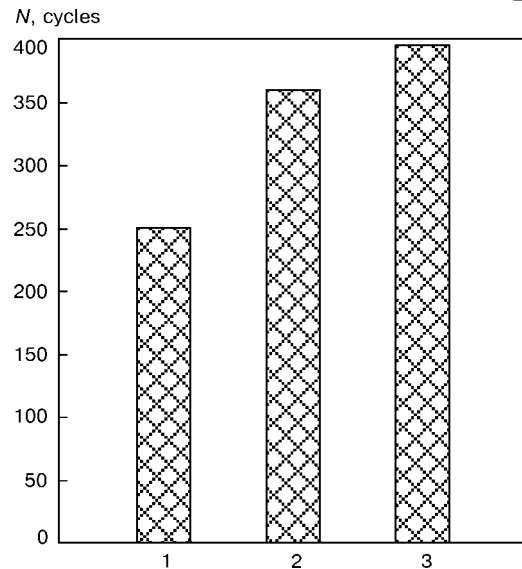


Figure 6. Thermocycling life of specimens with thermal barrier coatings during furnace tests in air ($50 \leftrightarrow 1150^\circ\text{C}$, 1 h cycle) depending on type of bond coat: 1 — traditional coating $\text{NiCoCrAlY}/\text{ZrO}_2(\text{Y}_2\text{O}_3)$ on alloys PWA 1480, Rene 142, CMSX-4 ZhS32; 2 — gradient coating $\text{NiCoCrAlY}/\text{Al} + \text{Cr}/\text{ZrO}_2(\text{Y}_2\text{O}_3)$ on alloys PWA 1480, Rene 142, ZhS32; 3 — gradient coating $\text{M}_x\text{C}_y + \text{NiAl}/\text{ZrO}_2(\text{Y}_2\text{O}_3)$ on alloys Rene 142, CMSX-4

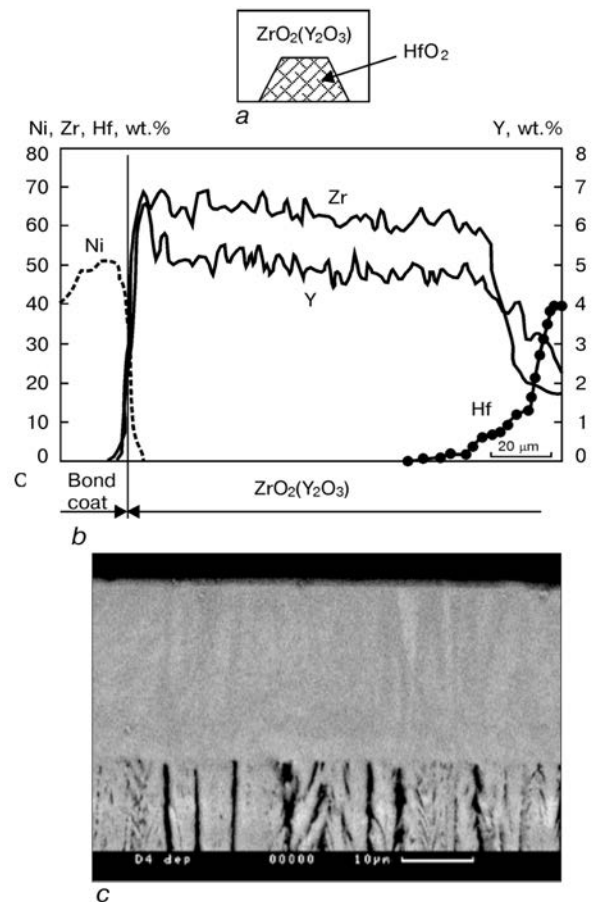


Figure 7. Structure of composite ceramic ingot (*a*), distribution of chemical elements across the thickness of gradient ceramic layer $\text{ZrO}_2(\text{Y}_2\text{O}_3)/\text{HfO}_2$ (*b*) and microstructure of surface of ceramic layer $\text{ZrO}_2(\text{Y}_2\text{O}_3)$ (*c*) compacted by a local overheating using electron beam

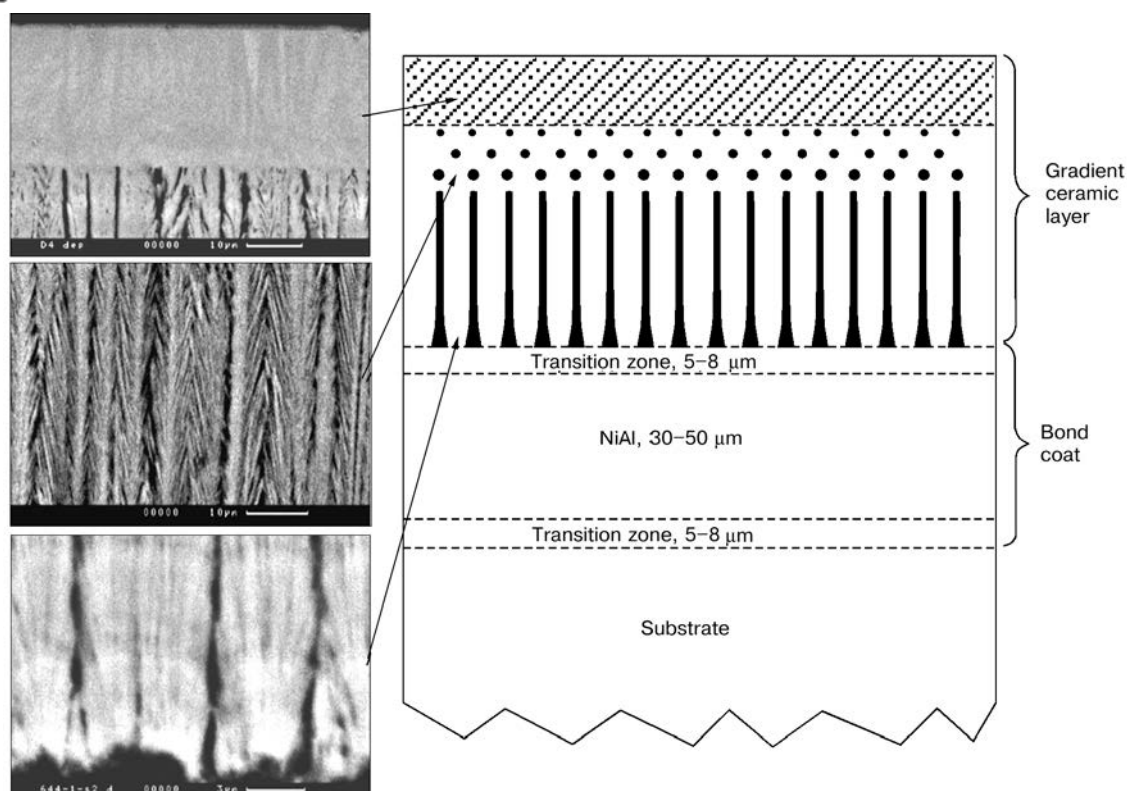


Figure 8. Scheme of structure of gradient thermal barrier coating deposited using the single-stage technology

$\text{ZrO}_2(\text{Y}_2\text{O}_3)$. As the investigations of microhardness and thermocycling life showed, the microhardness of the compacted surface of ceramic layer is by 1.4 GPa higher than that of traditional layer, moreover, the thermocycling life of the gradient coating is not deteriorated.

The compacting of the thermal barrier coating surface layer is performed also by a thermal operation, i.e. by a local overheating of ceramic layer surface at a final stage of the evaporation of composite ingot using an abrupt increase in beam power of electron gun designed for preheating the condensation surface. Microstructure of this ceramic layer is given in Figure 7, c. Here the microhardness of the compacted surface layer is twice increased, as compared with a traditional ceramic layer, and reaches 12 GPa.

At present the works are continued at the International Center for improvement of the single-stage thermal barrier coatings, having a gradient microporous ceramic layer with lower values of heat conductivity as compared with traditional thermal barrier coatings. Figure 8 shows scheme and fragments of microstructure of one of the variants of the gradient thermal barrier coating deposited per one technological cycle using a composite ingot. To deposit similar coatings the composite ingot has also, in parallel with earlier described inserts, additional inserts in the middle and lower parts which provide formation of gradient composition and structures of the ceramic layer. For example, additional inserts, containing sodium chloride and arranging in the ingot middle part, are evaporated after the beginning of evaporation of

$\text{ZrO}_2(\text{Y}_2\text{O}_3)$ and form gradient (columnar and dendritic) structure of the ceramic layer.

The application of electron beam technology for deposition of protective coatings using the composite ingot allows deposition of thermal barrier gradient coatings with a high degree of reproducibility of structure and properties.

The use of composite ingots for deposition of thermal barrier gradient coatings can make the technological cycle shorter and less expensive owing to the single-stage process.

The offered thermal barrier gradient coatings are 1.5 times superior by thermocycling life to traditional double-layer coatings $\text{MCrAlY}/\text{ZrO}_2(\text{Y}_2\text{O}_3)$.

1. Miller, R.A. (1987) Current status of thermal barrier coatings. An overview. *Surface and Coat. Technol.*, **1**, 1–11.
2. Beele, W., Marijnissen, G., Lieshout, van A. (1999) The evolution of thermal barrier coatings — status and upcoming solutions for today's key issues. *Ibid.*, **120/121**, 61–67.
3. Haynes, J.A., Lance, M.J., Pint, B.A. et al. (2001) Characterization of commercial EB-PVD TBC systems with CVD (Ni, Pt)Al bond coatings. *Ibid.*, **146/147**, 140–146.
4. Wortman, D.J., Duderstadt, E.S., Nelson, W.A. (1990) Bond coat development for thermal barrier coatings. *J. Engineering for Gas Turbines and Power*, **112**, 527–530.
5. Kablov, E., Muboyadzhan, S. (2001) Protective coatings of turbine blades of gas turbine engine. *Gazoturb. Tekhnologii*, **3**, 30–32.
6. Hirai, T. (1996) Functional gradient materials. *Mat. Sci. & Technology. Proc. of ceramics*. Part 2.
7. Movchan, B.A. (1996) EB-PVD technology in gas turbine industry: present and future. *J. Metals*, **11**, 40–45.
8. Movchan, B.A. (2002) Functionally graded EB-PVD coatings. *Surface and Coat. Technol.*, **149**, 252–262.
9. Evans, A.G., Mumm, D.R., Hutchinson, G.H. et al. (2001) Mechanisms controlling the durability of thermal barrier coatings. *Progress in Materials Science*, **46**, 505–553.



ELECTRON BEAM INSTALLATION UE-121

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Electron beam industrial installation of the UE-121 type is described and its technical data are given. Main functional features of installation units, such as working chambers, technological outfit, electron guns, power sources are presented.

Keywords: *electron beam remelting, installation, intermediate crucible, axial gun, melting of metals and alloys*

The use of the electron beam remelting with an intermediate crucible (EBRIC) [1] widens significantly the capabilities of the remelting process owing to the presence of an independent concentrated heat source, i.e. electron beam. At present the technologies of utilization of wastes and melting of alloys by the EBRIC method have been developed [2, 3]. To attain the maximum effect from the realization of these technologies the new high-efficient installations of the industrial type are required. A large experience has been gained at the E.O. Paton Electric Welding Institute in the development of these installations.

Based on the lab installation E-121 [1] the electron beam installation UE-121 has been designed (Figure 1), consisting of three chambers: melting, loading and ingot. All the elements of design have hollow walls for water circulation to have a forced cooling of ingot during melting and cooling. The installation is equipped also with an electric supply unit, vacuum system, control and stabilizing systems. The main technical characteristics of the electron beam installation UE-121 are as follows:

Set power, kV·A	900
Accelerating voltage, kV	30
Number of guns, pcs	3
Maximum dimensions of billet, m:	
length	2.2
section	0.50×0.45
Maximum dimensions of ingot, m:	
length	2.0
diameter	0.6

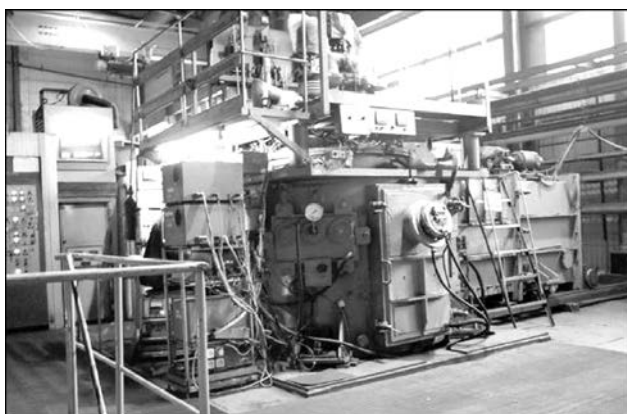


Figure 1. Appearance of electron beam installation UE-121

rectangular section	1.00×0.15
Efficiency of high-vacuum system	
pumping, l/s	18000
Operating vacuum, Pa:	
in guns	$(6.6-13) \cdot 10^{-3}$
in melting chamber	$(6.6-13) \cdot 10^{-2}$
Maximum consumption of cooling	
water, m ³ /h	80
Dimensions of installation, m	14×8×5

The melting chamber is a central part of the installation, in which the process of melting is realized. It represents a vertically arranged cylinder of 2.0 m diameter and 1.5 m height, confined by vacuum-packed covers from the top and beneath. The chamber wall thickness prevents completely the penetration of the secondary X-ray radiation outside, caused by retarding of electrons on material remelted. Inside the chamber there is a technological equipment, consisting of a mould and intermediate crucible (Figure 2). Three electron beam guns are arranged on the upper cover (Figure 3). They have the following technical characteristics:

Rated power, kW	300
Maximum frequency of scanning, Hz	1000
Maximum current, A	15
Angle of deviation of beam of electrons	
from gun axis, deg	0–35

To remove the upper cover with arranged electron beam guns beyond the melting chamber, a rail system is used. Owing to this system it is possible to withdraw the ready ingot with the help of a shop crane, and



Figure 2. Technological equipment for simultaneous melting of several ingots

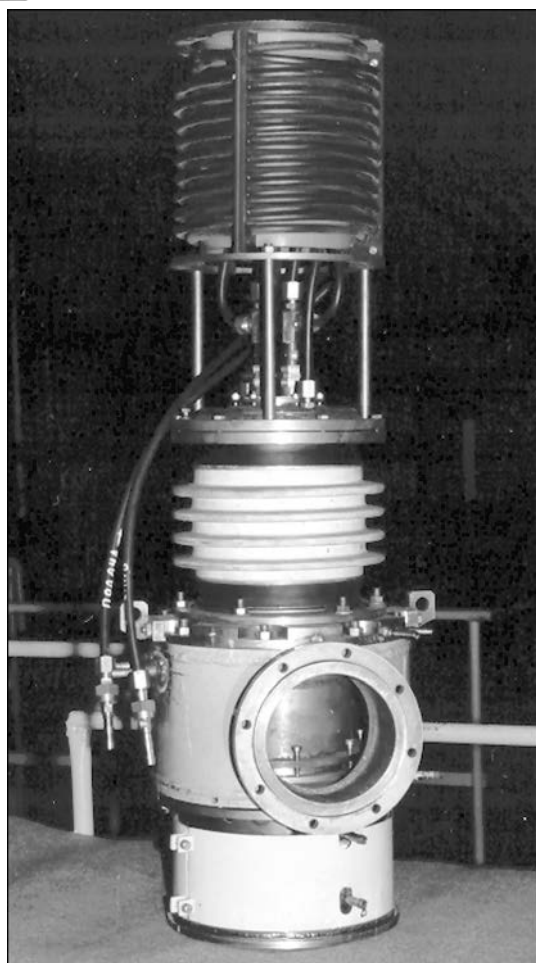


Figure 3. Electron beam gun «Paton-300»

also to clean the inner surfaces of the cover and guns from sublimates precipitated during melting. The ingot chamber is connected to a technological hole in a lower cover. Water is supplied to a mould and intermediate crucible with a system of flexible hoses through pipe connections, available at the lower cover, which are designed for cooling. At the lateral chamber wall are located: an observation system (of a stroboscopic type) of the operator, connectors for input of thermocouples and tubes-manometers. On the left from the operator's place there is a branch pipe DU 630 in the chamber wall through which a melting chamber is connected to a pumping system with the help of a vacuum gate. On the right from the operator's place there is a vacuum-tight technological door of 1.8×1.0 m at the lateral wall, on which an observation system used by a technologist for observation of the melting process is arranged. Opposite the operator's place a melting chamber is connected to a loading chamber.

The loading chamber is a hollow parallelepiped and consists of two parts connected between each other by a vacuum seal. Its total length is 2.2 m. To load the charge, the above-mentioned parts of the chamber are moved apart after releasing clamps located around the seal perimeter, then the rear part of the loading chamber is separated and moved aside with the help of an electric drive. In the loading

chamber a mechanism of charge feeding is arranged, which is removed together with a separated part of the chamber. The mechanism of charge feeding represents a number of parallel guides along which a pusher is moved with the help of a chain gear. Owing to the feeding mechanism it is possible to feed a whole billet, consumable box with charge materials, lumpy charge and bulky materials, for example spongy titanium. In the first two cases a roller conveyor is mounted along which a pusher feeds the billet to the melting zone. When the bulky charge is used, a non-consumable box is mounted, whose width does not exceed the width of a rear wall of an intermediate crucible, and a pusher feeds uniformly the charge materials to the intermediate crucible. Owing to loading chamber moving apart it is possible to load the charge very fast using a shop crane of 10 t capacity.

The ingot chamber represents a water-cooled cylinder of 1.4 m diameter which is fixed to a lower cover of the melting chamber through a flange. A rod, at the upper part of which a water-cooled bottom plate is arranged, is introduced to the ingot chamber through a vacuum seal from beneath. The bottom plate is fixed in the ingot chamber with the help of two traverses connected by screw tie rods. A drive is located outside the ingot chamber which moves the rod in vertical direction with the help of screw tie rods to withdraw ingot in the melting process. The drive consists of an electric motor and reducer. Before the melting beginning the «primers», made from the material of the ingot melted, are fastened on the bottom plate. In the lower part of the ingot chamber a technological hatch is located which provides access to internal parts of the withdrawal mechanism. Through this hatch the placing of «primers» before melting, release of the ready ingot after melting and its withdrawal from the installation are made.

Technological equipment in which the process of electron beam remelting is realized consists of an intermediate crucible and a mould. In walls of the intermediate crucible (cold hearth) there is an opening for the molten metal pouring (pouring lip). The charge which is fed from the loading chamber is melted in this crucible. The intermediate crucible serves for averaging the chemical composition, melt refining from impurities (including gas impurities) and inclusions [1]. During melting a skull is formed in the crucible, preventing its walls and bottom from interaction with the molten metal. The metal from the intermediate crucible is poured into a mould, representing a hollow closed contour (opening). Its inner part, which contacts the ingot metal, is made from the water-cooled copper. The intermediate crucible and mould are an integral unit mounted on a steel frame fixed in the melting chamber. The design scheme of equipment fastening inside the chamber enables operator to change quickly its units when the sizes of ingots are changed. To reduce the consumption of time and materials a radically new scheme of the technological equipment is used (see Figure 2). When changing the

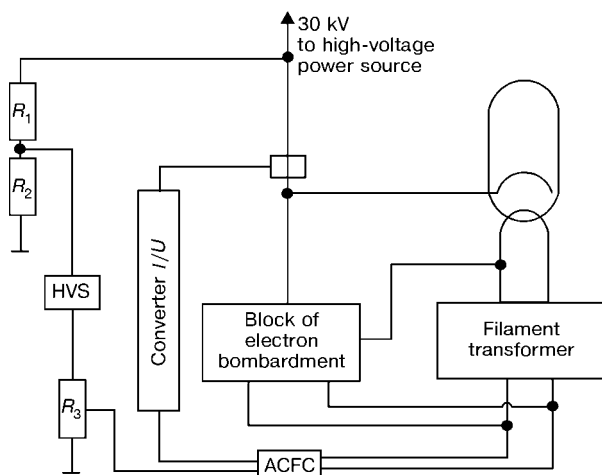


Figure 4. Schematic diagram of gun filament control

pouring lip the losses were decreased at opening in intermediate crucible wall, because the maximum overheating of the melt and its evaporation is occurred at the pouring lip. Owing to the openings in the mould the efficiency of the melting process in case of small-diameter ingots is increased.

Guns «Paton-300» (Figure 3) represent electron beam heaters of an axial type [1]. Each gun consists of a cathode unit with a tungsten electrode mounted on a high-voltage isolator, anode water-cooled unit, magnetic lens, deflecting system and beam guide. It is also equipped with an individual system of pumping. The guns are supplied from high-voltage source of 30 kV constant voltage, consisting of a commutation starting-protection equipment, a thyristor switch, choke, transformer, rectifier and sources of gun cathode filament. Control system provides the stabilization of the electron beam current by introducing feedback into the circuit of automatic adjustment of the cathode filament current. The elementary diagram of gun filament control (Figure 4) consists of the following functional units: resistor high-voltage dividers of voltage R_1 , R_2 ; high-voltage sensor HVS; filament current resistor-preset device R_3 ; automatic controller of filament current ACFC; measuring converter of electron beam current into constant voltage, galvanically decoupled from high-voltage circuits; source of gun filament (block of electron bombardment and filament transformer).

Vacuum system of installation UE-121 (Figure 5) includes vacuum lines, gates and pumps, such as mechanical, steam-jet and diffusion. Lines consist of steel pipes, connecting pipes between each other and also to the melting chamber and guns. Lines provide necessary passing cross-sections for maximum productivity of pumps. Evacuation of inner cavities of installation chambers from the level of atmospheric pressure is realized by a mechanical pump RVN-6. Due to its productivity the residual pressure $3 \cdot 10^{-4}$ Pa is attained in the melting chamber during 10 min. To have a further evacuation of the installation and to remove gases and vapours of metal during melting a main line is used consisting of mechanical pumps NVZ-300 (2 pcs), 2DVN 1500 (2 pcs), and also steam-jet

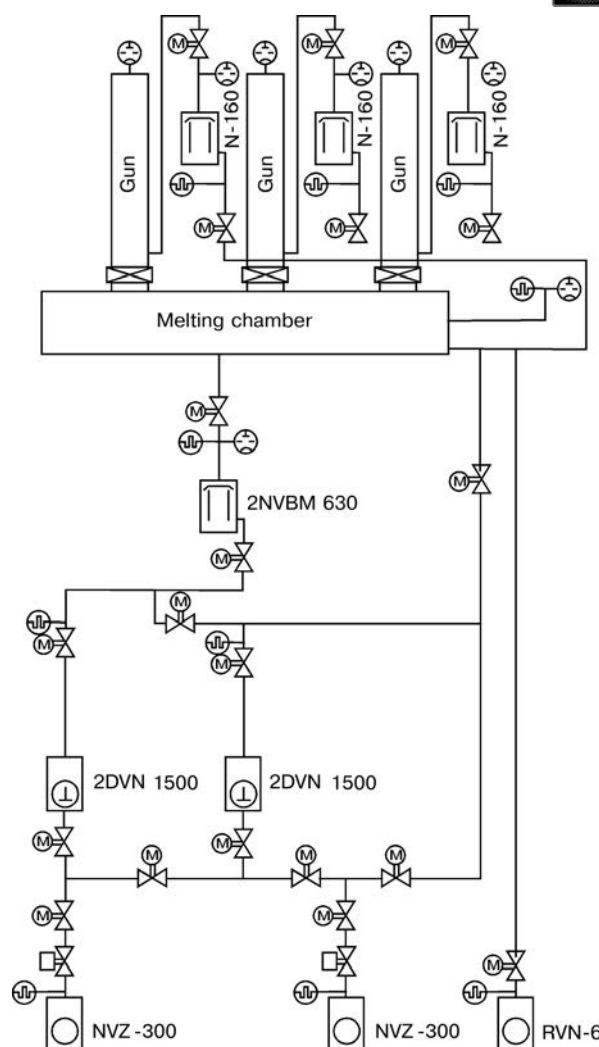


Figure 5. Scheme of vacuum system of installation UE-121

2NVBM 630 (1 pc) and diffusion N-160 (3 pcs) pumps.

The vacuum system of the installation UE-121 makes it possible to create pressure $1 \cdot 10^{-2}$ Pa in the volume of melting chamber and $1 \cdot 10^{-3}$ Pa in the guns that provides a continuous operation of guns and preserves the required level of refining metal being remelted during the entire technological process.

Thus, the electron beam installation UE-121 is the high-efficient unit of the industrial type for melting metals and alloys using an intermediate crucible. Both the solid consumable billets, and also lumpy waste or bulky materials can be used as charge materials. Owing to a quick change of the technological equipment it is possible to melt ingots of round and rectangular sections in this installation from alloys on the base of iron, nickel, titanium and refractory metals.

1. Paton, B.E., Trigub, N.P., Kozlitsin, D.A. et al. (1997) *Electron beam melting*. Kyiv: Naukova Dumka.
2. Tikhonovsky, A.L., Trigub, N.P., Kalinyuk, A.N. et al. (1991) Recycling of titanium production wastes by melting with intermediate crucible. *Problemy Spets. Elektrometallurgii*, 1, 59–63.
3. Kalinyuk, A.N., Kozlovets, O.N., Tsyban, I.V. et al. (1999) Structure and properties of VT6s titanium alloy of electron beam melting. *Ibid.*, 2, 45–50.



ACCELERATING COOLING OF TITANIUM INGOTS AFTER ELECTRON BEAM MELTING

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Time of cooling titanium ingots after EBM was 3 times reduced. Effect was attained by increasing radiation capability of surface of ingots in oxidizing by the air flow. The feasibility of chips remelting is described. Increase in production capacity of the melting shop bay is 21 %.

Keywords: titanium, ingot, cooling, electron beam melting

Cooling of titanium ingots in vacuum after electron beam melting (EBM) to the 300 °C surface temperature, safe for ingot withdrawal from the melting unit, is lasted about 6 h and represents an important part of the entire cycle of their production. It is possible to reduce the time of cooling ingots by an additional heat removal. The selection of method is defined both by its effectiveness and also by the feasibility to combine the used technology of withdrawal and subsequent processing of ingots. The present work illustrates an example of realization of such approach which was applied at the electron beam metallurgy plant Company «FIKO».

Effectiveness of different methods of heat removal was defined with time spent for cooling 640 mm diameter ingots and calculated using procedure of work [1] for a constant temperature of the ambient medium. It was established that the time of cooling in the methods considered is correlated as follows: cooling in vacuum — 1; argon — 0.91; helium — 0.87; air

at ingot arrangement in its chamber without fan blowing — 0.37; with fan blowing — 0.35; in air at ingot arrangement in a wider chamber of melting, without blowing — 0.26; with blowing — 0.25. The ingot withdrawal from the melting unit just after completion of melting, and also the process of cooling with a subsequent fusion of surface, due to design features of the melting unit, not allowing the conductance of these operations, were not considered.

Cooling of the ingot started just after completion of the operation of the shrinkage cavity fade out and consisted of the following stages: air leak-in to the working space of the melting unit, opening of chamber, ingot lifting to the melting chamber, uniform blowing of its surface with the fan. Diagram of cooling ingot in the melting chamber is shown in Figure 1.

Contact of a hot surface of the ingot with air led to the formation of a scale layer, increasing the degree of titanium blackness from 0.3 [2] to 0.9 [3] and, respectively, heat removal by radiation by 3 times. The calculation shows that as the losses for radiation are the main mechanism of cooling ingot in the conditions being considered, then the time of this process was also reduced 3 times as compared with a vacuum cooling.

Figure 2 shows curves of reduction in surface temperature of ingots during the process of vacuum cooling and in air blowing in the melting chamber. Temperature was measured by differential thermocouples in the surface region, corresponding to the lower edge of the mould. It is seen from the Figure that during

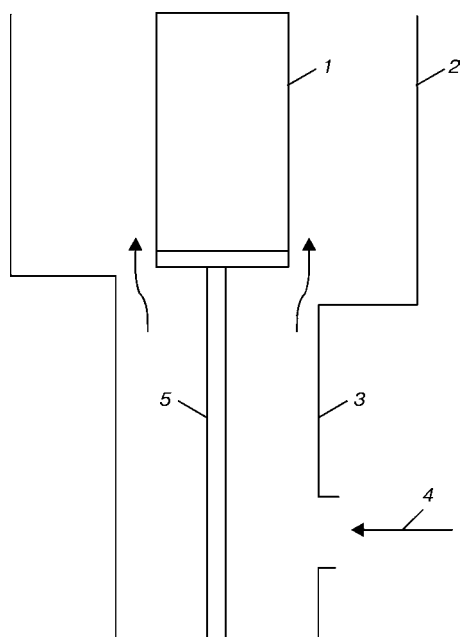


Figure 1. Scheme of cooling ingot in air blowing: 1 — ingot; 2 — melting chamber; 3 — ingot chamber; 4 — air flow; 5 — rod with a bottom plate

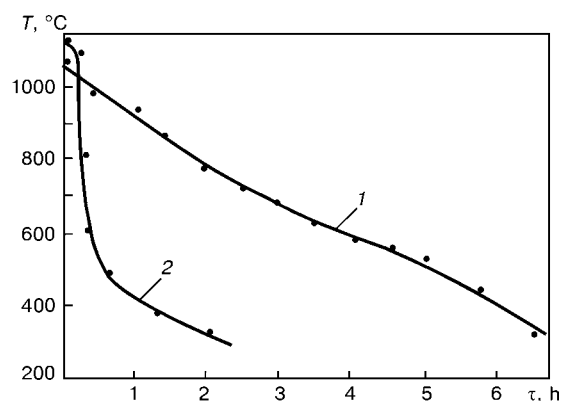


Figure 2. Change in temperature of ingot surface depending on cooling time: 1 — in vacuum; 2 — in melting chamber with air blowing



Content of impurities in air-cooled ingots melted using chips

No. of ingot	Ingot material	Mass of chips, %	Content of impurities, %		
			N	O	C
40	VT1-0	11.6	0.017	0.15	0.044
			0.029	0.18	0.054
41	VT1-0	6.3	0.035	0.19	0.058
			0.018	0.15	0.046
22	VT1-0	3.3	0.020	0.17	0.050
			0.028	0.18	0.054
31	VT1-0	2.3	0.027	0.15	0.039
			0.020	0.17	0.047
17	Gd2	3.7	0.016	0.18	0.027
			0.024	0.21	0.030
16	Gd2	3.1	0.018	0.19	0.030
			0.023	0.20	0.025

Notes. 1. Over the line the content in ingot head part is given, under the line — in ingot bottom part. 2. The content of hydrogen in both parts of ingot was less than 0.008 %.

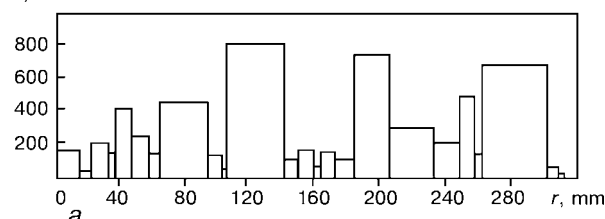
the initial period of air cooling, when the scale layer is formed, the highest reduction in ingot surface temperature is occurred. The ingot arrangement in a wide melting chamber promotes the additional fast cooling, where the receiving of its radiation is increased due to a larger area of the water-cooled walls.

Numerical estimation of the role of a convection mechanism of cooling at used conditions of fan cooling shows that the heat dissipation by convection is approximately 20 times inferior to the heat removal by radiation. Nevertheless, the blowing of the ingot was not excluded from the technology of the process as it contributed to a fast removal of a hot air from the melting chamber of the unit, thus preventing the rubber gaskets from damage.

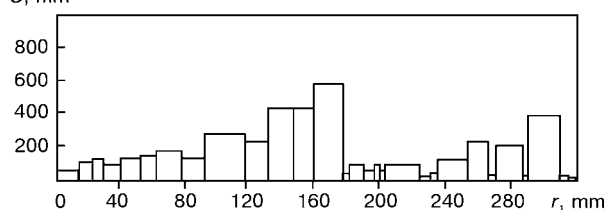
It is clear from the above-described that the control of the radiation capacity of the ingot surface makes it possible to change the time of its cooling within the wide range.

The accelerating cooling of the titanium ingots influences favorably on their macrostructure leading to some decrease in size of crystals. Figure 3 shows the change in area of crystals in a radius of templets cut out from ingots cooled during 6 h in vacuum and 2 h in air blowing. Templets were cut out at the distance of 150 mm from the upper edge of the ingot, i.e. beyond the region of action of shrinkage effects, and etched according to procedure of work [4]. It was calculated on the basis of the Figure that the mean area of crystals in the first case is 255 mm², crystal size is 16 mm, while in the second case it is 153 mm² and 12.4 mm, respectively, i.e. the observed decrease of crystals is 22 % at a rapid cooling.

The rapid cooling of ingots down to low temperatures is well combined with traditional technology of enterprise for their withdrawal from the melting unit by the upper edge with the help of a hoisting device. Stresses, initiating in the places of gripping, are 2.5 kgf/mm², i.e. much lower than their limiting values for titanium at the temperature 300 °C ($\sigma_{0.2} = 50-70$ kgf/mm²) [5] and cannot lead to the deformation and slipping of the ingot. In addition, the low temperature allows personnel to work with a hoisting device directly near the ingot.

S, mm²

a

S, mm²

b

Figure 3. Distribution of area of crystals in radius of templets from ingots, cooled in vacuum for 6 h (a) and in air blowing for 2 h (b)

On the other hand, the air cooling is combined with a lathe machining of ingots used at the enterprise. The scale layer forming at the surface in contact with air has a small thickness, up to 50 μm, therefore, when removing it by machining the losses in ingot mass are also small and do not exceed 1 %.

The removed layer of the top chips is greatly contaminated with gases, for example, the nitrogen content reaches 0.05–0.06 % in it at allowable level 0.04 % for VT1-0. Therefore, the chips are not suitable for the repeated remelting. However, the chips taken from deeper layers to remove surface defects, do not contain the excess of gas impurities and allowed to be remelted.

To prevent the contamination of chips in machining the conditions of cutter running was selected carefully to remove overheating and metal oxidizing caused by it, the machine oil was not allowed that could lead to carburizing, the drying as-pressed chips was performed during 2 h in blowing with hot air (80 °C) to remove the water remnants, cooling the cutter, which can increase the oxygen and hydrogen content in titanium. Mass of chips taken from deep layers was up to 3 % of the ingot mass.

The Table gives the content of the mentioned impurities in metal of ingots melted using the chips of deep layers. As is seen from the Table, even adding the large amount of chips to the ingots, up to 12 % of ingot mass, the content of admixtures in metal does exceed the rated value.

The positive effect reached due to shortening the time of cooling ingots from 6 to 2 h is expressed in increase in efficiency of the melting shop bay by 21.1 %. Here, the losses caused by removing the top layer of oxidized chips, are comparable with a gain obtained from reduction in expenses for service of the melting unit and mutually compensated.

1. Tajts, N.Yu. (1962) *Technology of steel heating*. Moscow: GNII on Ferrous and Non-Ferrous Metallurgy.
2. Kozelkin, V., Usoltsev, F. (1974) *Principles of infrared technique*. Moscow: Mashinostroenie.
3. Samsonov, G.V. (1978) *Physical-chemical properties of oxides*. Moscow: Metallurgiya.
4. Borisov, E.A. (1980) *Titanium alloys. Metallography of titanium alloys*. Moscow: Metallurgiya.
5. Eryomenko, V.N. (1960) *Titanium and its alloys*. Kyiv: AN Ukr. SSR.



STUDY OF SPECTRA OF ARGON ARCS FOR CREATION OF AUTOMATIC SYSTEMS OF CONTROL OF PLASMA-ARC MELTING AND WELDING PROCESSES IN ARGON

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Experimental data on study of argon arc spectrum are presented. The obtained experimental data are necessary to create the systems of technical vision operating in the conditions of argon arcs.

Keywords: automation of processes, plasma-arc melting, argon arc welding, spectrum of argon arc, system of technical vision, CCD of matrix

Automation of technological processes of plasma-arc melting and welding envisages the presence of a technical vision system (TVS) allowing us to obtain a visual information about the parameters of technological processes (sizes and shape of metal pool, distance from pool to plasmatron nozzle exit section, level of metal relative to mould edge, spatial position of butt, parameters of edge preparation, etc.) in a real time. In non-automated systems these functions are fulfilled by the operator or welder.

The aim of this work is to study the spectra of argon arcs to decrease the effect arc radiation to TVS used in technological processes of plasma-arc melting and welding in argon.

The relative sensitivity of receptors of human vision depending on the wave length is shown in Figure 1 [1]. To protect the human vision from intensive radiation of the electric arc the serial-produced optical filters are used. Figure 2 shows spectra of absorption

of the most widely spread filters S-3 and S-4. As it follows from Figures 1 and 2 the spectrum of absorption of filters S-3 and S-4 covers almost completely the range of wave lengths to which a human eye is sensitive.

At present a charge-coupled device (CCD) of matrix is used as a light-sensitive device in most TVS.

The principle of operation of matrix CCD is as follows. A matrix of light-sensitive elements is created on the bases of semiconductor material (silicon, germanium). Each light-sensitive element has a property to accumulate charges proportionally to the amount of photons falling on it. Thus, two-dimensional matrix of charges proportional to the luminosity of initial image is obtained over the period of exposure on the accumulation sections. The accumulated charges are firstly transferred to a storage section, and then line-by-line to the matrix output.

In spite of a visible variety of TV cameras, CCD of matrix, used in them, are almost similar, as the technology of their manufacture is similar in all the manufacturers. Major parameters of CCD of matrices are the dimension in pixels and spectral sensitivity.

Resolution of CCD of cameras is determined mainly by the dimension of CCD of matrix in pixels and quality of an objective. CCD of matrix with the resolution oriented to TV standard, i.e. 512×576 and 768×576, refer to most widely applied. For TVS, used in the automatic systems of control of plasma-arc melting and welding processes, the use of the matrix of

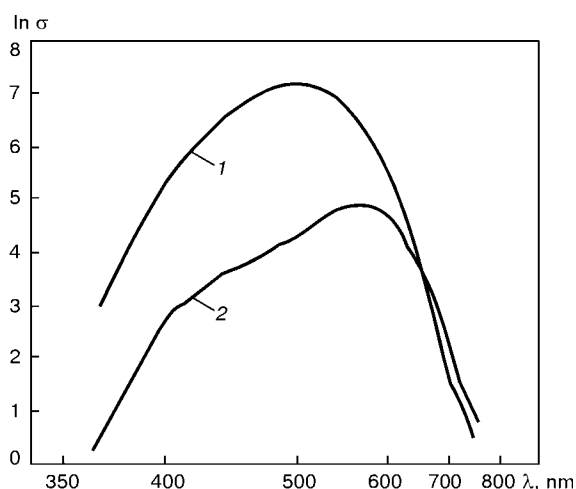


Figure 1. Relative sensitivity of receptors of human vision: 1 — rods; 2 — cones ($\ln \sigma$ — logarithm of relative sensitivity, λ — wave length)

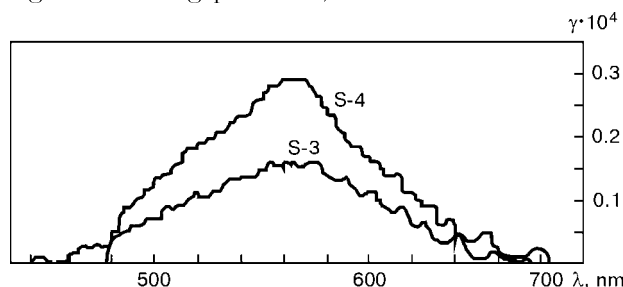


Figure 2. Spectrum of absorption of welding glasses S-3 and S-4 (γ — absorption coefficient)

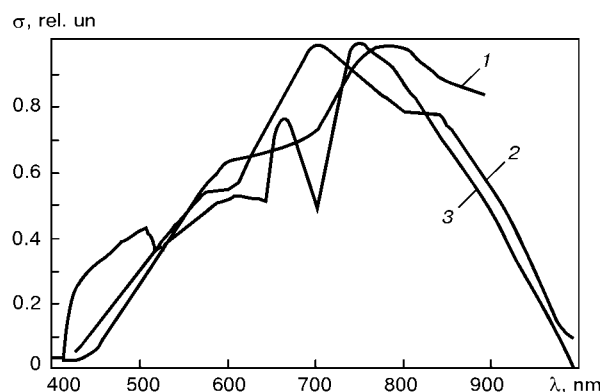


Figure 3. Spectral characteristics of CCD of matrices of different manufacturers: 1 – Dalsa; 2 – Thomson; 3 – Texas Instruments (σ – spectral sensitivity)

768×576 format is most suitable. This is stipulated by the following factors:

- CCD of matrix of 768×576 format produce maximum resolution for a standard TV signal;
- unlike the matrices of 512×576 format they have a network of arrangement of light-sensitive elements close to a square, and, consequently, similar resolution in horizontal and vertical.

When the CCD of matrix with a high resolution is used, additional difficulties arise with the processing of images in a real time. For TVS, operating under the conditions of electric arc, a spectral sensitivity of CCD of matrices is the important factor. Work [2] describes spectral characteristics of some CCD of matrices (Figure 3).

CCD of matrix are manufactured mainly on the silicon base. Therefore, in spite of variety of charac-

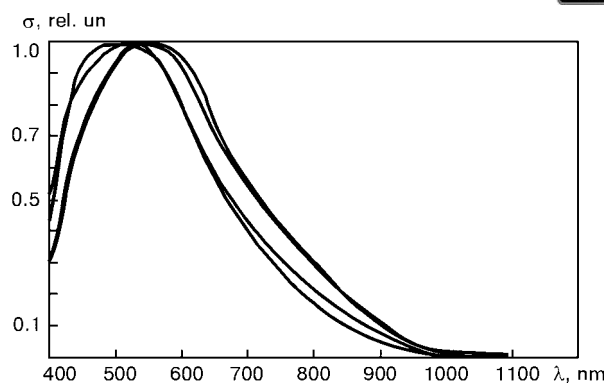


Figure 4. Family of typical characteristics of spectral sensitivity of some CCD of matrices of Sony

teristics they are characterized also by the maximum sensitivity in red and near infrared (IR) range. Germanium CCD of matrix are not almost used in TVS due to their high cost in spite of having the wider range of sensitivity in the far IR region of the spectrum. From the data of [3], the Sony Company produces all its black-white matrices with a spectral characteristic shown in Figure 4.

CCD of matrix possess the higher range of spectral sensitivities as compared with the human vision, therefore, the use of standard optical filters is impossible. Difficulties arise in determination of parameters of the optical filter protecting CCD matrix from the electric arc intensive radiation in construction of TVS system for control of processes of plasma-arc melting in argon.

Most TVS, designed for following butt line in argon welding, include an illuminator [4–8]. Selec-

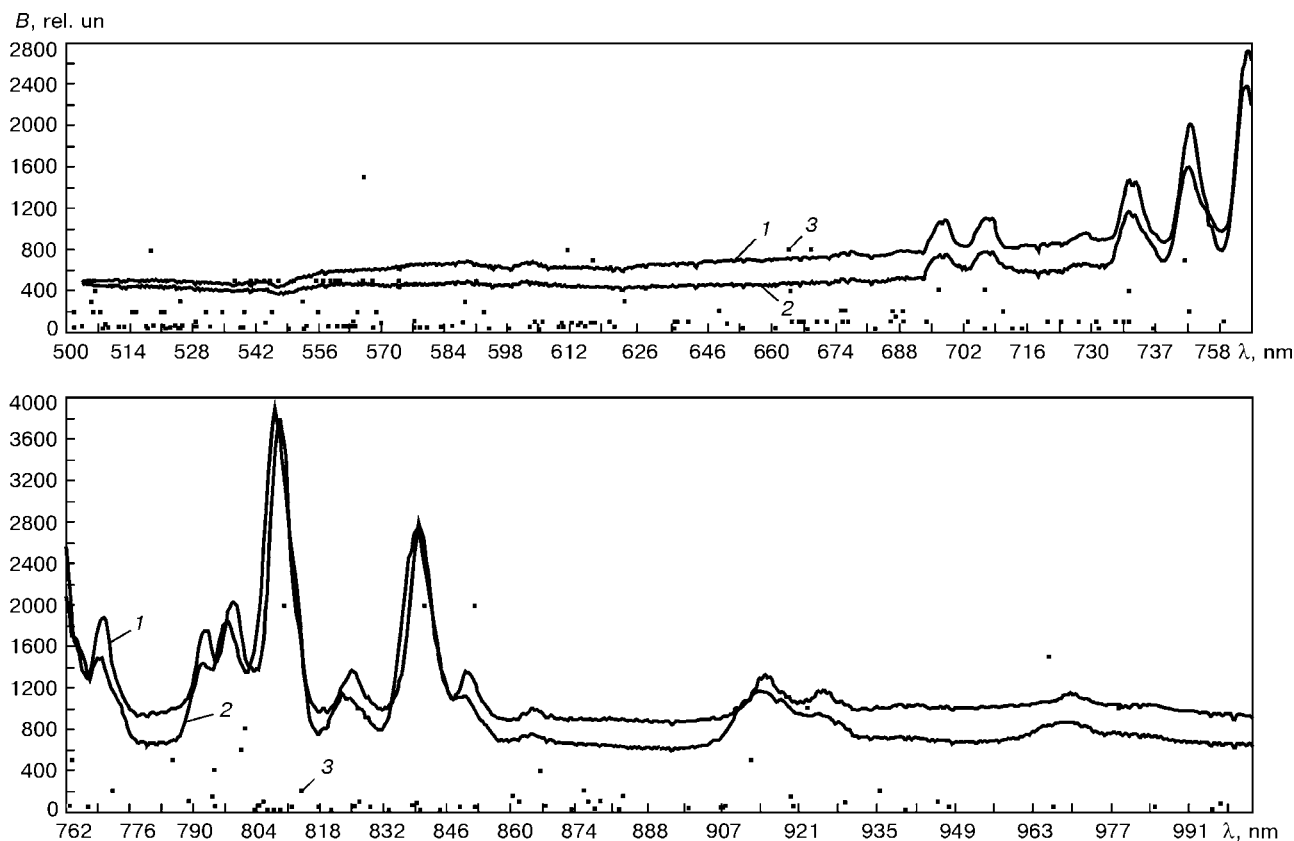


Figure 5. Spectral characteristics of argon arcs: 1 – aluminum; 2 – steel; 3 – argon (B – luminosity)



tion of a wave length of this illuminator is one of the important scientific problems as the arc in this case should have as low as possible effect on the TVS operation, and CCD matrix should have a sufficient sensitivity to this wave length.

To solve the above-mentioned problems, the experimental investigations of a spectrum of argon arc using a diffraction spectrometer were carried out at the E.O. Paton Electric Welding Institute. The spectrometer design includes four main units: diffraction grating, objective, photodetector, microprocessing block for data processing. CCD matrix was used as a photodetector. Radiation of argon arc was focused on the spectrometer diffraction grating using a prism and objective. The measurements were made in four ranges: 500–632, 632–762, 762–893, 893–1000 nm. Experimental spectral characteristics of argon arcs of steel and aluminium are shown in Figure 5.

Shapes of experimental curves for steel and aluminium have no noticeable differences. This can be explained by the fact that the spectral lines of atoms of used metals are not characterized by a high luminosity in the range of 500–1000 nm. Absorption of these spectral lines is also possible by the shielding gas (argon) or air. The experimental data obtained are necessary for determination of parameters of optical filters used in TVS of plasma-arc melting and welding in argon.

According to experimental data, the maximum values of argon arc luminosity were recorded in the range from 680 to 870 nm, and the ranges 500–680 nm are most favourable for the TVS operation.

Figure 5 presents also the theoretical values of luminosity of argon spectral lines [9]. Difference in experimental and theoretical data is stipulated by

some factors. In the latter the absorption of arc radiation by the passing medium (air), the effect of temperature luminous emittance of the molten metal were not taken into account. Some widening of spectral lines can also be outlined that is explained by a chaotic thermal motion in the gas. The width of spectral lines is influenced by collisions between radiating particles, strong disturbances in frequency of ions, caused by their random arrangement in a crystalline lattice, change in frequency of ions radiation due to Doppler effect.

Taking into account the results obtained at PWI a system of torch tracking along the butt using a TV sensor has been developed [7]. The use of the band filters in the range from 500 to 680 nm made it possible to observe the metal pool during argon plasma-arc melting in the UPP-3 type furnace using CCD of the video camera.

1. Prett, U. (1982) *Digital treatment of images*. Moscow: Mir.
2. Majorov, V.P., Ovchinnikov, L.F., Syomin, M.S. (1998) Reasonings about TV cameras. *Kompiuterra*, **14**, 17–21.
3. Chura, N.I. (2000) IR-illumination in TV observation. *Spets. Tekhnika*, **1**, 35–38.
4. Kisilevsky, F.N., Butakov, G.A., Dolinenko, V.V. et al. (2001) Quality improvement of joint following on the base of technical vision. In: *Proc. of Int. Scie.-Pract. Conf. and Exhibition on Problems of Quality Assurance in Welding Production*, Kyiv, April 3–6, 2001.
5. Ustinov, N.G., Karpilenco, A.V. (1992) Optical sensor for automatic welding. *Avtomatich. Svarka*, **7/8**, 37–40.
6. Boillot, J.P., Noruk, J. (2002) The benefits of laser vision in robotic arc welding. *Welding J.*, **8**, 32–34.
7. Kisilevsky, F.N., Pritula, S.I., Dolinenko, V.V. (2003) System of welding torch following along the butt using a TV sensor. *The Paton Welding J.*, **1**, 49–50.
8. Kisilevsky, F.N., Butakov, G.A., Dolinenko, V.V. et al. (2003) Optical sensor for butt following at gap sizes close to zero. *Ibid.*, **2**, 48–50.
9. Zajdel, A.N., Prokofiev, V.K., Rajskey, S.M. et al. (1997) *Tables of spectral lines*. Refer. Book. Moscow: Nauka.



INDUCTION HEATING. CAPABILITIES AND PROSPECTS OF ITS APPLICATION IN PROCESSES OF SPECIAL ELECTROMETALLURGY.

Part 1. Classification of Methods of Induction Melting of Metals and Alloys and Methods of Crucible-Free Melting

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Classification of different methods of metal melting based on induction heating is given. Technical characteristics of crucible-free methods of melting are considered and analysis of their technological capabilities is made.

Keywords: inductor, electromagnetic field, metal pool, ingot, sectional mould, cold crucible, metal crystallization

Induction heating is widely used in different processes, including also in melting different metals and alloys that is stipulated by a complex of the following technological properties typical of induction heat source [1–6], namely:

- high sterility of heat energy source, as it has no negative effect on properties of material being heated;
- intensive stirring of melt during melting levels the temperature and chemical composition in the pool volume;
- absence of a local overheating, thus resulting in small loss in alloying elements;
- absence of a rigid relation between the supplied power and melting speed;
- feasibility to maintain metal melt in a molten state for unlimited time;

- simplicity in control and maintaining the melt temperature in a preset range;

- high degree of reliability in operation and a good adaptation in the automation system of technological equipment used in the induction heating processes;

- no need in creation of any special conditions for its operation and, therefore, the technological processes can be performed in a gaseous medium of any composition and pressure, including also in vacuum.

The above-described features and technological advantages of induction heat sources stipulate a continuous widening of the sphere of their application in different branches of industry. Depending on the process purpose, type of material or product treated and a final product, all the technological processes, based on induction heating, can be classified as follows (Figure 1).

Traditional fields of application of induction heating are heat treatment (quenching, tempering, nor-

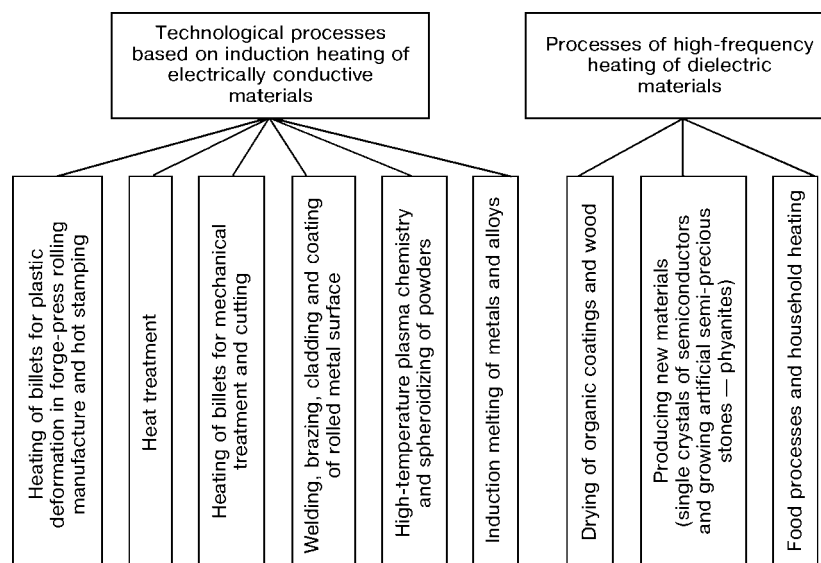


Figure 1. Classification of processes and equipment using induction heating



malizing), heating of billets before pressure treatment (pressing, stamping, bending) and mechanical treatment (milling, lathe operations and cutting) [4, 5, 7–10]. In this case the values of heating temperature for these processes may vary from 700 to 1500 K. Sometimes, some processes, for example deformation and heat treatment, can be combined. Induction heating makes it possible, here, to stabilize and optimize the temperature condition of the process, to increase the efficiency of the mechanical equipment and to reduce the metal wastes.

The induction heating found the widest spreading in the field of welding, brazing and coating deposition on sheet metal [7, 11–15]. Welding, based on high-frequency heating of metal in the weld zone, is advantageous by the high efficiency of the process, reaching 100 m of weld per minute, versatility of the process, because it can weld almost any metals without use of shielding media, high quality of the joint owing to a localization of the heat energy in the narrow zone of edges being welded. In separate cases, for example in welding cable sheaths, the high-frequency is only possible.

The use of the induction heating in the processes of brazing can solve one of major problems, such as providing homogeneous temperatures of bodies joined and brazing alloy in the brazing zone. At single-type products and in mass production the brazing process can be automated.

Induction heat sources are used successfully in the processes of high-temperature plasma-chemical synthesis of chemical compounds of metal with other elements, in producing ultra-pure materials and spheroidizing of metal and ceramic powders using a high-frequency plasma [16–19].

The wide application of the induction heating for melting metals and alloys is explained by its specific

difference from other methods. It consists in the fact that heat, required for heating, is generated directly in the material itself. Moreover, the heat generation in the body heated can be realized, depending on the problems to be solved, from any side: from beneath, lateral and from the top.

As the molten metal, available in the alternating electromagnetic field of the inductor, is stirred continuously under the action of electromagnetic forces it seems possible to create the favourable hydrodynamic condition when developing the technological process by selecting the necessary current frequency and design of the heater (inductor).

Processes of melting and treatment of the molten metal using the induction heating can be divided into three main groups:

- heat energy is generated in the material heated, and the metal melt does not contact the crucible material;
- metal melt during the entire cycle of heating contacts the refractory material and the heat energy is generated directly in the melt or charge;
- heat energy is generated in a vessel (crucible), made from electrically-conductive material, whose specific electric resistance and melting temperature are much higher than those of material being remelted. Here, the heating and melting of charge, and also overheating of metal melt occur due to heat dissipation by the more heated wall of the crucible.

Depending on the type and material of crucibles used and method of heat supply to the melt, the variety of technological methods of induction melting and appropriate melting equipment can be classified as follows.

At present the processes and devices, allowing melting metals without contact of melt with refractory materials, compose a separate group of the induction melting methods [5, 20–29]. They include such types of melting as:

- levitation;
- crucible-free zone;
- with electromagnetic melt maintaining on support;
- skull;
- in cold crucibles.

Method of the *levitation induction melting* has been well developed and found a wide application in conductance of physical-chemical investigations [20–22, 30–35]. Its principle is as follows. The electromagnetic field is generated using one inductor or a system of inductors with a so-called potential pit, i.e. the field, inside of which a low intensity zone is located (Figure 2). Metal weight, placed into this zone, is steady suspended if the gravity forces are levelled by a resultant force created by the field of a lower inductor. In the metal weight the currents are induced causing heating and subsequent melting. The space position of a weighed metal drop is well stabilized in the inducing system of two co-axial sections of inductors, located co-axially one over another. Here, the direction of currents in sections should be opposite.

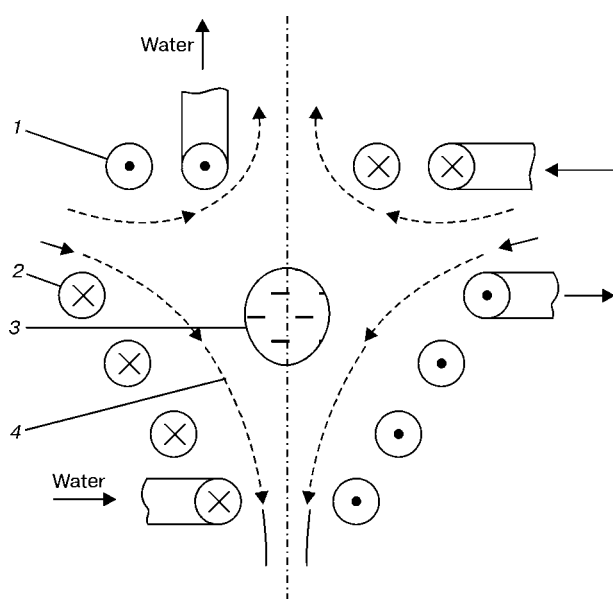


Figure 2. Scheme of induction levitation melting: 1, 2 — upper and lower sections of inductor, respectively; 3 — molten weight of metal; 4 — force lines of electromagnetic field (X and • — directions of current in inductor turns)



With change in power supplied to the inductor, not only the intensity of the electromagnetic field is changed, but also its configuration that leads, in turn, to the change in space position of the molten metal in the inductor. In a steady condition, the power generated in the melt, is equal to the power lost by the metal surface due to radiation and convection.

The principle of a *crucible-free zone melting* is based on the capability of the molten zone to redistribute impurities between the liquid and solid phases [23–25, 36]. Effectiveness of this method is defined by many factors including design features of the installation, method of zone heating, and also characteristics of the material being treated. The most important characteristic of the material is an effective coefficient of distribution of impurities K , which represents a ratio of impurity concentration in a solid phase C_s to its concentration in a liquid phase C_l , i.e. $K = C_s / C_l$ [23–25]. Coefficient of distribution K can be larger and smaller than unity depending on the fact how the impurity influences the temperature of melting solvent (matrix). If the impurity contributes to the increase in temperature of the solvent melting, then its concentration in the solidified phase will be higher than in the liquid phase ($K > 1$) and, vice versa, i.e. $K < 1$.

Scheme of the process of a vertical zone melting is presented in Figure 3. The principle of this method of melting consists in the fact that zone 3 is melted in a cylindrical rod 1 using inductor 2, metal of this zone is maintained by surface tension forces and electromagnetic forces of alternating field. The zone is slowly moved along the rod. Here, the impurities are moved together with the molten zone and, thus, pushed aside to the rod end.

The process can be performed in vacuum or gaseous atmosphere of a preset composition. Ingot with a very low content of impurities is produced for several passes along the rod. The purification degree depends on the number of passes. Zone crucible-free melting can be used not only for purification of the material remelted from harmful impurities and their uniform distribution across the section and length of the rod. Zone melting makes it possible to add the required amount of impurities to the material and to prevent almost completely the segregation of impurities in the material treated.

The modern procedure of zone melting and advanced technologies give opportunity to produce materials with the content of impurities in several dozens of atoms per million of matrix atoms. Diameter of ingots melted is varied from several millimeters to several tens of millimeters.

The process of zone melting is combined in most cases with the producing of a preset crystalline structure in the ingot, including single-crystal structure.

Melting with the electromagnetic maintaining of melt on the support is characterized by the fullest use of properties of the electromagnetic field. Heating and melting of the material are combined here with

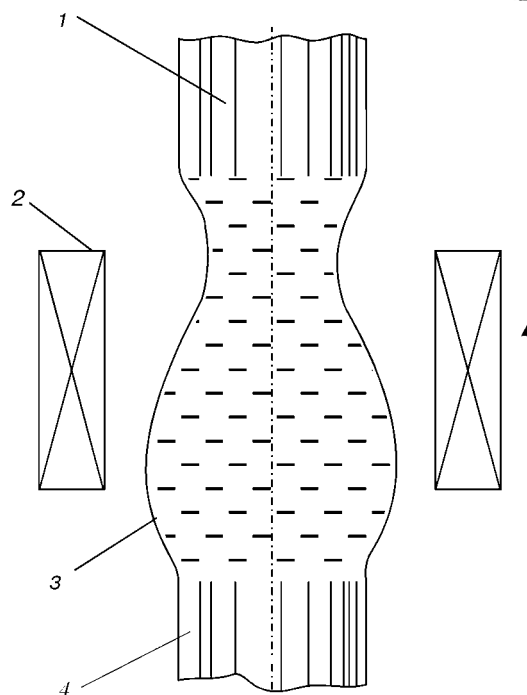


Figure 3. Scheme of crucible-free melting: 1 — cylindrical rod being treated; 2 — inductor; 3 — molten zone; 4 — remelted metal

the maintaining of melt by interaction forces occurring between induced currents in material and alternating magnetic field of the inductor [5, 26, 28, 29, 37, 38].

With allowance for the electromagnetic maintaining of melt on the support, two methods of producing ingots were developed: semicontinuous casting in the so-called magnetic mould (Figure 4, a) [38] and growing of single crystals by the method of Czochralski (Figure 4, b) [28, 37].

Depending on nature of technological process, a solidifying ingot, monolithic billet or charge, skull or water-cooled bottom plate can serve as a support for the melt.

During casting ingots the molten metal from the melting furnace enters a bottom plate 4, mounted in the zone of inductor 2. Thus, a metal pool 1 is set on the bottom plate. The molten metal pool is squeezed and maintained on the bottom plate by the electromagnetic field generated by the alternating current passing in the inductor 2. With increase in metal pool volume the bottom plate 4 is slowly lowered down and cooling water is supplied to a lateral surface of the solidifying ingot 3 through holes in the inductor.

Casting with the formation of the lateral surface of ingot in the electromagnetic field avoids completely the mechanical interaction between the ingot and mould wall, thus providing the high quality of the surface. The produced ingots have no surface defects (cracks, overlaps, cold shuts and others) and do not require mechanical trimming before deformation [38].

As to its technical capabilities, including the purity of the metal melted, the induction melting on the support is close to the levitation melting. At the same time the presence of support under the melt allows maintaining of a sufficiently large masses of the molten metal. The mentioned specifics of the process was

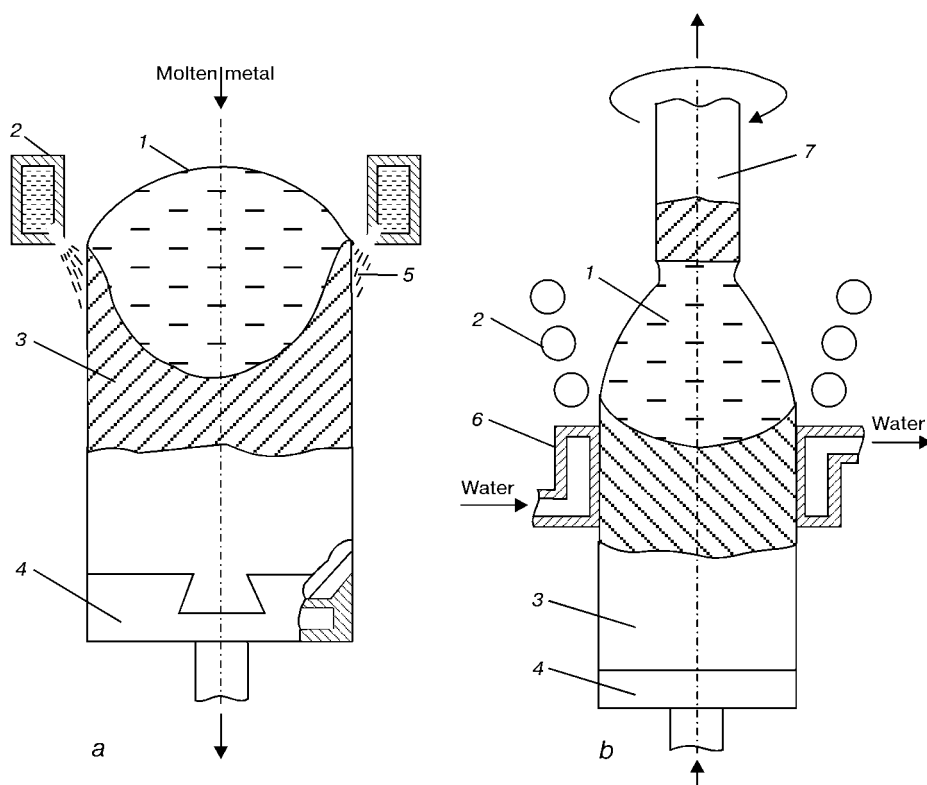


Figure 4. Scheme of processes with electromagnetic maintaining of melt on the support: *a* – ingot casting in an electromagnetic mould; *b* – growing of single crystals; 1 – metal pool; 2 – inductor; 3 – ingot; 4 – bottom plate; 5 – water jets; 6 – mould; 7 – single crystal

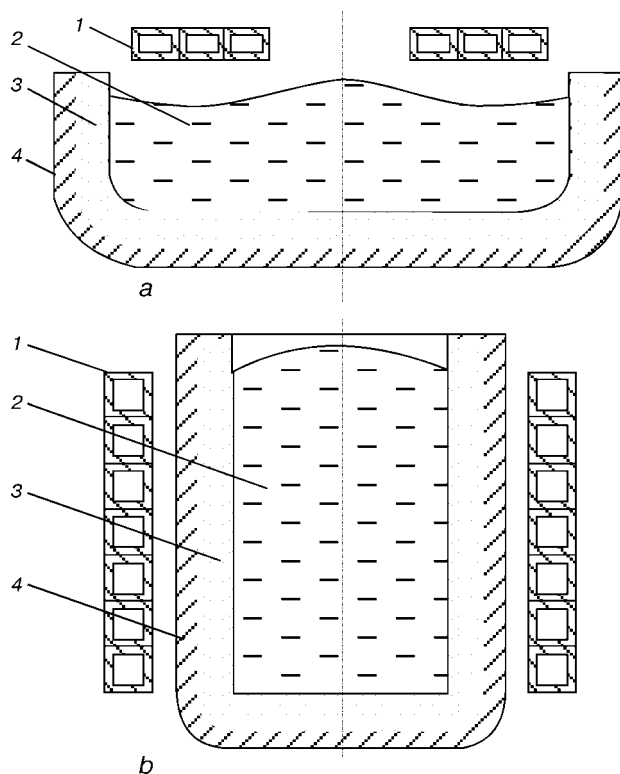


Figure 5. Scheme of induction skull melting: *a*, *b* – upper and lateral energy supply to metal, respectively; 1 – inductor; 2 – metal melt; 3 – skull; 4 – cooled surface of skull

further developed to grow the single crystals (see Figure 4, *b*). Electromagnetic field, generated by the inductor 2, is used for melting the top part of the ingot (consumable billet) 3 and formation of a metal pool 1 in this zone. Using a single-crystal primer (not shown in Figure), which is set in contact with the pool top at the beginning of the process, a single crystal 7 is «withdrawn» from the pool. To average the temperature fields of single crystal in the zone of contact with a metal melt the single crystal is rotated around a longitudinal axis. This method is widely used for producing single crystals from semiconductor materials, and also single crystals of many highly-reactive metals.

Specifics of any *skull melting* is that the metal being remelted contacts the solid metal of the same chemical composition as the melt. In addition, the solid metal separates the metal from its contact with elements of furnace structure and, thus, protects from contamination [39, 40]. Both highly-concentrated sources (electric arc, arc plasma and electron beam) and also sources with a dissipated heating (induction) can be used as sources of heat energy [27, 41].

Two schemes of induction skull melting are used. They are differed by the method of power supply to the metal: through the open mirror of pool or from one side through a skull (Figure 5). The first scheme



(Figure 5, *a*) does not differ from other methods of skull melting where the highly-concentrated sources of heat energy are used. Its main advantage is the absence of electrical losses in skull during supply of heat energy to the pool. However, it is characterized by a poor electromagnetic coupling, resulting in a very low electrical efficiency factor of edge inductor-loading system. Due to this, the scheme with a top supply of power does not find a practical application.

The second scheme of induction skull melting with a lateral supply of power is considered more preferable (Figure 5, *b*). Electrical efficiency factor of cylindrical inductor-loading system is higher than at the top power supply. The lateral skull is made from metal powder which is remelted. The fine-dispersed particles of powder are «transparent» for the electromagnetic field and, therefore, the temperature of their heating is much lower than the melting temperature. During melting the powder is sintered with the formation of a crust in which melt is arranged. In addition, the part of the supplied energy is lost in the skull.

In spite of the fact that this method was suggested more than 40 years ago and the large volume of theoretical and laboratory investigations have been already carried out, there is no information in the literature about its practical application.

In works [25, 42–47] two technological diagrams of *induction melting of metals in cold crucibles* were described, differing by the site of connection of the electromagnetic field energy to the metal melt: upper, through the open mirror of metal pool using an edge inductor (Figure 6, *a*), and lateral, through the crucible wall using a cylindrical inductor (Figure 6, *b*).

The charge to be remelted is placed into a cold crucible 2 made in the form of a blind-bottom water-cooled vessel. Supply and drain of the cooling water from a cold crucible is made through a hollow rod (see Figure 6, *a*). Edge inductor 3 made in the form of a ring (single-turn) or an Archimedean spiral (multiturn) is mounted coaxially over the cold crucible. Arrows show the direction of energy transfer to the metal melt and its removal from the melt.

At this scheme of energy supply to the charge (melt) to be remelted, repeating the principle based on use of the highly-concentrated sources of heat energy (electric arc, low-temperature plasma or directed flow of electrons), the induction heating is low-effective, as the edge inductor has a weak coupling with melt in the crucible. Therefore, the heat energy, generated in the melt, does not provide setting of a sufficient volume, and also necessary overheating of the melt. Moreover, the pairs of metals which are condensed on the inductor, can cause the electrical breakdowns between the inductor turns [26, 27]. The given scheme of the induction melting did not find the practical application due to the above-described reasons.

Induction melting in a cold crucible with an energy supply to the metal pool through its lateral surface (see Figure 6, *b*) is more promising and less power

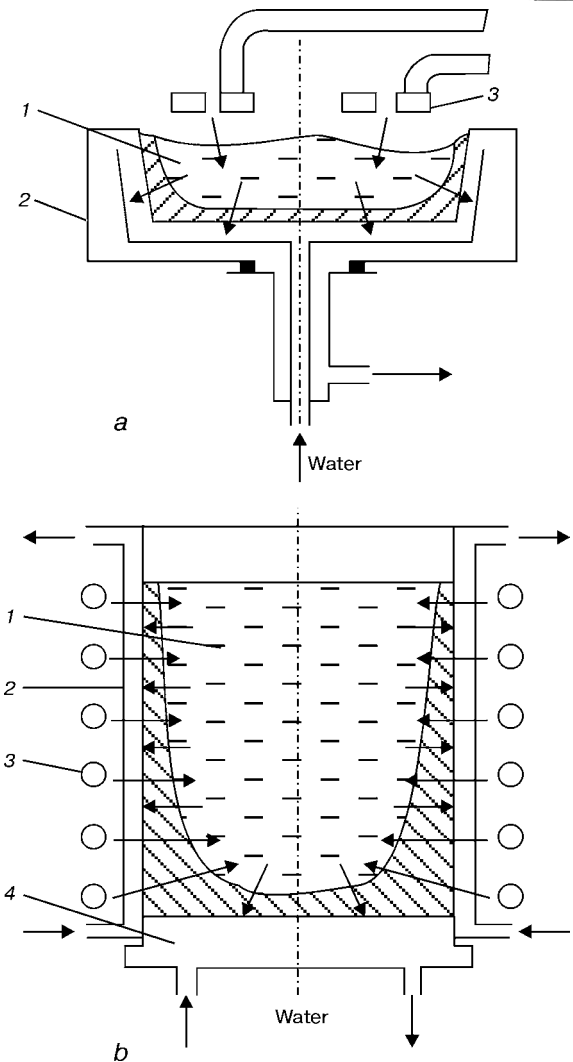


Figure 6. Scheme of induction melting in a cold crucible: *a, b* — energy supply through open mirror of metal pool and through the cold crucible wall, respectively; 1 — metal pool; 2 — cold crucible; 3 — inductor; 4 — bottom plate

consuming. Metal pool 1 is located in a cold crucible 2, whose cylindrical wall is made from separate cooled sections, isolated electrically from each other, and «transparent» for electromagnetic field generated by a high-frequency current passing in inductor 3. Inductor is made in the form of a cylindrical spiral and a cold crucible is placed into it.

Melting in a cold crucible differs from the conventional crucible induction melting by the conditions of energy transfer from inductor to melt, as the cold crucible wall, which distorts electromagnetic field, generated by the current in the inductor, is located between the inductor and metal melt.

Solid metal wall of a conventional water-cooled crucible is a screen for the high-frequency electromagnetic field generated by the inductor as the eddy currents induced in the crucible wall form the closed electric circuit along the external surface of its wall. The cold crucible wall made from separate electrically isolated cooled sections represents a secondary winding of the transformer. Owing to this, the transfer of

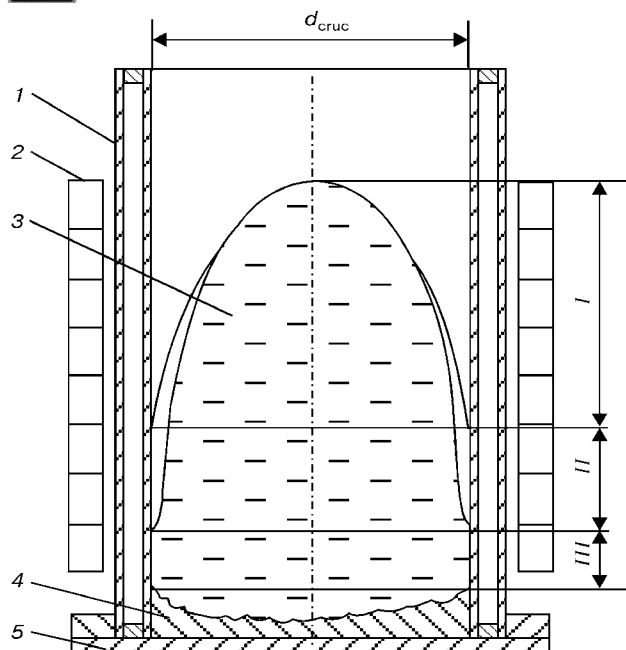


Figure 7. Scheme of metal pool in melting in a cold crucible: *I* — zone of complete melt squeezing from crucible wall; *II* — zone of slot squeezing of melt; *III* — zone of a full contact of melt with crucible wall; *1* — cold crucible; *2* — inductor; *3* — metal pool; *4* — skull; *5* — bottom

electromagnetic field energy occurs from inductor to the melt in a cold crucible [43–45].

In spite of the fact that the part of electromagnetic field energy is lost in the cooled crucible wall, a rather high value of power factor of the cylindrical inductor (as compared with edge inductor) provides the evolution of heat energy in the charge, sufficient for its melting and subsequent overheating of the metal melt. Uniform lateral heating and intensive stirring of the melt in the electromagnetic field can produce pool with a homogeneous chemical composition and temperature.

In induction melting in a cold crucible its geometric parameters are close to those of crucibles made from refractory materials used in conventional furnaces, i.e. height of crucible and inductor several times exceeds the crucible diameter. Therefore, the induction melting in a cold crucible is typical of a large depth of the metal pool. In height of the metal melt, locating in a cold crucible, three typical zones can be distinguished (Figure 7) [25]. Upper *I* is the zone of a complete squeezing out of melt from the cold crucible wall, middle *II* is the zone of a partial (slot) squeezing out of melt from crucible wall and lower *III* is the zone of a full contact of melt with a cold crucible wall.

An essential drawback of furnaces with a cold crucible is the fact that during metal pouring its large part is frozen on the crucible wall and pouring lip. Amount of the poured metal does not exceed 60–65 % [43–46]. In addition, ingots, cast into mould, have defects of a shrinkage origin and developed liquation of alloying elements that is typical of conventional methods of casting. In spite of the fact that many aspects of the process of induction melting in cold

crucibles are well-studied both in theoretical and in design direction (problems of electrical parameters and power characteristics of the process as a whole, design of cold crucibles, etc.), its practical use for producing castings and ingots was not realized.

The induction units with a cold crucible are used in technological processes which are not related to a metal pouring. One of them is metallothermic reduction, widely used in producing metals characterized by high reactivity in a molten state, for example, zirconium, vanadium and others [44, 47]. Processes of metallothermic reduction are realized in special reactors or thermal units. Induction units with a water-cooled sectional mould can be used as these units. They give an opportunity to realize the input of heat energy of the electromagnetic field additionally to the heat of chemical reactions which is generated in the reaction mass. This contributes to a uniform heating of the reaction mass and to the better separation of the formed metal and slag in a molten state.

Work [44] describes design and characteristics of the industrial installation «Impuls» with a cold crust designed for producing such metals as vanadium, zirconium and others. Installation consists of four melting modules, having a common vacuum system, and one set of high-frequency equipment (Figure 8). Each of melting modules contains a pressurized melting chamber, inside of which a sectional water-cooled crucible (0.65 m diameter, 2 m height) with inductor is mounted, and also a mechanism of ingot unloading.

The processes of loading, melting, cooling of reaction products and their unloading from melting chamber are realized in each melting module successively with a shifting in time with respect to other modules.

Crucible represents a cylindrical metal water-cooled structure, assembled from electrically isolated sections (50 copper sections of a trapezoidal form with channels for cooling water flow).

The installation «Impuls» is equipped with four machine frequency converters of 2000 kW total capacity. Operating frequency of current supplied to the inductor is 2.4 kHz.

During heating of the reaction mass by the electromagnetic field the temperature, sufficient for initiation of chemical reaction in the loaded mass, is reached. Metal and slag are formed as a result of proceeding the redox reaction. Due to a large difference in density the metal and slag are well separated. The metal ingot is formed on the bottom plate and the slag pool is located over it. After completion of the reduction process and ingot cooling the latter is withdrawn from the melting chamber using a withdrawal mechanism.

Duration of cycle in each melting module can be from 2 to 3.5 h taking into account the time of the ingot cooling.

The metal ingot produced by this technology contains an increased amount of gas impurities, non-me-

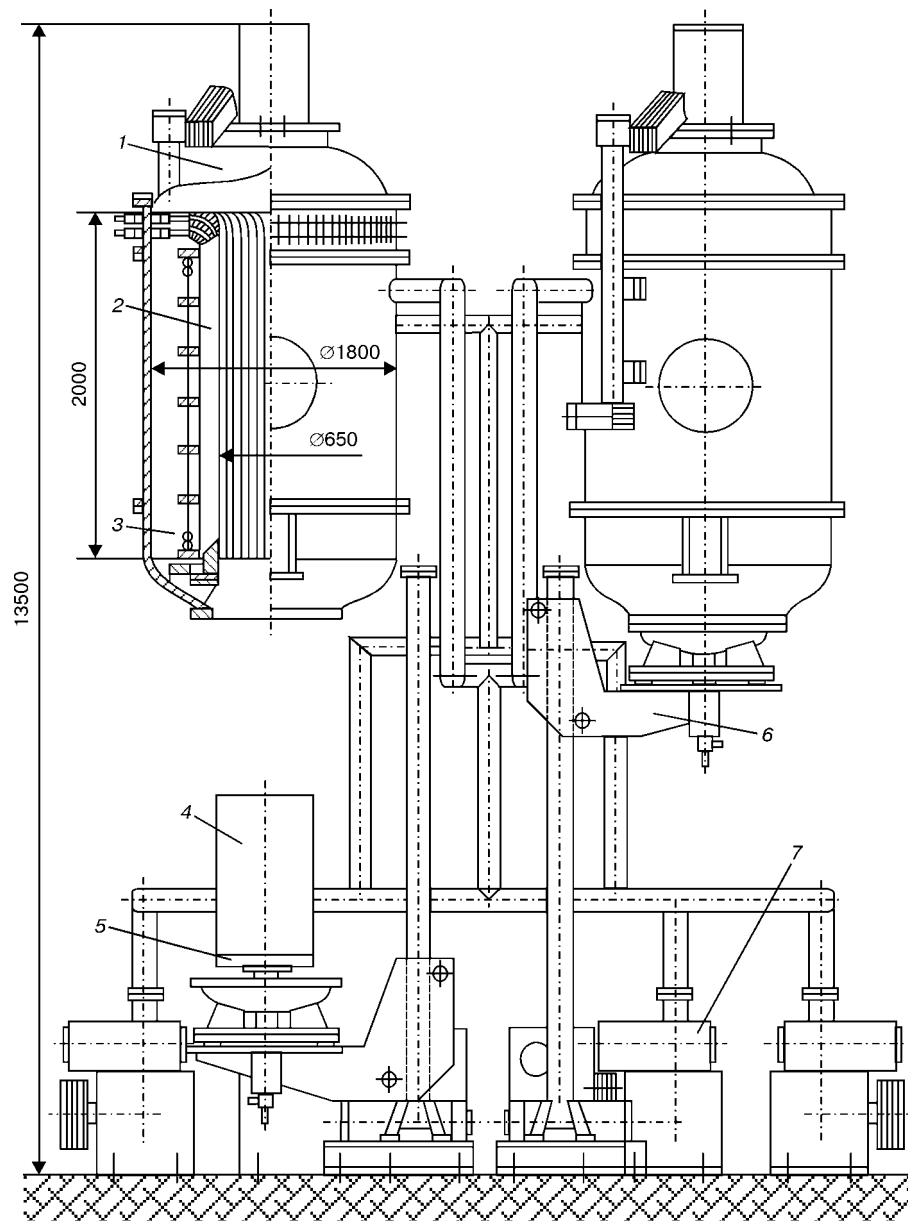


Figure 8. Scheme of induction installation «Impuls» for metallothermic reduction: 1 — melting chamber (reactor); 2 — cold crucible; 3 — inductor; 4 — ingot of metal; 5 — bottom plate; 6 — mechanism of ingot withdrawal; 7 — vacuum system

tallic inclusions, and also technogeneous impurities (increased content of a reducer metal). Therefore, these ingots are subjected to refining remelting in furnaces of vacuum-arc or electron beam remelting.

So, it can be concluded from analyzing the schemes of processes of induction crucible-free melting, their technical characteristics, peculiarities and capabilities, that the industrial application of levitation melting will be hardly possible in the near future.

The induction levitation melting is indispensable and, probably, the only modern method of physical-chemical investigations of metal melts.

Zone melting and melting with electromagnetic maintaining of melt on the support have already found application in industry in production of ultra-pure metals.

As to the induction melting in a cold crucible, then it should be noted that in spite of application in industrial scale this process requires great modifica-

tions in technologies and melting equipment to improve its technical-economical characteristics.

1. Vajnberg, A.M. (1960) *Induction melting furnaces*. Moscow: Gosenergoizdat.
2. Brockmayer, C. (1972) *Induction melting furnaces*. Moscow: Energiya.
3. Prostyakov, A.A. (1977) *Induction furnaces and mixers for cast iron melting*. Moscow: Energiya.
4. Batash, G.I. (1965) *Induction heating of metals and its industrial application*. Moscow-Leningrad: Energiya.
5. Slukhotsky, A.E., Nemkov, V.S., Pavlov, N.A. et al. (1981) *Induction heating units*. Manual for higher education schools. Leningrad: Energoizdat.
6. Glukhanov, N.P. (1979) *Physical principles of high-frequency heating*. Issue 1. Leningrad: Mashinostroenie.
7. Shamov, A.N., Bodazhkov, V.A. (1974) *Design and service of high-frequency units*. Leningrad: Mashinostroenie.
8. Golovnyova, M.A., Atroshenko, A.P. (1962) *Equipment and technology for hot stamping*. Manual for machine-building technical secondary schools. Moscow-Leningrad: Mashgiz.
9. Prostyakov, A.A. (1970) *Induction heating units*. Moscow: Energiya.



10. Ryskan, S.E., Smirnov, V.M., Blagoveshchensky, G.V. (1966) *Induction heat-treatment equipment*. Moscow-Leningrad: Mashinostroenie.
11. Skachko, Yu.N., Popov, N.V., Moshkin, V.F. et al. (1976) Unit for high-frequency welding of spirally-welded pipes. *Avtomatich. Svarka*, **11**, 72–73.
12. Pismenny, A.S. (1998) New in induction heating application for welding and related technologies. *Ibid.*, **11**, 54–60.
13. Lebedev, V.K., Tabelev, V.D., Pismenny, A.S. (1983) Butt pressure brazing of steel pipelines. *Ibid.*, **9**, 25–27.
14. Shamov, A.N., Lunin, I.V., Ivanov, V.N. (1977) *High-frequency welding of metals*. Leningrad: Mashinostroenie.
15. Vologdin, V.V., Kushch, E.V. (1979) Induction brazing In: *Library of specialist in high-frequency welding and heat treatment*. Issue 7. Leningrad: Mashinostroenie.
16. Rebouxf, J. (1985) Les plasmas induction: un outil exceptionnel pour une metallurgie de qualite. *J. Fr. Electroterm.*, **5**, 29.
17. Lakomsky, V.I., Melnik, G.A. (1966) Spheroidising in high-frequency discharge of aluminium oxide powder. *Poroshkovaya Metallurgiya*, **2**, 6–8.
18. Arseniev, P.A., Kustov, E.F. (1966) Investigation of high-frequency gas discharge of high pressure. *Teplofizika Vys. Temperatur*, **2**, 166–170.
19. Antipov, I.V., Gugnyak, A.B., Dmitriev, S.N. (1968) Process of production of titanium pigment dioxide in high-frequency discharge of oxygen plasma. *Fizika i Khimiya Obrab. Materialov*, **4**, 146–149.
20. Lakomsky, V.I. (1964) Procedure of investigation of hydrogen solubility in liquid metals at the wide temperature range. In: *Gases in cast metals*. Moscow: Nauka.
21. Fogel, A.A. (1979) *Induction method of confinement of liquid metals in suspension state*. Ed. by A.N. Shamov. Leningrad: Mashinostroenie.
22. Fogel, A.A., Korin, I.V. (1968) Levitation melting using electron beam heating. *Izv. AN SSSR, Series Metals*, **2**, 138–145.
23. Ratnikov, D.G. (1976) *Crucible-free method of zone melting*. Moscow: Metallurgiya.
24. Vigdorovich, V.N., Volpyan, A.E., Kurdyumov, T.M. (1969) Application of zone recrystallisation for physicochemical analysis. *Zavod. Laboratoriya*, **11**, 1350–1356.
25. Tir, L.L., Fomin, N.I. (1975) Current methods of induction melting. In: *Library of electric heat-treater*. Issue 59. Moscow: Energiya.
26. Byndin, V.M., Dobrovolskaya, V.I., Ratnikov, D.T. (1980) *Induction heating in production of superpure metals*. Ed. by A.N. Shamov. Leningrad: Mashinostroenie.
27. Kogan, M.G. (1967) Autocrucible induction melting. *Teplofizika Vys. Temperatur*, **3**, 485–491.
28. Gubchenko, A.P. (1986) Melting and solidification of melt in electromagnetic field on support. *Magnitnaya Gidrodinamika*, **1**, 132–133.
29. Fomin, N.I., Tir, L.L. (1963) Assurance of predetermined configuration of melt contained by magnetic field. In: *Proc. of 7th Riga's Meeting on Magnetic Hydrodynamics*, Riga, March 1963. Vol. 3.
30. Grigorenko, G.M., Pomarin, Yu.M., Lakomsky, V.I. et al. (1974) Temperature dependence of solubility in liquid iron-manganese alloys. *Izv. AN SSSR, Series Metals*, **6**, 11–16.
31. Lakomsky, V.I., Grigorenko, G.M., Torkhov, G.F. et al. (1973) Influence of chrome and nickel on nitrogen solubility in iron alloys at high temperatures. In: *Interaction of nitrogen with metals*. Moscow: Nauka.
32. Pomarin, Yu.M., Shejko, I.V., Griorenko, G.M. et al. (1981) Study of nitrogen solubility at increased pressure in low-alloy stainless steel 03Kh25N5AM3. In: *Problems of Special Electrometallurgy*. Issue 14.
33. Fedorchenko, V.N., Averin, A.V. (1973) Study of solubility and kinetics of nitrogen solubility in iron-oxygen and iron-sulfur melts using the crucibleless method. In: *Interaction of metals and gases in steel-making processes*. Moscow: MISiS.
34. Shimayo, I., Takami, T. (1972) Investigation of kinetics of reaction between liquid iron and nitrogen by the levitation melting method. In: *Physical-chemical principles of metallurgical processes*. Moscow: Nauka.
35. Wada, H., Gundi, K., Wada, T. (1968) Solubility of nitrogen and interaction with oxygen in liquid iron. *Transact. of Iron and Steel Inst. Jap.*, **5**, 323–328.
36. Nedzvetsky, Yu.E. (1961) Methods of increase of rod section in crucibleless zone melting. In: *Industrial application of high-frequency currents*. Moscow: Mashgiz.
37. Artsyshevsky, P.P., Kravetsky, D.Ya., Zatulovsky, L.M. (1971) Investigation of growing process of profile silicon crystals from pedestal. *Izv. AN SSSR, Series Physics*, **3**, 469–472.
38. Livanov, V.A., Gabidullin, R.M., Shipalov, V.S. (1977) *Continuous casting of aluminium alloys*. Moscow: Metallurgiya.
39. Neustruev, A.A., Khodorovsky, G.A. (1967) *Vacuum skull furnaces*. Moscow: Metallurgiya.
40. Volokhonsky, L.A. (1966) *Thermophysical processes and energy balance in skull melting*. Moscow: VNIEM.
41. Glukhanov, N.P., Zhezherin, R.P., Melikov, M.A. et al. *Induction melting method of chemically active metals in crucible from the same metal*. USSR author's cert. 113211. Int. Cl. C21C 5/56. Publ. 1958.
42. Fomin, N.I., Tir, L.L., Vertman, A.A. (1971) Use of induction melting devices with cold crucibles and electromagnetic reduction of melt for high-temperature physicochemical investigations. In: *Electrothermics*. Issue 10.
43. Petrov, Yu.B., Ratnikov, D.G. (1972) *Cold crucibles*. Moscow: Metallurgiya.
44. Tir, L.L., Gubchenko, A.P. (1988) *Induction melting furnaces for processes of increased accuracy and purity*. Moscow: Energoizdat.
45. Kudryavtsev, Yu.N. (1993) Induction crucible furnaces for melting and casting of titanium alloys. *Titan*, **1**, 39–42.
46. Donskoj, A.V., Ratnikov, D.G. (1993) On use of cooled crucibles in induction furnaces. In: *Electrothermics*. Issue 3.
47. Kachur, L.I., Gubchenko, A.P. (1978) Peculiarities of melting and production of homogenous alloys in induction furnace with a cold crucible. *Tsvetn. Metall*, **3**, 67–69.



INVESTIGATION OF ELECTROMAGNETIC FIELDS OF MELTING AND PREHEATING INDUCTORS IN CRUCIBLE-FREE ZONE MELTING

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In this work the magnetic fields of melting and preheating inductors are calculated. Their influence on the processes proceeding in induction crucible-free zone melting of silicon both inside the melt and also at its surface is analyzed. Method of improving the degree of magnetic field action is offered.

Keywords: inductor, magnetic field, Taylor's criterion, Hartmann's criterion, convection

Over the recent years the methods of control of hydrodynamics, heat and mass transfer, based on application of magnetic fields, found the wide spreading in the processes of producing single crystals of semiconductors [1]. The premise for application of electromagnetic fields is a rather high electric conductivity of semiconductors in a liquid state, i.e. $\sigma = 1 \cdot 10^4 - 1 \cdot 10^6 (\text{Ohm} \cdot \text{m})^{-1}$. The effect of electromagnetic fields is manifested in the fact that they hinder the change in rate of averaged flow of melt, and also its temperature and concentration. In producing single crystals using the method of crucible-free zone melting (CFZM) the electromagnetic fields of melting and preheating inductors also influence the molten zone [2, 3]. In the mentioned works the effect of electromagnetic field of the melting inductor is analyzed, but the effect of electromagnetic field of the preheating inductor on the molten zone is not accounted for.

The present work is devoted to the calculation of magnetic fields of melting and preheating inductors, and also to the analysis of their effect on the processes proceeding both inside the molten zone and also at its surface. The calculated model of the process is given in Figure 1. It maximum approaches its real

model for the case of growing silicon single crystals of 76 mm diameter. Inner diameters of melting and preheating inductors are 32 and 90 mm, respectively; current of melting inductor — 1000 A; ratio of melting and preheating inductor currents is $I_{\text{melt}}/I_{\text{preheat}} = 2.5$; current frequency — 2.8 MHz.

To calculate the electromagnetic field the differential equation in partial derivatives relative to a complex amplitude of a vector magnetic potential A which is associated with a vector of magnetic induction by the following equation:

$$B = \nabla A. \quad (1)$$

It is assumed that the vector of the magnetic induction is located in the model plane, while the vector of electric current density j and vector magnetic potential A are orthogonal to it.

The equation of vector magnetic potential for axisymmetric case has a following form:

$$\frac{\partial}{\partial r} \left(\frac{1}{r \mu_z} \frac{\partial (rA)}{\partial r} \right) + \frac{\partial}{\partial z} \left(\frac{1}{\mu_r} \frac{\partial A}{\partial z} \right) - \omega \sigma A = -j_0, \quad (2)$$

where z , r are the space coordinates; μ_r , μ_z are the components of relative magnetic permeability; ω is the angular frequency, s^{-1} ; σ is the material electric conductivity, $(\text{Ohm} \cdot \text{m})^{-1}$; j_0 is the current-sided com-

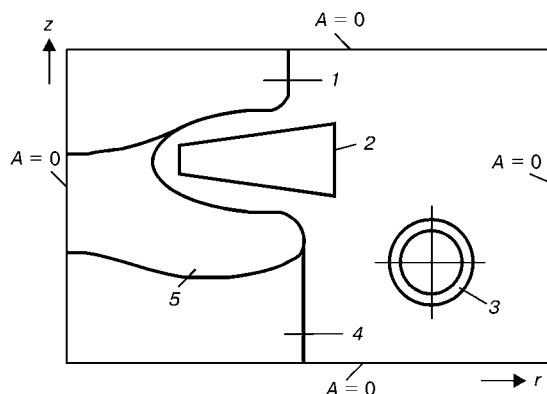


Figure 1. Geometrical model of CFZM: 1 — feed core; 2, 3 — melting and preheating inductors, respectively; 4 — single crystal; 5 — molten zone

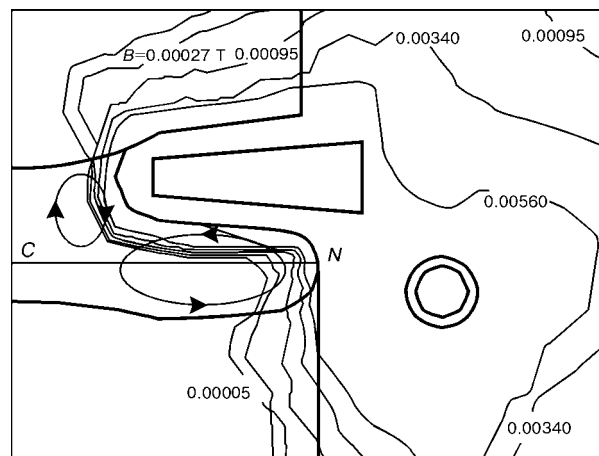


Figure 2. Calculated pattern of magnetic field

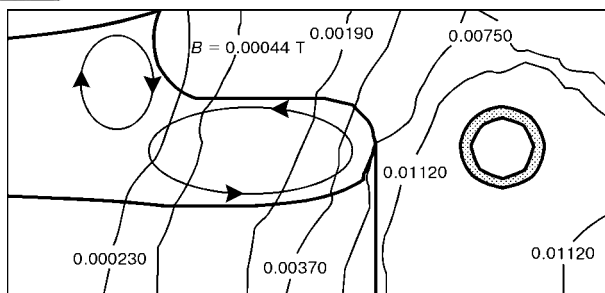


Figure 3. Calculated pattern of magnetic field obtained in 50 Hz frequency of current

ponent caused by applied external voltage, A. Values μ_r , μ_z , σ , j_0 for each material were taken constant. Field change with time was supposed to be sinusoidal.

The region considered was in vacuum and included a feed core, melting inductor, melt, single crystal and one turn of the preheating inductor. The effect of the rest turns of this inductor on the melt was not taken into account, as they are located below the mentioned turn at the relatively large (20–30 mm) distance from each other. The selection of region boundary was realized so that a magnetic potential vector, arranging on it, was equal to zero. The distance between the region boundary, front of crystallization and inductor were selected from considerations of a minimum distortion of the magnetic field pattern.

The task put forward was solved by the method of finite elements using software QuickField 4.3T. Results of calculation are given in Figure 2. As is seen from the Figure, the calculated magnetic field is combined with a supposed movement of the melt caused by an electrodynamic convection [4]. It is also noticeable that the magnetic field does not penetrate deeply into the melt, but is concentrated near the free its surface. Consequently, it has the greater influence on the thermocapillary forces than on viscosity forces. To evaluate the interaction between the thermocapillary convection and rotating magnetic field the dimensionless Taylor's criterion was used [2]:

$$Ta = \frac{B^2 \omega_r R^4 \sigma}{2 \rho \nu^2}, \quad (3)$$

where ω_r is the angular speed of rotating magnetic field, s^{-1} ; R is the radius of a single crystal, m; ρ is the density of molten silicon; $\rho = 2530 \text{ kg/m}^3$; ν is its viscosity, $\nu = 3.5 \cdot 10^{-7} \text{ m}^2/\text{s}$. However, in this case the magnetic field was stationary, and the single crystal was rotating. Therefore, in formula (3) the angular speed of rotation of the single crystal was used

$$\omega = \frac{n\pi}{30}, \quad (4)$$

where n is the frequency of rotation of a single crystal, rpm. In calculation n was taken equal to 30 rpm. After substituting values of physical parameters of the molten silicon and calculated values of vector of magnetic induction to formula (3) we shall obtain that the Taylor's criterion is $Ta > 1 \cdot 10^5$. It corresponds to the condition with a dominating action of the magnetic field, at which the thermocapillary flow is decreased significantly [2]. Thus, the magnetic field of melting and preheating inductors at current frequency 2.8 MHz suppresses the thermocapillary convection.

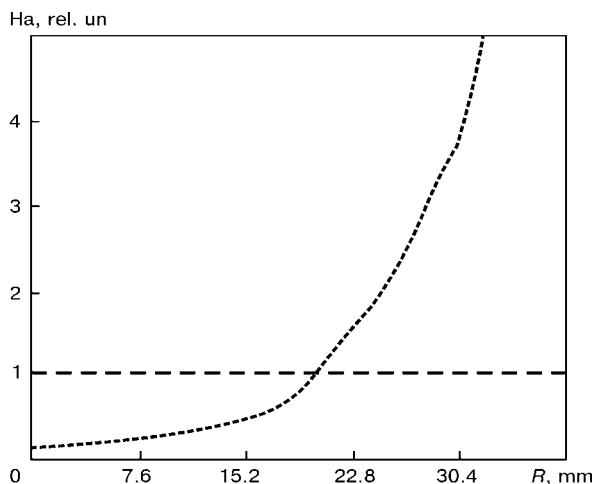


Figure 4. Curve of distribution of Hartmann's criterion along the single crystal radius

The highest permeability of the magnetic field in the silicon melt volume is attained at 50 or 400 Hz frequency of current [2, 5]. As it is impossible to decrease the frequency of current of melting and preheating inductors down to the mentioned values without disturbance of optimum conditions of melting, then an additional inductor, which is arranged between the melting and preheating inductors, is used. The pattern of magnetic field generated by this inductor is shown in Figure 3. It differs noticeably from that presented in Figure 2. It is seen that the larger part of the melt is located in the magnetic field. It is the area where the «main» vortex influencing the crystallization conditions is developed.

Degree of action of magnetic forces on the viscosity forces was determined by the Hartmann's criterion

$$Ha = BR \sqrt{\frac{\sigma}{\rho \nu}}. \quad (5)$$

The calculated values of the Hartmann's criterion along the length CN (see Figure 2) are shown in Figure 4. At $Ha > 1$ the magnetic forces begin to dominate over the viscosity forces that can hinder the change in temperature and rate of the melt movement.

Thus, the magnetic field of melting and preheating inductors suppresses the thermocapillary convection, and the application of the additional inductor with 50 Hz frequency of current can lead to the improvement of the crystallization conditions. Moreover, in this case an additional possibility in control of concentration of impurities in silicon single crystals is appeared.

1. Gelfgat, Yu.M., Zemskov, V.S., Raukhan, M.R. et al. (1988) Growing of semiconductor single crystals by electro-magnetic action on melt. In: *Processes of growing of semiconductor crystals and films*. Novosibirsk: Nauka.
2. Dold, P., Croll, A., Lichtensteiger, M. et al. (2001) Floating zone growth of silicon in magnetic fields. Part 4. Rotating magnetic field. *J. Crystal Growth*, **231**, 95–106.
3. Nancy, Ma., Walker, J.S., Ludge, A. et al. (2000) Silicon float zone process with a weak transverse magnetic field and crystal rotation. *J. Electrochemical Soc.*, **147**, 3529–3534.
4. Muhlbauer, A., Erdmann, W., Keller, W. (1983) Electrodynamic convection in silicon floating zones. *J. Crystal Growth*, **64**, 529–545.
5. Jonston, V.S., Tiller, V.A. (1966) Liquid flow control during solidification. In: *Zone melting*. Moscow: Metallurgiya.



OPTIMIZING OF CONDITION OF STEEL MELTING IN ARC STEELMAKING FURNACE WITH ALLOWANCE FOR ENTERPRISE PROFIT

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Dependence of production effectiveness of steelmaking shop on technological parameters of the steel melting process is analyzed. It is shown that at different variants of the technology and also in automated systems of control of technological processes of melting and ladle treatment a final aim of any production, i.e. enterprise profit, should be used as a purposeful function of optimizing, but not the indirect indices of shop operation (efficiency of the unit, cost of products).

Keywords: technology of electric melting, oxygen blowing in, exothermal reactions, output of efficient metal, arc furnace efficiency, cost, enterprise profit

To analyze the profit dependence on production volume (or furnace efficiency) the following considerations are taken into account [1]. Expenses of the enterprise for products manufacturing are

$$Z = SG, \quad (1)$$

where S are the expenses for main materials and energy suppliers per ton of ready products, US\$/t; G is the mass of produced metal, t/year. Profit of enterprise from metal selling is

$$Y = CG, \quad (2)$$

where C is the price of products, US\$/t.

As a result, the following formula is obtained for determination of annual profit of the enterprise:

$$P = Y - Z - Z_{\tau} = (C - S)G - Z_{\tau}, \quad (3)$$

where Z_{τ} is the conditionally constant expenses (salary, taxes, payment for land, equipment repair, i.e. everything paid by the enterprise independently of the products manufacturing), US\$/year.

It follows from the formula that the enterprise becomes unprofitable at the productivity of less than $Z_{\tau}/(C-S)$. The increase in the productivity leads always adequately to the increase in the profit. The above-mentioned dependence is illustrated by a diagram shown in Figure 1 [1].

In these consideration there is one drawback: it is considered that with increase in furnace efficiency all initial data (cost coefficients) remain constant. This situation corresponds to «extensive» way of increasing productivity (increase in number of furnaces, their capacity, etc.). If the method of increasing furnace efficiency by changing melting technology is considered (in particular, intensification of oxygen blowing in), then it is necessary to take into account that in this case not only the melting duration is decreased (due to additional heat of chemical reactions), but

also the mass of the molten semi-product at the outlet (due to increased iron loss). Here, the expenses for main materials and energy suppliers per one melting are not almost changed, that is equivalent to the growth of all the cost coefficients per 1 t of molten metal. Thus, formula (1) does not already reflect the dependence of enterprise expenses on the mass of produced metal and, therefore, it is necessary to consider the expenses fixed for each melting. In other words, a metal scrap of a definite cost is loaded into the furnace, then this cost will not depend on the results of melting, i.e. 10 or 50 % of metal will be transferred to the slag.

As an example we shall consider two variants of technologies: basic and comparative. Let us assume that the comparative variant is differed from the basic variant only by a smaller mass of the produced metal and melting duration, all other characteristics will be considered unchanged: conditionally-constant expenses $Z_{\tau} = 12$ mln US\$/year (approximate estimation; it is shown further that this value does not influence the results of comparison); the price of molten semi-product (price of billet minus expenses for al-

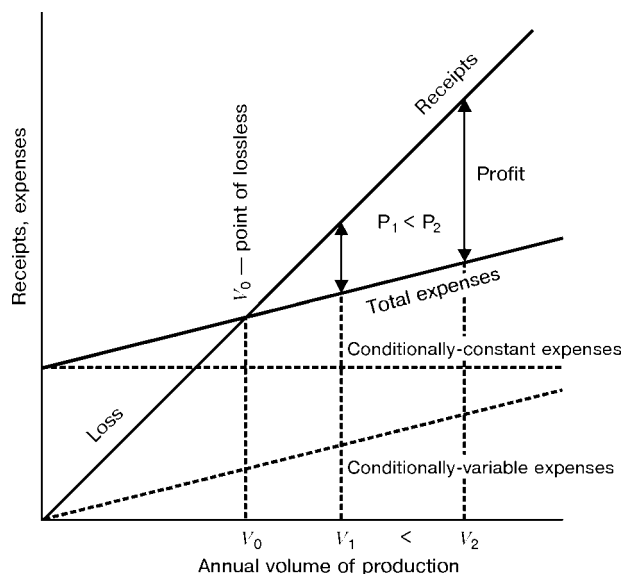


Figure 1. Dependence of profit on volume of production and expenses

**Table 1.** Cost coefficients (expenses for main materials and energy suppliers) in a basic variant at output mass $M = 125$ t, US\$

Description of resources	Price of resources unit	Consumption of resources per 1 t of steel	Cost of resources per 1 t of steel	Cost of resources per melting
Scrap, t	50	1.2	60	7500
Electric energy, kW·h	0.03	400	12	1500
Electrodes, kg	3	3	9	1125
Lime, kg	0.05	50	2.5	312.5
Natural gas, m ³	0.05	10	0.5	62.5
In total:			84	$Z_m = 10500$

loying, rolling, pouring, transporting and so on) $C = 105$ US\$/t; duration of furnace operation per year $T = 8000$ h; expenses for main materials and energy suppliers per one melting $Z_m = 10500$ US\$ (approximate calculation is given in Table 1).

Let us estimate the reduction in mass and melting duration with increase in intensity of oxygen blowing in. The total heat consumption for melting 1 t of metal is ≈ 540 kW·h/t or 1944 MJ/t. To reduce the melting duration for 1 min (from 60 min in a basic variant to 59 min in a comparative variant), it is necessary to introduce $1944/60 = 32.4$ MJ/t of heat at the expense of iron oxidation by the blown-in oxygen. The reaction of iron oxidizing with gaseous oxygen has a thermal effect of not more than 5.9 MJ/kg of iron. Consequently, the additional iron loss per each minute of reduction in melting duration will be 5.5 kg/t, and at average mass of melting 125 t the reduction in mass of the output metal will reach 0.686 t.

Let us analyze the dependence of profit per time unity on intensity of oxygen blowing in to the arc steelmelting furnace. The changes in characteristics with increase in intensity of blowing in are given in Table 2.

Table 2. Comparison of characteristics

Description of characteristics	Basic variant	Comparative variant	Change
Duration of melting τ , min	60	59	-1
Output mass M , t	125	124.32	-0.68
Furnace efficiency $Q = M/\tau$, t/h	125	126.43	+1.43
Number of melts per year $N = T/\tau$	8000	8135	+135
Specific expenses for main materials and energy suppliers $S = Z_m/M$, US\$/t	84	84.46	+0.46
Volume of annual production $G = QT$, ths t	1000	1011.41	+11.41
Total expenses per year $Z = Z_m N$, ths US\$	84000	85424	+1424
Receipts of plant per year $Y = GC$, ths US\$	105000	106199	+1199
Profit per year $P = Y - Z - Z_\tau$, ths US\$	9000	8775	-225
Profit from one melting P/N , US\$	1125	1078.60	-46.40
Profit per hour P/T , US\$/h	1125	1096.88	-28.12

The calculations show that the comparative variant is not profitable (annual profit is decreased by 22500 US\$) in spite of increase in production productivity by 11400 t of steel per year. To simplify the analysis of different variants of the technology, it is desirable to have the analytical form of dependence of profit on above-given factors.

Substituting expressions of Table to formula (3) gives the following form of dependence of enterprise profit per year on melting duration:

$$P = T \frac{CM - Z_m}{\tau} - Z_\tau. \quad (4)$$

To analyze formula (4) we shall calculate the derivative

$$\begin{aligned} \frac{dP}{d\tau} &= T \left(C \frac{dM}{d\tau} - (CM - Z_m) \right) = \\ &= NC \left(\frac{dM}{d\tau} - Q \left(1 - \frac{S}{C} \right) \right). \end{aligned} \quad (5)$$

Reduction in melting duration leads to the increase in profit ($dP/d\tau$), if

$$\frac{dM}{d\tau} < Q \left(1 - \frac{S}{C} \right). \quad (6)$$

It is interesting that only two characteristics in formula (6) are of importance: productivity and material expenses-to-semi-product price ratio. All other characteristics (τ , M , T , Z_τ) do not influence the technology profitability. At the above given basic characteristics the profitability of intensification of oxygen blowing in is determined by expression

$$\frac{dM}{d\tau} < 25 \text{ t/h (0.43 t/min)}, \quad (7)$$

i.e. reduction in melting duration by 1 min should lead to the decrease in metal mass by not more than 0.43 t (or, in other words, each ton of the oxidized metal should provide reduction in melting duration by not less than 2.5 min). If the metal mass is reduced by more than 0.43 t (0.68 t in a comparative variant),



then it is more profitable not to increase the intensity of oxygen blowing in, and, vice versa, to decrease it. Here, the productivity will decrease, however, the decrease in cost of main materials and energy suppliers per metal ton will be dominating that will increase the production profit.

The above calculations do not deny the economical efficiency of intensification of oxygen blowing in to the arc furnace. The thing is that the reaction of oxidation of metal impurities (carbon, manganese, silicon) provides 2–5 times higher heat (per kilogram of impurities) than the reaction of iron oxidation. The oxidation of the above impurities leads to the decrease in metal mass by 0.14–0.34 t (per each minute of reduction in melting duration) that is below the critical value 0.43 t. As a result, the production profit with increase in oxygen consumption is growing, but only at the advantageous oxidizing of impurities, but not of iron. At the further increase of oxygen consumption the dependence is changed for opposite. In other words, carbon, manganese and silicon as heat sources are profitable, while «to heat» the furnace with iron is not profitable. Therefore, there is a definite limit after which all the blown-in oxygen is consumed for iron burning and further increase in its consumption becomes not rational (Figure 2). This extremum can be determined using automated systems of control of technological process of steel melting, based on strict thermodynamic models, for example system TP-ORAKUL [2–4].

Formula (6) allows making one more conclusion: economical rationality of iron burning (and position of critical point) is determined mainly by ratio of expenses for materials to semi-product price. For example, if the expenses for materials and energy suppliers are less than 67 % of price of molten semi-product, then «to heat» the furnace with iron becomes profitable (operation on «free of charge» metal scrap).

In the above-described calculations only general principles («skeleton») of analysis of economical «solvency» of technological variants of steel melting are considered. In particular, in condition (6) only one of influencing factors is considered, therefore, it is simplified and rather approximated. In automated control system TP-ORAKUL not only major, but also many other factors contributing to increase in intensity of use of oxygen blowing in (though influencing the economical efficiency of technology to a less extent) are considered: decrease in consumption of electric energy due to an additional heat of chemical reactions; increase in consumption of electrodes due to a more intensive oxidation with oxygen; oxygen cost; increase in consumption of deoxidizers and loss in alloying elements during alloying at pouring of semi-product to the ladle.

Moreover, with increase in intensity of oxygen blowing in the technical capabilities of units for oxygen adding to metal, presence of reserves for intensification of gaseous oxygen producing, facilitating the

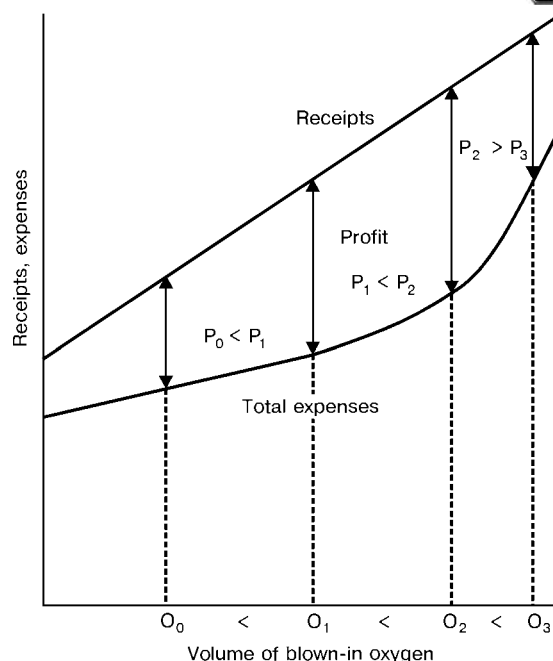


Figure 2. Dependence of profit on intensity of blowing in

technology of treatment of steels with a decreased content of carbon and phosphorus in furnace–ladle unit, deterioration of conditions of operation of lining, gas purification and others are considered.

CONCLUSIONS

1. It is established that the increase in productivity (production volume) does not always lead to the increase in profit. The latter is guaranteed only in that case if the cost coefficients of main materials and energy suppliers per unit of products are preserved unchanged (or changed negligibly).

2. Increase in furnace efficiency by changing technology of melting semi-product causes always the change in cost coefficients, therefore, a more comprehensive analysis of either changes in technology are required (whether the enterprise profit is increased, but not the steel production volume).

3. All possible variants of technology of steel melting are «counted» using automated control system TP-ORAKUL, which makes it possible to select an optimum method of conductance of each definite melting with allowance for today's economical conditions and the above-mentioned additional factors.

1. Elansky, D.G. (2001) Tendencies in development of electric furnace steelmaking. *Elektrometallurgiya*, 5, 3–18.
2. Starosotsky, A.V., Kerejnik, A.V., Shcherbina, T.V. et al. (2002) Complex process control system of steel melting. In: *Proc. of 2nd Int. Sci.-Pract. Conf. on Automated Furnace Units and Energy-Saving Technologies in Metallurgy*. Moscow: MISiS.
3. Khrapko, S.A., Starosotsky, A.V. (2002) Automatic control system of steel deoxidation and alloying. *Ibid.*
4. Starosotsky, A.V., Babichev, A.K., Derevyanchenko, I.V. et al. (2001) Creation of automatic following system of melting in ASF as a first step of use of intelligent control systems in steelmaking production. In: *Proc. of 6th Congress of Steelmakers*. Moscow: Chermetinformatiya.

Brief information on research works carried out on the below-given subjects at the E.O. Paton Electric Welding Institute of the NAS of Ukraine over the period of 2000–2002.

«Development of Fundamentals of Technological Processes of Titanium Melting Using Sponge and Non-Compact Charge Materials in Electroslag Process and Other Heat Sources for Melting»

Manager — Prof. L.B. MEDOVAR

The aim of works on R&D subject was to develop fundamentals of technological processes of melting titanium using sponge and non-compact charge materials in electroslag process, and also other methods of heating for melting, which can be used effectively in creation of new energy-saving technologies for manufacture titanium semi-products and their implementation in production. These investigations were started by the initiative of Prof. B.I. Medovar.

In spite of the fact that the titanium melting has almost a century history, interest to the selection of method of production of titanium ingots remains suf-

ficiently acute, as it defines to a great extent the cost of melted metal and its quality.

The growing demand of enterprises of different branches for titanium semi-products requires the creation of titanium production in Ukraine, the rationality of which is confirmed by the presence of large industrially exploring deposits of titanium raw material in the country. The important argument is also the existing Saporozhie Titanium-Magnesium Concern.

Many leading companies of the world are searching for ways of improvement of technology and equipment for melting titanium alloys, providing 100 % guaran-

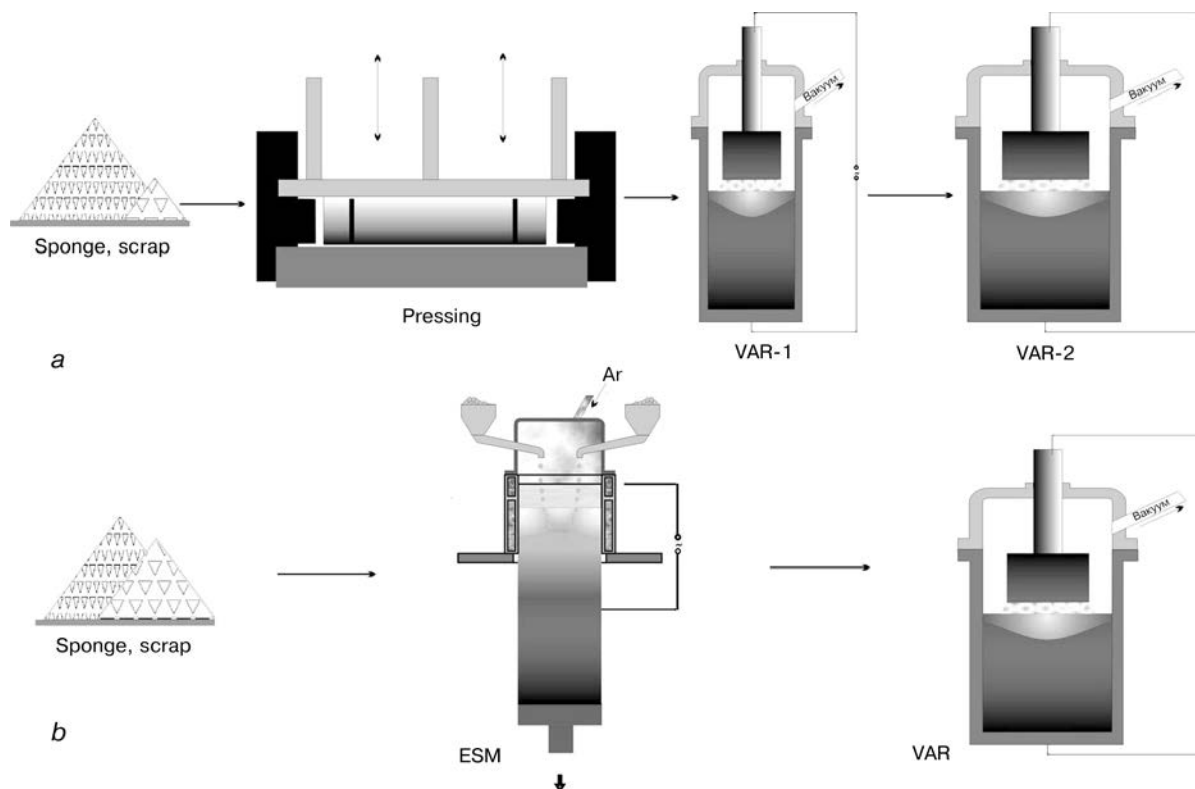


Figure 1. Scheme of ESM application in production of titanium ingots: *a* — traditional, *b* — with use of ESM CM



tee of melting refractory high-nitrogen α -inclusions which can be contained in the consumable charge materials. The main trend in these works is the creation of the technology and furnaces with a separation of zones of melting and crystallization of the ingot. In particular, in Russia a method of vacuum skull melting using a skull as a consumable electrode of the previous melting has been developed.

New opportunities in the solution of problem of producing ingots on the base of electroslag technology without hard inclusions are opened up owing to the use of ESM process in a current-carrying mould (ESM CM), where the most optimum technological ESM scheme is provided, consisting of separation of zone of melting consumable materials and zone of the ingot formation. The most important advantage of the ESM CM is also the fact that it can be used as a process of sponge compacting. In this case there is no need in such expensive operation as pressing of consumable electrodes from sponge and non-compact charge materials.

Complex of investigations according to R&D plan resulted in the development of technological scheme for realization of remelting of non-compact titanium sponge and charge materials [1, 2]. Production of titanium ingots using the process ESM CM in comparison with the traditional scheme of remelting of pressed electrodes is shown schematically in Figure 1.

Scheme of the developed process ESM CM of titanium sponge in a chamber furnace is shown in Figure 2. The process of producing the monolithic titanium ingot 7 from sponge is started from filling chamber 1 with argon, pouring of molten slag to the melting space of current-carrying mould 3 on bottom plate 10 mounted inside forming section 4 of the mould in such a way that the upper edge of bottom plate 10 was located a little lower than the upper edge of forming section 4 and connection of supply sources 9. Sections of the mould 2–4 are separated by isolating inserts 5. Slag pool 6 is electrically conductive and closes the electrical circuit: current-carrying section 2–bottom plate 10–ingot 7 and non-consumable electrode 11–bottom plate 10–ingot 7, in which current starts its passing and heats slag pool 6 up to temperature 1700–1800 °C. Current is adjusted by varying open-circuit voltage in the circuit current-carrying section 2–bottom plate 10–ingot 7 and by changing the non-con-

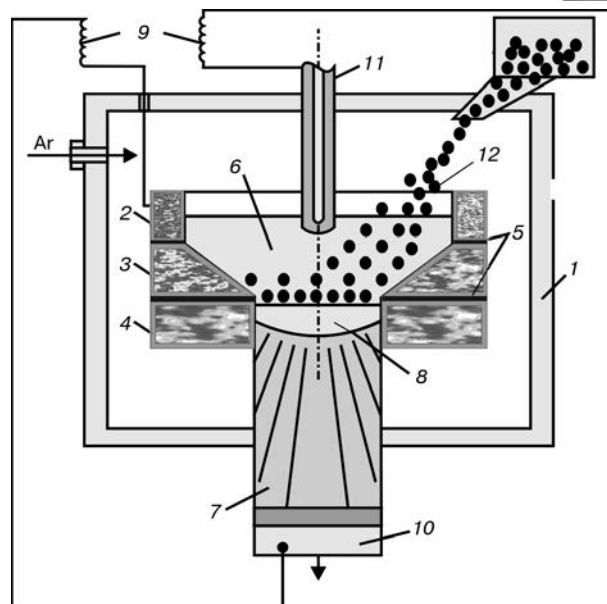


Figure 2. Scheme of ESM CM of titanium sponge [2]

sumable electrode 11 immersion into slag pool 6 in the circuit non-consumable electrode 11–bottom plate 10–ingot 7. After heating of slag pool to the preset temperature a titanium sponge 12 is fed from a batcher to slag pool 6 into the mould melting space. Owing to the higher density than that of a slag, the titanium sponge is lowered by heating in slag pool 6 on bottom plate 10 where it is melted in the zone of contact resistance of slag–bottom plate with the formation of a metal pool 8. The speed of withdrawal of ingot 7, fixed on bottom plate 10, from forming section 4 of the mould is maintained with the help of inductive sensor of a molten metal pool level. Experimental meltings of titanium sponge of 12–20 mm fractional composition according to this scheme were performed in a current-carrying mould of 350 mm inner diameter of the current-carrying section and 100 mm inner diameter of the forming section.

The application of ESM CM process in ESM of titanium ingots is more effective means for prevention of hard high-nitrogen inclusions. Effect of a quick dissolution of large nitrogen inclusions in slag in ESM CM was established experimentally, these inclusions were implanted into a specially prepared consumable electrode (Figure 3). Naturally, that in this case they are not melted, but, refined and uniformly distributed

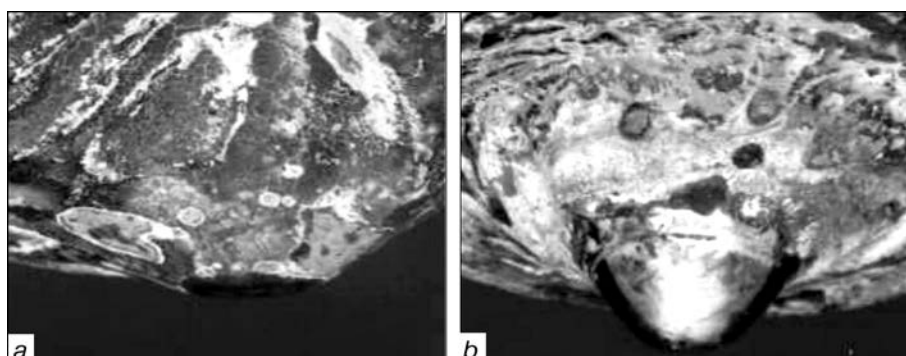


Figure 3. Appearance of fused ends of electrodes, containing 30 (a) and 49 (b) % of high-nitrogen inclusions



in the titanium ingot volume. In case of use of additions of metal calcium to the slag in ESM CM the rate of dissolution of high-nitrogen inclusions can be increased significantly. However, the realization of this active technological process of ESM is possible only in a chamber furnace with a controllable atmosphere. The use of the lower-energy consuming method of arc-slag process instead of ESM can appear to be rather promising.

As a result of fulfillment of R&D works, the fundamentals of technological processes of titanium melting using sponge and non-compact charge materials providing application of electroslag process and other heat sources for melting. Initial data were obtained for the development of new effective technologies and equip-

ment for production of titanium semi-products using method of semi- or continuous electroslag casting.

The results obtained can be used in organizing new industrial production of titanium semi-products using method of semi- or continuous casting at enterprises of Ukraine, in particular at «Dneprospetsstal» Works, where this production is planned to be created in the nearest future.

1. Paton, B.E., Medovar, B.I., Medovar, L.B. et al. *Metal method of continuous casting of titanium and its alloys in the chamber*. Pat. 31837 Ukraine. Int. Cl. 6 C 22 B 9/00. Publ. 17.12.01.
2. Medovar, B.I., Medovar, L.B., Fedorovsky, B.B. et al. *Metal method of production of monolithic consumable electrode from titanium sponge*. Pat. 34625 Ukraine. Int. Cl. 7 22 B 9/18. Publ. 15.03.02.

«Development of Electron Beam Technology of Deposition of Hard Gradient Coatings with a Non-Equilibrium Structure on Carbon and Boron Base»

Manager — Prof. B.A. MOVCHAN

Investigations and development of the process of electron beam evaporation and condensation in vacuum of hard gradient protective coatings on the base of carbides of titanium, chromium and boron were performed, during which the composition of produced condensates and structure of coatings in thickness and also their properties were examined.

Technology has been developed for a simultaneous evaporation of a multicomponent mixture (tablet) from one crucible with producing of complex carbide coatings. It provides repetition and reliability of the process, eliminates the need in use of ready carbide compounds as initial raw material, and also promotes the reduction in time of technological process and increase in power characteristics that simplifies it significantly and makes not so expensive as compared with other technological schemes.

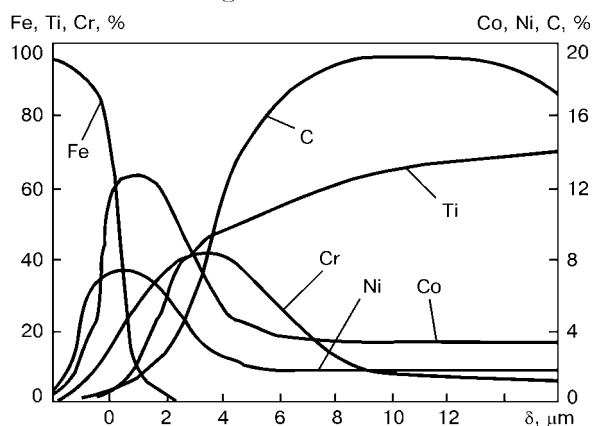


Figure 1. Distribution of elements in thickness δ of coatings of Ni-Co-Cr-Ti-C type

Regularities of formation of hard coatings with variable, preset composition and properties in thickness within the wide range are studied.

From evaporating tablets Ni-Cr-C; Co-T-C; Ni-Co-Ti-C and Ni-Co-Cr-Ti-C the 15–20 μm thick hard carbide coatings were produced on base of chromium and titanium carbides with a gradient of composition, structure and properties in thickness.

Coatings of Co-Ti-C and Ni-Co-Ti type in hard region are close by composition and properties to a stoichiometric titanium carbide. Microhardness of coatings reaches 30–34 GPa in this case.

In coatings of Ni-Co-Cr-Ti-C type a mixture of titanium and chromium carbides is formed. Due to a high content of elements with a high vapour pressure, the beginning of growth in concentrations of titanium and carbon is shifted with respect to the beginning of coating that promotes the increase in transition zone, shifting of hardness peak to the external surface at a smooth rate of its change (Figure 1). The microhardness of these coatings is 30–32 GPa (Figure 2).

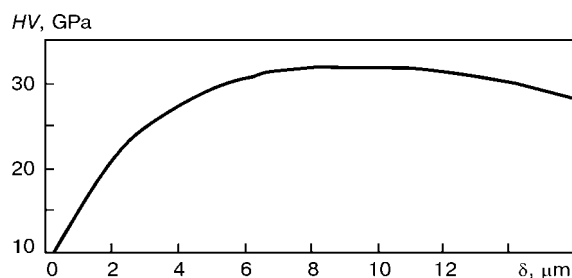


Figure 2. Change in microhardness HV in thickness of coatings of Ni-Co-Cr-Ti-C type



It was established that in use of the electron beam technology it is possible to produce the complex coatings with components different in their properties that was demonstrated on the example of coatings of Ni–Cr–C type. Composition, structure and properties of these coatings have a clearly expressed gradient nature, and a main parameter (microhardness) is increased gradually in coating thickness and equal to 20–22 GPa in a surface area, that corresponds to the properties of a higher carbide of chromium Cr_3C_2 .

The application of the technology developed makes it possible to synthesize successfully the coatings of boron carbide base B_4C directly on the substrate having coefficients of thermal expansion close to those of boron carbide (for example, molybdenum plates). Thus, the produced carbide coatings have a gradient of composition, structure and properties in thickness. Microhardness of coating is 30–32 GPa.

During investigations of properties on the base of condensates of TiC–Cu system, their high microhard-

ness (20–25 GPa), not depending on copper content up to 30 wt.%, was recorded.

Study of composition and structure of condensates of TiC–Cu system showed that they consist of hard grains of titanium carbide, located in copper matrix, filling the space between TiC sites up to ≈ 30 wt.%. At a mass fraction above 30 % the copper in condensates of TiC–Cu system is also located inside grains that reduces their microhardness.

The results of investigations can be a basis for further optimizing technology for producing hard coatings and improving their quality. The coatings produced can be recommended for deposition on steel and hard-alloy cutting tool; on steel products operating under the conditions of friction (sliding) without lubrication, including those at increased temperatures; on parts subjected to effect of erosion and corrosion, aggressive media and increased temperature.

«Investigation of Physical-Chemical Processes and Development of Technological Parameters of Producing New Metallic Materials (on Dispersed Hearth, Flaky, Amorphous and Single Crystals) Using Plasma-Arc and Induction Heaters of the New Generation»

Manager — Dr. V.A. SHAPOVALOV

The progress in the modern engineering requires the application of new metallic materials, sometimes with radically new combination of properties. In industrialized countries the new metallic materials are created using the newest technologies, and the existing technologies and equipment for their production are improved and updated.

The report on this subject consists of three sections:

- the first section is devoted to the study of physical-chemical and technological peculiarities of plasma-arc melting on dispersed hearth and development of the technology of compacting refractory and heat-conductive metals and alloys;
- the second section describes investigations of plasma technology of melting and refining of steel and ferroalloys;
- the third section is integral. It includes study of specifics of melting homogeneous ingots of titanium and manganese in the conditions of induction melting in a sectional mould of the electroslag process, growing of single crystals of refractory metals and dispersion of metal melt.

Conversion in defense industry of Ukraine has led to the formation of large amount of wastes of rare and valuable metals and alloys. One of the directions of the present work was to create the technological process and equipment for compacting wastes of molybdenum, chromium, niobium, tungsten, titanium and other expensive metals into ingots and billets, and also production of ferroalloys and master alloys on their base required for metallurgical industry and production of welding consumables.

High technologies were directed to the use of processes providing the high level of quality of the produced steels and ferroalloys at minimum energy- and resources consumption. This is a duplex-process in steel production, at which the metal is melted in high-efficient units, and metal improvement in chemical composition and its refining are made by ladle treatment using electric arc heating of metal by graphitized electrodes.

The aim of investigations in the scope of this subject was to improve the quality of steel and ferroalloys to the level of world standards, to save energy and material resources, to decrease contamination of environment.



Over the recent years the interest increased to the problems of production and application in industrial scales of metallic materials produced by the method of fast quenching from melt, and also to the growing of large single crystals of refractory metals. These materials are much superior by their properties to conventional cast or wrought metal. Report gives results of investigations of processes for producing the mentioned materials, on the basis of which the technologies and equipment for their production were developed.

The report presents results of investigations of physical-chemical processes proceeding in metal pool in melting and refining of melts, containing highly-active components, using fine-dispersed charge materials in plasma-arc and induction heating, and also in electroslag process with a non-consumable electrode.

One of the directions of the present work was the development of technologies of remelting of wastes of reactive and refractory metals, compacting of which by conventional metallurgical processes using open units leads, as a rule, to significant losses in valuable components or to their contamination with gas impurities. The aim of these investigations was to produce cylindrical or slab billets of titanium, niobium, molybdenum, tantalum from their wastes using plasma metallurgical technology. Optimum conditions of compacting chromium, titanium, tantalum into round billets were defined. It was shown that the reprocessing of wastes into ferroalloys and master alloys is the most suitable way of reprocessing the wastes of conversion.

The report presents procedures of study of heat processes which are proceeding in a dispersed formation, and also effect of sizes of particles and thickness of dispersed formation on power characteristics of the process.

The main drawbacks of application of electric arc heating in metallurgy are the increased consumption of electric energy, refractory materials and graphitized electrodes.

We have suggested the plasma-arc heaters of open type (PAHOT) which represent multiarc heating complexes. They are supplied from sources of direct, alternating current or from combined circuits. Schematic diagrams for PAHOT were developed, on the

basis of which the laboratory and pilot-industrial models of these heaters were created. The change in electrical parameters of PAHOT with hollow graphitized electrodes depending on their geometric sizes were investigated. Power parameters of process of melting ferroalloys using PAHOT were studied. The following specific parameters of arc steelmelting and ore-reduction furnaces were recommended: 600–1000 kW/m² power on hearth surface; 450–600 kW/m³ power in pool volume; 1800–4400 kW/m² actual power on the area of breakdown of electrodes; 5000–9000 A/m² current density at pool surface.

In production of some precision and special alloys the need arises in use of manganese with a low content of impurities. At the E.O. Paton Electric Welding Institute, a method of electroslag refining of electrolytic manganese in the form of flakes of thickness of several millimeters by remelting in a molten slag layer has been developed and realized successfully.

Technology of melting of highly-damping Mn–Cu alloys was mastered on the basis of method of electroslag refining of manganese. The attained degree of metal purity in combination with high efficient metal output gives ground to consider this method very challenging for producing alloys of Mn–Cu system used for manufacture of high-quality vibroabsorbing devices.

In report the existing methods are analyzed and data are given about radically new method of producing large single crystals of refractory metals.

It is shown that plasma-induction method of growing large single crystals makes it possible to reduce to minimum the temperature gradient and mechanical stresses in it by flexible control of temperature field of the ingot.

The report presents results of investigations of process of fast quenching of metal melts in the conditions of induction melting in a sectional mould. The investigations carried out resulted in the development of technological regulations of processes of production of high-quality steels and methods of melting ferroalloys from ores and industrial wastes, growing of single crystals of refractory metals, producing flaky metallic materials using plasma-arc and induction heaters of the new generation.



«Development of Fundamentals for Improving Service Properties of Welded Joints and Protective Coatings by the Method of Examination of Their Fine Structure, Chemical Inhomogeneity and Determination of Parameters of Optimizing Structural-Phase Composition»

Manager — Prof. G.M. GRIGORENKO

In the scope of subject the complex of analytical, research, metals science and technological works was fulfilled. During investigations the methods of chemical, atomic-absorption, coulometric, emission-spectral analyses were used. Metallographic examinations were carried out using optical, scanning and transmission microscopy. Composition of phases was examined by the method of X-ray diffraction and differential thermal analysis. Induction, electric arc and plasma melting, diffusion and percussion welding in vacuum were used in technological works.

Different methods of welding, surfacing and spraying were used in works which were carried out in collaboration with technological departments: electric arc, electron beam, flash-butt welding, electric arc and plasma surfacing, plasma and plasma-denotation spraying.

Works on the subject were divided into ten sections.

The first section included investigations of kinetics of nitrogen sorption by liquid highly-reactive metals at different conditions of heating. The results obtained allowed us to determine the numerical values of constants of rates of reaction of nitrogen absorption in induction, arc and plasma melting and to develop the physical and mathematical models of nitrogen sorption with metals of IV and VA groups. Model allows us to optimize the processes of welding and melting of the highly-reactive metals and alloys on their base.

In the second section the regularities of formation of transition zone in joints of difficult-to-weld dissimilar metals at different thermodeformational conditions of flash-butt welding were considered. Thin structure, phase transformations, change in concentration of elements and formation of intermetallic phases in welding austenitic steel 110G13L with rail steel M76, copper with aluminium and steel with aluminium were examined. The conditions at which this method of welding can be used for joining difficult-to-weld metals were defined.

The third section was devoted to investigations of processes of formation of structure and properties of coatings with an increased level of wear, heat- and

corrosion resistance by combining methods of thermal spraying, process of self-propagating high-temperature synthesis with a subsequent impregnation of coatings, heat and chemical-heat treatment. The thermal spraying with a subsequent impregnation with aluminophosphate binders and heat treatment 1.5 times increases adhesion with a base and 6 times increases the wear resistance in the conditions of abrasive wear. Composition of powders is determined and spraying conditions are corrected, thus providing the highest quality of coatings at detonation and microplasma spraying of FeTi + B₄C and air-gas spraying of FeTi + SiC.

In the fourth section the structural transformations in welding and repair of heat-resistant hull steels were investigated. It was established that the use of flux SFT-6 in welding heat-resistant hull steel 25Kh2NMFA prevents the developing of polygonization in weld metal, provides 2 times decrease in a volume share of non-metallic inclusions, their refining and uniform distribution in weld. The mentioned factors promote the 1.5 times increase in impact strength as compared with welding using flux AN-43.

The fifth section was devoted to investigations of structure of high-strength welds made by electrodes with ultra-low content of carbon. Regularities of structural composition and composition of non-metallic inclusions depending on oxidizing potential of flux were obtained and it was shown that the highest values of strength and toughness are typical of welds with ultra-low content of carbon, made using neutral or basic flux.

The sixth section included investigations of regularities of formation of phases and phase transitions in heterogeneous structure of multilayer corrosion-resistant deposited Fe-based metal alloyed with vanadium, chromium, molybdenum and phosphorus. Composition and structure of the deposited metal were optimized from the results of investigations that allowed us to increase its hardness and wear resistance by 2–3 times.

The seventh section was devoted to investigations of chemical microheterogeneity in welded joints of Al–Li alloys and in HAZ in electric arc and electron



beam welding. It was shown that alloying with lithium contributes to strengthening of weld and does not influence the redistribution of other alloying elements. Electron beam welding makes it possible to produce welded joints with the higher level of mechanical properties.

The eighth sections included materials related to the new technology of manufacture of oxide cathodes. The new method was offered for manufacture of the oxide cathode including the use of insert from a powder mixture of zirconium with lanthanum hexaboride and its subsequent joining with copper using the method of a percussion deformation in vacuum. Comprehensive metallographic examinations in argon, CO₂ and air showed the monolithic nature of welded joints and their reliability in service.

The ninth section was devoted to the study of regularities of formation of structural and chemical inhomogeneity, and also non-metallic inclusions in near-contact volumes of metal in pressure welding of pipe steels. It was shown that the appearance of a ferritic layer and a white band in the welded joint zone is due to physical and chemical inhomogeneity in it. Mechanism of formation of a ferritic layer including combination of diffusion and recrystallization processes leading to decarburization of the near-contact zone was suggested. Nature of a white band was studied and it was shown that these structural changes have no negative effect on the welded joint quality.

The tenth section included developed and certified new procedures of emission-spectral analysis of con-

tent of lithium in aluminium and its alloys in the 0.4–2.7 wt.% range; lithium and copper in the 1–10 wt.% range; phosphorus in copper, brasses and bronzes in the 0.035–1 wt.% ranges.

The following practical results were obtained after fulfillment of works on subject.

Determined are the physical-chemical constants characterizing the nitrogen interaction with molten highly-reactive metals which make it possible to control the process of metal alloying with nitrogen from gas phase.

Created are the new analytical procedures for chemical and spectral analysis of lithium and phosphorus in metals and alloys.

Developed are the fundamentals for improving service properties of welded joints and protective coatings by optimizing structural-phase and chemical composition of welds, deposits and coatings for the processes: thermal spraying with a synthesis of coating materials; pressure welding of dissimilar metals; electric arc welding of heat-resistant steels and low-alloy high-strength steels resistant against brittle fracture; electric arc and electron beam welding of high-strength aluminium alloys, alloyed with lithium and scandium; surfacing of wear-resistant materials, strengthened by carbon and phosphorus; flash-butt welding of pipe steels with increased resistance against fracture at low temperatures; creation of the new type of oxide thermochemical cathodes with an insert of powder materials.

«Mathematical Modelling of Macrophysical Processes in Welding Dissimilar Steels, Hydrodynamic Phenomena in Welding and Special Electrometallurgy, Kinetics of Growth of Defects in the Conditions of Loading of Welded Joints»

Manager — Prof. V.I. MAKHNENKO

The work was carried out in four directions.

Section 1. «Mathematical Modelling of Macrophysical Processes in Welding Dissimilar Steels».

On the basis of comprehensive literature review of processes of fusion welding of dissimilar steels (ferritic-austenitic), the following seven major problems defining the quality of welded joint were formulated, in the solution of which the role of the mathematical modelling can be very important:

- heating of product, size of penetration zone and its chemical composition;

- primary crystallization, peculiarities of a local chemical inhomogeneity and microstructure near the fusion boundary;

- formation of carbides;
- microstructure and properties of welded joint;
- welding stresses and strains in welding dissimilar metals;

- risk in occurrence of hot and cold cracks;
- behaviour of welded joint under service conditions, in heat changes in particular.

Most of the above-listed problems are closely connected with each other, that requires in many cases



an integral their consideration in modelling real processes of welding (surfacing) of dissimilar steels.

It should be noted that during surfacing the dissimilarities are manifested most clearly and the use of mathematical modelling for their solution is not less actual than for welding. During surfacing, the number of technological parameters, which are varied, as a rule, is larger and the problem of their rational selection using appropriate mathematical models is solved more effectively than using the pure experimental way.

In the scope of the above-mentioned, the works of this section were dealing with the creation of definite calculation algorithms and fulfillment of appropriate numerical investigations of typical cases of welding (surfacing) of dissimilar steels.

Typical cases, dictated by the demands of industry of Ukraine and foreign companies, are described below:

- surfacing under angle of edges of ferritic steel sheets with austenitic layer for producing dissimilar butt joint ferritic steel–austenitic steel (cooperation with power engineers according to Agreement);
- welding of tubes from austenitic steel to tube sheets from ferritic steel (cooperation with German companies «SLV Mecklenburg» and «Infracon»);
- surfacing of corrosion-resistant layer by electric arc spirally welding on the surface of shafts made from steel of type 35 or 40X (cooperation with ship-building enterprises);
- surfacing of wear-resistant layer on large thin plates from ferritic steel of appropriate billets for stamping parts, for example, blades of special fans and so on (cooperation with «SLV Mecklenburg»);
- flash-butt welding of railway rails from steels R65 and Hatfield in frogs (cooperation with department of PWI and metallurgical enterprises of Ukraine – manufacturers of frogs);
- specifics of hydrogen transfer in dissimilar compounds (cooperation with Ukrainian company «KORBA»);
- butt welding through a solid interlayer of foam plates (cooperation with «SLV Mecklenburg»).

Section 2. «Computer Modelling of Hydrodynamic Phenomena in Technological Processes of Welding and Special Electrometallurgy».

Developed are the conjugate axisymmetric models of hydrodynamics and heat-mass exchange in formation of ingots using methods of special electrometallurgy: electron beam remelting of ingots of titanium alloy and electron beam crucible-free zone melting of silicon single crystal. Models are based on a complete system of equations of dynamics of motion of viscous non-compressed liquid in the Boissinesq approximation, equation of convective-conductive transfer of energy and equation of convective diffusion. Several force factors are considered, influencing the melt motion:

- thermogravitational convection occurring in thermally non-homogeneous liquid under the action of the gravity force;

- thermocapillary convection, stipulated by a coefficient gradient of surface tension on the metal pool free surface;

- forced convection occurring as a result of action of jet of metal which is periodically poured into mould from an intermediate crucible. Task of the hydrodynamics is solved in the region of a complex shape formed by boundaries of phase transitions whose geometry is defined in the process of solution of the conjugate problem. The boundary conditions for determination of field of temperatures take into account the radiation heat exchange of surface with the chamber wall (heat screen), different variants of distribution of density of electron beam heat source, scanning of electron beam over the free surface of the metal pool. At zone melting of silicon single crystal a feasibility of melting in the weightlessness condition is provided. To study the redistribution of alloying (impurity) elements in the crystallization process the evaporation flow by the Langmuir law, and also the dilution of melt by its drain from intermediate crucible is taken into account.

A comparative analysis of conditions of formation of silicon single crystal in electron beam crucible-free melting of microgravitation was performed. It was determined that during microgravitation the hydrodynamics of the molten zone is stipulated by the action of Marangoni force, and the rate of melt motion is 5 times decreased as compared with rate in the earth conditions. This leads to high losses in energy for radiation, to the decrease in height of molten zone and appearance of a convex front of crystallization with 0.35 mm bending height. It was shown that the use of a short heat screen, located below the crystallization front, makes it possible to preserve parameters of the molten zone at the level meeting the earth conditions of melting. Rationality of scanning of electron beam with frequency 200 Hz and more was established, as this technological procedure can decrease the intensity of thermocapillary convection in the microgravitation conditions at the expense of lower overheating of a free surface of the molten zone. In addition, the decrease in electrical power is attained simultaneously at the same geometric parameters of the zone that is important in conductance of space experiment in the conditions of a limited energy supply.

Section 3. «Mathematical Modelling of Defects in the Zone of Welded Joints and Development of Calculated Algorithms and Programs for Evaluation of Kinetics of Growth of Defects up to Critical Sizes in the Conditions of Loading of Welded Joints».

In this section the mathematical models are created for the evaluation of load-carrying capacity of the welded sub-assemblies from dissimilar steels (mainly thick-walled welded shells of ferritic steel with a deposited corrosion-resistant layer of austenitic steel) in typical conditions of loading, corresponding to emergency loading of casings of nuclear power reactors of WWER-1000 type which are under service in Ukraine.



In the scope of this same section the mathematical model is developed for evaluating safe conditions of welding-up of pit defects at the external surface of gas- and oil pipelines without interruption of service of appropriate regions. Results of this work were applied in practice in the working out of standardized materials for repair of the above-mentioned regions.

Section 4. «Development of Information System of Computer Designing of Conditions of Electric Arc Welding Structural Alloy Steels for Welding Consumables of Different Forms».

The interest to modern information systems in the solution of different technological problems of welding, surfacing, coating deposition was always one of priority problems in activity of the E.O. Paton Electric Welding Institute of the NAS of Ukraine. Over the past years a number of works was done, related to the creation of databases, expert and calculation-experimental systems on electron carriers. However, the progress in computer engineering, methods of mathematical modelling, growing demands of technology require new approaches in this direction.

In this connection the works were carried out in two directions. The first direction was dealing with updating of existing databases and expert systems. For example, database «Mechanical Properties of Welded Joints» or expertise system «Surfacing». The second direction was connected with the creation of systems on the basis of mathematical modelling and definite information subsystems in which a great at-

tention was paid to the mathematical modelling to obtain quantitative data necessary for the development of technologies. In particular, the computer system «Selection of Welding Consumables for Arc Welding of Structural Materials», created in collaboration with company «KORBA», is designed, to a certain extent, for replacement of experiments conducted on appropriate samples of welded joints.

Using certificate data of the company-manufacturer of welding consumables (electrodes, flux-cored wires, fluxes) about the recommended conditions of arc welding, deposition coefficient, chemical composition of deposited metal, the system provides information for cases of welding butt and T-joints of different structural steels about:

- sizes and shape of penetration zone (PZ) for root weld and next passes;
- chemical composition of PZ;
- microstructural composition in PZ and heat-affected zone (HAZ);
- mechanical properties in PZ and HAZ, including hardness, ultimate strength, yield strength, elongation, impact strength;
- risk of formation of hot and cold cracks;
- local concentration of hydrogen in PZ and its effect on cold crack formation.

At the present moment the system is tested at some enterprises of Ukraine, in particular, at «Okean» Works in Nikolaev city.

«Development of Electron Beam Technology of Producing Composite Materials on the Base of Light Alloys and Strengthening Fibres from Dispersed Melt in Vacuum»

Manager — Prof. N.P. TRIGYB

The new method of dispersion of metal melt from an intermediate crucible using a rotating drum-mould has been developed (Figure 1). Melting of a consumable billet or charge is performed in electron beam installation, the same as in electron beam remelting. Accumulated molten metal of the consumable billet in the intermediate crucible during melting is poured periodically to the rotating drum-mould. Then, the high rate of rotation is set to the drum (2000 rpm) and the molten metal is detached from the drum surface in the form of flow of dispersed molten drops. The flow of melt drops is directed to the shape-forming surface (substrate) where the drops are spreading and immediately crystallized without molten pool forming. Water-cooled mould (for ingot producing), metal plate (for producing bimetal combinations), groove of parts being welded (for welding), framework of

strengthening elements (for producing composite materials) can be used as a substrate.

Electron beam installation UE-208 was used for experimental investigations of producing fibrous metallic composites. A mechanism of dispersion, consisting of a dispersion drum, its fastening elements, system of rotation transmission with a vacuum-tight transition piece, electric motor and control system, was mounted on this installation.

The rotation mechanism is controlled using an electron system «Razmer», here the rotation speed of a divider is adjusted smoothly in the 0–2500 rpm range. The residual pressure during the process in melting chamber was 0.05 Pa, in chamber of electron beam heater it was 0.005 Pa. Scrap of aluminium and titanium alloys was used as a charge. A jet of drops of the dispersed melt was formed and directed to the

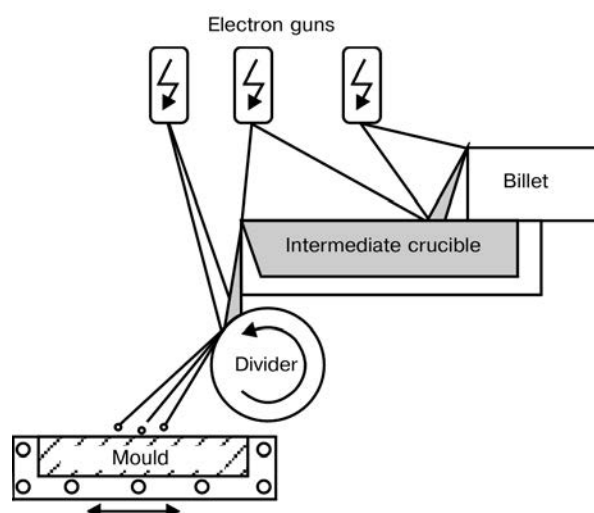


Figure 1. Scheme of process of melt dispersion from intermediate crucible

substrate on which a steel framework with stretched fibres (steel, tungsten) was mounted. Fibres were not heated preliminary. The efficiency of dispersed melt jet was 150 kg/h. After deposition of matrix of 30–40 mm thickness the process was interrupted and the product was hold in vacuum for 1 h.

A mathematical model of heat processes in central-symmetrical system of fibre–matrix with a center on fibre axis was created (Figure 2). The process was modeled, where the matrix material was deposited using the method of electron beam dispersion on substrate, over which the strengthening fibres are stretched at different levels. At the first stage the thermophysical processes in substrate–matrix system were modeled without allowance for effect of fibres; at the second stage the local temperature fields were calculated in the direct vicinity to the fibre.

In the scope of the model suggested the calculations of thermal fields for aluminium and titanium matrices were performed. It was determined that to prevent the molten pool occurrence at the surface of the forming matrix the rate of dispersed melt deposition for titanium should not exceed 3.0 and for aluminium 1.8 kg/s. In addition, the temperature in the matrix area during the entire process is 820–855 K for aluminium and 1350–1500 K for titanium, that guarantees the satisfactory quality of joining of the deposited metal layers.

Samples of composite materials on the base of aluminium and titanium matrix strengthened by steel and tungsten fibres, respectively, were investigated.

Macrostructure of transverse section of composite has a banded structure with wavy boundaries which

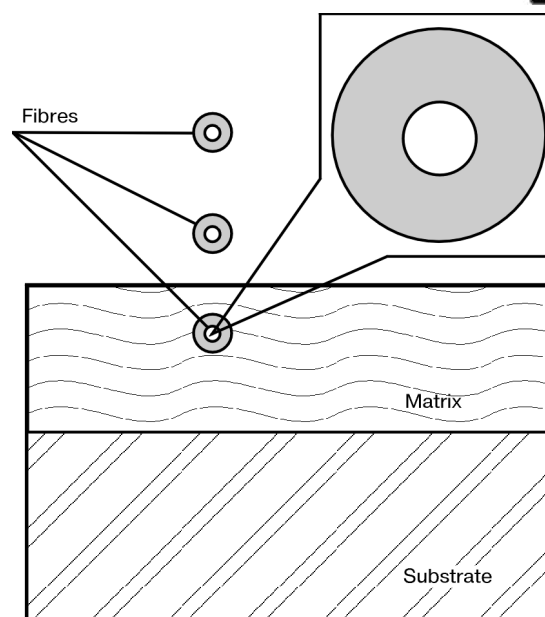


Figure 2. Scheme of modelling of process of producing fibrous composite material

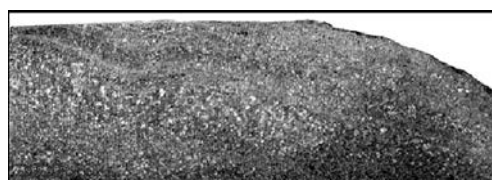


Figure 3. Macrostructure of transverse section of composite (x5)

correspond to the crystallization layers (Figure 3). Defects in the form of pores and discontinuities, which can be caused by a lack of fusion of successively crystallizing layers, were not observed.

The layers of crystallization of samples, observed on macrosection, are differed by a grain size and degree of etching. Alongside with areas of a fine grain (80–130 μm), the areas, where the grain size reaches 400 μm , are observed.

At a preheating of substrate at the matrix–fibre interface the chemical interaction of metals takes place in Al-based composite and interlayer FeAl_3 is formed whose thickness is varied in the range of 10–50 μm depending on temperature of substrate preheating.

Mechanical tests of produced samples were performed. Ultimate strength of composites along the fibres for aluminium matrix AMg1, reinforced with steel fibres, was 90 MPa, for titanium matrix VT1-0, reinforced with tungsten fibres — 550 MPa.



«Development of Fundamentals and Investigation of Physical-Chemical Peculiarities of Processes of Deposition of Coatings, Combined With a Synthesis of Refractory Compounds and Use of Thermosetting Heat Sources»

Manager — Prof. Yu.S. BORISOV

At the modern stage of development of the surface engineering, including the technologies of coating deposition and modifying of surface, the processes in which coating deposition is combined with a synthesis of coating material, and also the processes of activation by effect of plasma, laser or other energy sources are of the more importance. Examples can be illustrated by such vacuum methods as activated reactive evaporation, reactive ion deposition, process of gas-phase deposition, by activated plasma and others. Thus, it is possible to increase the rate of coating deposition, widen their range and improve their quality.

Similar ideas are also progressing in the field of thermal spraying (TS). In the processes of reactive plasma-arc spraying the activity of components of plasma jet is used for synthesis of nitrides and carbides in the process of heating powders of metals with the formation of strengthened coatings. Another method of combination of synthesis of coating material with TS process is the use of composite powders (CP) and powdered wires at heating of which the interaction of components occurs with the formation of the new substance, for example, intermetallic, which is a material of the coating. However, all the mentioned results were obtained in separate experiments and demonstrated mainly only the principal feasibility of these solutions in the field of TS.

The aim of the present work was to investigate the process of exothermic synthesis of coating material in TS CP with allowance for peculiarities of different types of TS, namely plasma, microplasma, detonation; in evaluation of feasibility of activation of the process of chromizing; in updating of technology of reactive vacuum-arc deposition of nitride coatings and defining of conditions of combination of plasma-detonation treatment of surface with alloying of the modified layer.

In the development of the first section of the subject the analysis was made of present status of this direction in TS, and also of modern level of theory and practice of the self-propagating high-temperature synthesis (SHS) as challenging in the conditions of TS for realization of the synthesis process due to high rates of its proceeding. As a result of this analysis the SHS characteristics are distinguished which should

play the most important role in the TS conditions. They include the heat of synthesis reaction and, due to it, the adiabatic increase in temperature of combination, characteristic of process kinetics influencing the linear rate of SHS front movement.

As an object of investigations the CP were selected, consisting of ferroalloys of titanium, vanadium or chromium, and also carbides of boron or silicon. Thermodynamic evaluation and data of differential thermal analysis made it possible to determine the characteristics of the process of exothermal synthesis in these combinations and the most effective compositions of these combinations (FeTi-15B₄C, FeTi-23SiC, FeV-20B₄C, FeV-22.5SiC, Fe-Cr-18B₄C, Fe-Cr-14.5SiC). To produce the pilot batches of these powders for experimental investigations the technologies of CP by methods of conglomeration on organic binders and reactive sintering of components were developed.

For calculation-theoretical evaluation of effect of exothermal reaction of synthesis on heating and motion of CP particles in a plasma jet a mathematical model of the process of plasma spraying, combined with exothermal synthesis of the coating material was developed. A software was created on its base with allowance for experience in the development of Ni-Al CP for numerical investigation of peculiarities of plasma spraying in the given conditions. It is shown that the highest effect on dynamics of heating of exothermally reacting particles is made by a kinetic characteristic related to mechanism of interphase interaction, contact area and some other characteristics. High rates of the synthesis process lead to excessive overheating of particles, up to their partial evaporation, while low rates lead to the transfer of part of the synthesis process on the base with its proceeding in the period of formation of the coating layer. Other factors, influencing the proceeding of synthesis process in the condition of plasma spraying, refer to size of particles, powder consumption and temperature of plasma jet (or powerful plasmatron). The obtained results of numerical investigation allow issue recommendations as regards to peculiarities of technology of plasma spraying of exothermally reacting CP.

Experiments on TS of the above-mentioned CP were conducted in the conditions of plasma, micro-



plasma and detonation spraying, differed by temperature and rate of high-temperature gas jet that should influence the duration of particles in heating zone and degree of synthesis process completion in the period of particles motion to the base surface.

Structure and composition of both sprayed coatings and also sprayed particles, trapped by a water pool, were examined using the methods of optical microscopy, photometry and X-ray phase analysis. Results of examinations showed that the highest degree of completion of the synthesis process was observed in case of microplasma spraying, and the sufficiently high degree — in conventional plasma spraying. At detonation spraying the process of interaction is started even in the gun shaft, but it is already completed, as a rule, on the base during coating formation, that is explained by the duration of particles in the jet.

Structure of produced coatings contains such products of synthesis as borides (in use of CP with B_4C — VB , V_2B_3 , V_5B_6 , TiB_2 , CrB , FeB , etc.), carbides (VC , V_4C_3 , Cr_7C_3 , TiC , etc.), silicides (in use of CP with SiC — V_6Si_5 , $TiSi_2$, Ti_5Si_3 , $CrSi_2$, etc.), and also ternary phases ($Fe-TiSi$, $FeSiC$). Except the products of synthesis, a number of oxide phases was revealed, moreover, the largest its amount was observed in detonation coatings. Microhardness of coatings containing boride phases reach 8000 MPa at detonation spraying ($Fe-Cr-B_4C$) and 16900 MPa at plasma spraying ($FeV-B_4C$). Microhardness of plasma coatings, containing carbides and silicides, in spraying of $FeV-SiC$ is 8200–18900, in case of $FeTi-SiC$ it is 6000–11000 MPa.

Results of testing coatings for gas-abrasive wear in combination with the mentioned values of their hardness made it possible to recommend the developed CP for practical application as a wear-resistant component in spraying in the composition of mechanical mixtures with nickel or iron alloys.

Except ferroalloy/non-metallic refractory compound combinations, the conditions of formation and properties of alumoceramic coatings produced in plasma spraying aluminium/ilmenite CP were studied. The presence of aluminothermic reaction was shown in heating of this combination with the formation of aluminium oxide, as well as aluminides of titanium and aluminium as products of synthesis. The produced coatings are characterized by the higher wear resistance (5–10 times) than the coatings of pure aluminium, preserving high resistance to corrosion, typical of aluminium.

It was established during investigation of the feasibility of accelerating of processes of chromizing of

steel products that adding of activating additions to the saturated mixture in the form of titanium hydride (2 wt.%) and powder of aluminium alloys with lanthanum or silicon (7 wt.%) makes it possible to form the diffusion layer of 100–170 μm during 60 min. The produced coatings are characterized by high resistance to wear and corrosion. Tests of parts with chromium-carbide coating in industrial conditions showed the 2–5 times increase in their life.

The effect of rate of evaporation of cathode material, pressure of reaction gas in operating chamber and energy of ions in a plasma jet on the morphology of surface of growing layer of titanium nitride, coating structure, adhesion of condensate to the base and physical-mechanical properties of the coating were studied. It was shown that formation of the layer of stoichiometric titanium nitride occurs at nitrogen pressure in operating chamber $(2-3) \cdot 10^{-1}$ Pa, and maximum microhardness and minimum viscosity of coatings are reached at the reaction gas pressure $(1.2-2.5) \cdot 10^{-2}$ Pa. The new design of cylindrical vacuum-arc evaporator of continuous operation with a lateral surface, eroded in charge, has been developed and tested. This equipment is designed for coating deposition on large surfaces to provide the uniformity of thickness of the layer deposited.

To improve the method of the plasma-detonation modifying (PDM) of surface, a mathematical modelling of the process of interaction of a pulsed plasma jet with the surface was made. It was shown that the heat flow into surface is maximum when the product becomes anode, and minimum — at isolating of product from a current discharge. It was established that the most intensive combination of PDM process with surface alloying from vapour-drop phase, formed by products of erosion of a central electrode, occurs in the condition of discharge of product-cathode bank of capacitors. The effect of conditions of generation of a plasma pulse on the process of modifying and alloying of surface was defined. Capacity of the bank of capacitors, distance from nozzle exit to product and from the central electrode end to nozzle exit influence mainly the current. It was shown that at PDM of steel U8 the rate of quenching in surface layers reached $7.5 \cdot 10^6 \text{ deg} \cdot \text{s}^{-1}$, that leads to the formation of a modified layer of 60 μm thickness, while in use of the central molybdenum electrode it is possible to alloy it with molybdenum for depth up to 10 μm . Practical application of PDM method with surface alloying provides the 2–6 times increase in tool serviceability.



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