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DEVELOPMENT OF SCIENTIFIC-PRODUCTION BASE FOR MANUFACTURING ELECTRODE PRODUCTS AT OJSC «UKRAINIAN GRAPHITE»

Analysis of parameters of electrode properties prove that world trend in improvement of extraordinary energy-intensive electric arc or electrolysis production consists in increase of electric current that flows through the electrode. At flowing of current minimization of heat losses is achieved due reduction of specific electric resistance (SER) of the electrode proper. So, present leading producers of electrode products guarantee SER of graphite electrodes at 100–140 kA current within range of 4.0–5.5 $\mu\text{Ohm}\cdot\text{m}$. Technical-economic analysis shows that reduction of SER of electrodes by 0.2 $\mu\text{Ohm}\cdot\text{m}$ allows reducing energy losses approximately by 6–8 % per ton of a metal.

It is necessary to emphasize that technical-economic information in production of carbon-graphite products is in many respects close and especially confidential. On the other hand, problem of production of good quality electrodes concerns strategically important sectors of national economy, in particular metallurgical and power engineering ones.

In mid-1990s analysis of situation in regard to manufacturing of good-quality products at OJSC «Ukrgralit» showed that for improving quality of the

products and their competitiveness it was necessary to carry out a complex of systemic scientific-technical works, directed at improvement of both the technology and the production base. For this purpose management of the plant approved comprehensive plan of carrying out innovation works for development of competitive products. Main factors, which preceded this work, were as follows:

- analysis of general trends of the electrode branch development of leading countries which showed that they were based on fundamental and comprehensive scientific investigations of physical properties of initial materials, investigation of the process used in production of electrode products, and introduction into practice of the quality control indices of finished products;
- comprehensive marketing analysis of the feedstock, price policy, market development trends, requirements of consumers of the electrode products, and determination of scale and direction of innovations;
- development of the plan of scientific-technical modernization of production, taking into account need in producing wide range of products.

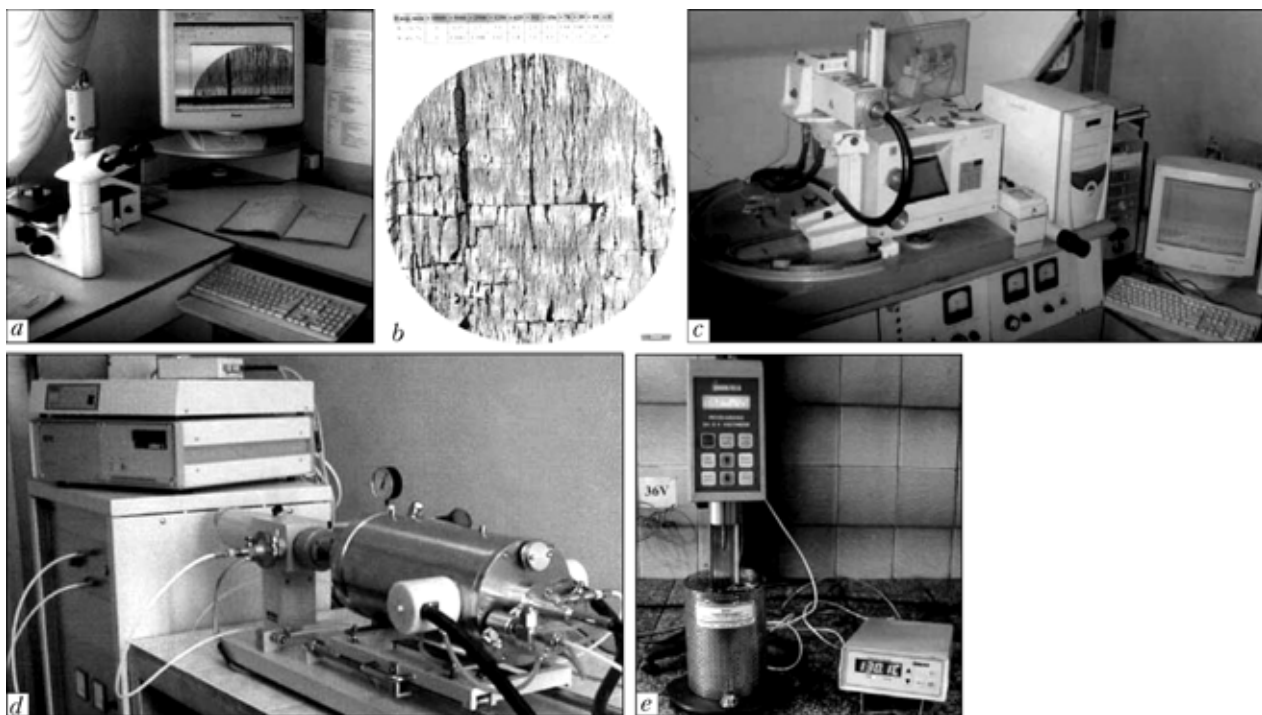


Figure 1. Laboratory support of scientific-technical system of assessment parameters of feedstock base for optimization of press-mass compounding: *a* — image analyzer; *b* — panorama of coke microstructure; *c* — DRON-3 X-ray diffractometer; *d* — DIL 402/8 G-Py dilatometer; *e* — Brookfield RV DV-II viscometer

As a result main goal of the works consisted in development of state-of-the-art through cycle, which would allow producing items, level of quality of which would meet world standards. Mentioned goal may be achieved by means of systemic wide-scale introduction into the plant practice of scientific trends and approaches to the production. This is dictated, first of all, by range of nomenclature of the items and geography of consumers of the products, manufactured at the plant. Fields of technical application of the products include cathode blocks of aluminium electrolytic furnaces, anodes and beams of magnesium electrolytic furnaces, high-temperature lining of the ferrous metallurgy units, electrodes of arc melting facility, and rammed masses and furnished parts of electrode products. Observance of parameters of mentioned items and technology of their production require for rather high level of scientific and technical skill and knowledge which should possess technicians and engineers of the plant.

However, a number of issues and scientific-technical problems had to be solved using state-of-the-art computer and laboratory means of scientific organizations and subdivisions. Reasons for attracting national scientific staff to solution of technical tasks of improvement of the production were uniqueness of conditions of the technological processes (up to 2500 °C) and material flows proper with variable structure and properties; absence of national branch laboratories of carbon-graphite production; need in using methodologies and means of investigation which had no analogues in plant practice.

In this way a creative team was established, which included leading specialists of the plant, the E.O. Paton Electric Welding Institute, SPE «Militeks», National Technical University of Ukraine «Kiev Polytechnic Institute» and National Metallurgical Academy of Ukraine. Successful combination of management and scientific-technical approach to solution of the problem allowed obtaining scientific and technical results.

Scientifically substantiated system of assessment parameters of the feedstock base for optimization of compounding of the press-mass according to the data on physical properties of the initial feedstock materials was suggested: thermal expansion, strength, elasticity, adsorption factors, microstructure of the coke, rheological characteristics of pitch, etc. (Figure 1).

For the first time regularities of anthracite calcination in the electric calcinator were investigated on a physical model and a laboratory installation with visualization of the calcination process. Regularities of electric current flow through bulk layer of anthracite were obtained.

On basis of fundamental investigations of physical processes in granulated carbon materials, structural transformations and change of thermodynamic characteristics of anthracite for the first time scientific concept of a single-stage electric calcination of anthracite with application of an orifice plate was sug-

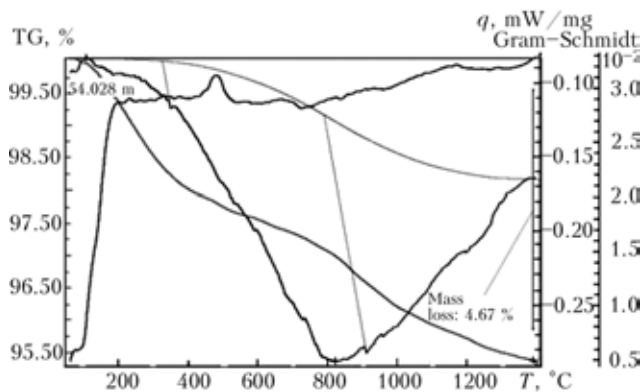


Figure 2. Thermo-kinetic parameters of anthracite calcinations

gested, which ensured achievement of calcination temperatures due to increase of current density with simultaneous reduction of specific consumption of electric energy.

For the first time data on thermo-kinetic investigations of Donetsk anthracite were obtained and influence of heat effect of the reactions on efficient power of an electric calcinator was determined.

A numerical thermoelectric model of the electric calcinator was developed with application of generalized physical properties of bulk layer of Donetsk anthracite, using which for the first time data were obtained on distribution of electric potential and density of current, temperature, and heat flow density in two- and three-stage calcinations of anthracite.

Calculation-experimental investigation of the electric calcinator is presented in Figures 2–4.

For the first time on basis of scientifically substantiated methods experimental data were obtained (within temperature range up to 2500 °C), which significantly changed idea about character of distribution of the working zone temperatures of the graphitization furnace in space and time.

A three-dimensional numeric thermoelectric model of the graphitization furnace was developed with application of the obtained information about physical properties of materials, which passed verification according to data of full-scale experiments. For the first time three-dimensional numeric thermoelectric fields of the graphitization furnaces, which significantly expanded physical ideas about conditions of the technological process progress, and data on instant and

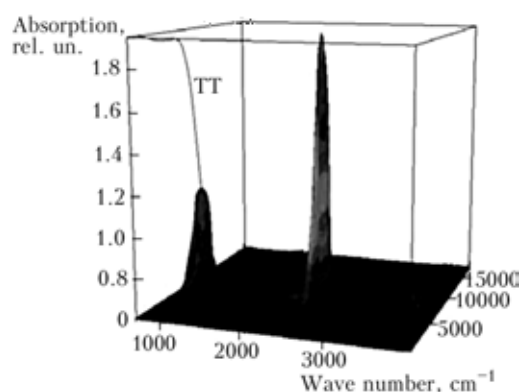


Figure 3. IR-diagram of gas release in anthracite calcinations

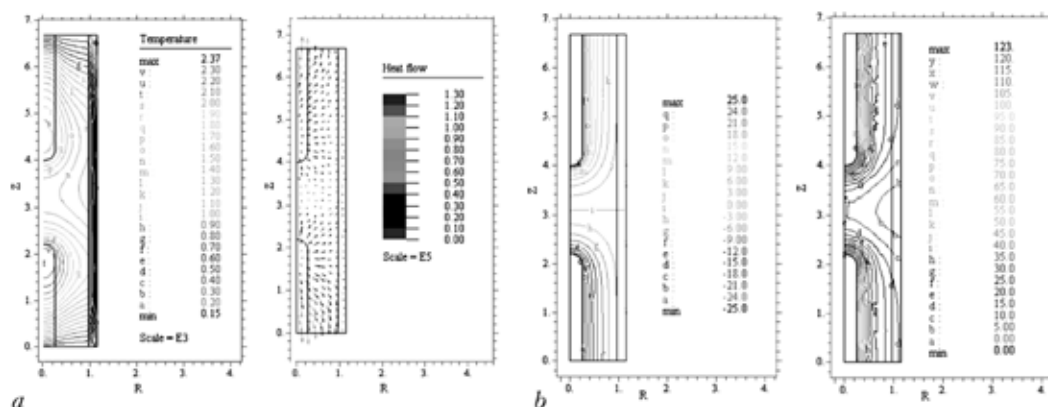


Figure 4. Computer modeling of heat (a) and electric (b) parameters of electric calcinations

final energy balance were obtained that determined potential and direction of energy conservation in graphitization of electrodes.

In Figures 5 and 6 stages of experimental-calculation investigation of temperature conditions of the graphitization furnaces are shown.

Long-term work resulted in introduction of the following approaches and measures. Using latest developed laboratory equipment and scientific-technical approaches of analysis of properties of initial materials a systemic approach to choice of the feedstock base was introduced, which allowed bringing to minimum influence of fluctuations of the feedstock delivery market; on basis of scientific generalizations and investigations a single stage calcination of anthracite in composition of seven electric calcinators of

1600 kV·A power was introduced; an automated system of dosing of the filler components with assurance of necessary accuracy of the technology reproducibility was introduced; upgrading of the press-mass processing for manufacturing of the electrode billets by method of extrusion was carried out; upgrading of heat treatment of carbon billets in annealing (heat treatment) furnaces of new generation was performed; the coke processing bay was re-equipped by means of introduction of the calcination technology; graphitization process of carbon billets in high-temperature furnaces was improved. On basis of carried out scientific-technical investigations of heat conditions of the annealing furnaces a new furnace No 10 of production capacity more than 2000 t of annealed products per month was built, which brought production to the

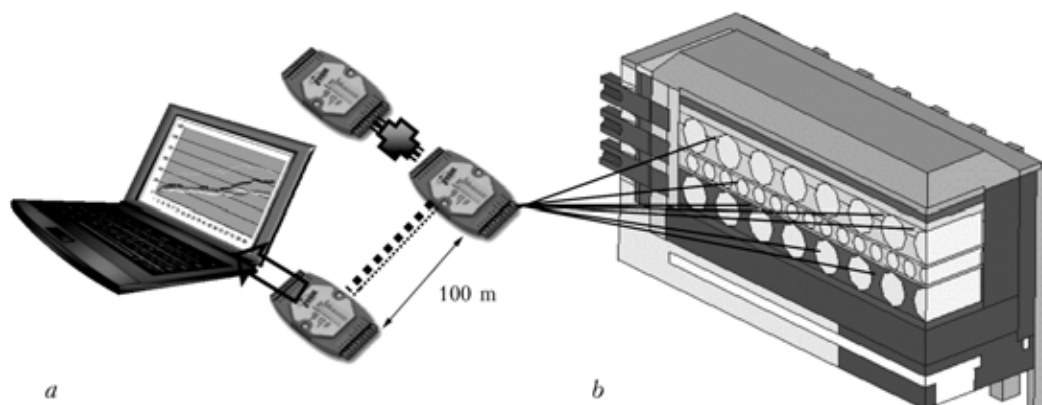


Figure 5. Monitoring of temperature field of graphitization furnace: a — instrument-program interface for collection and recording of information; b — temperature sensors in furnace are installed according to developed scheme

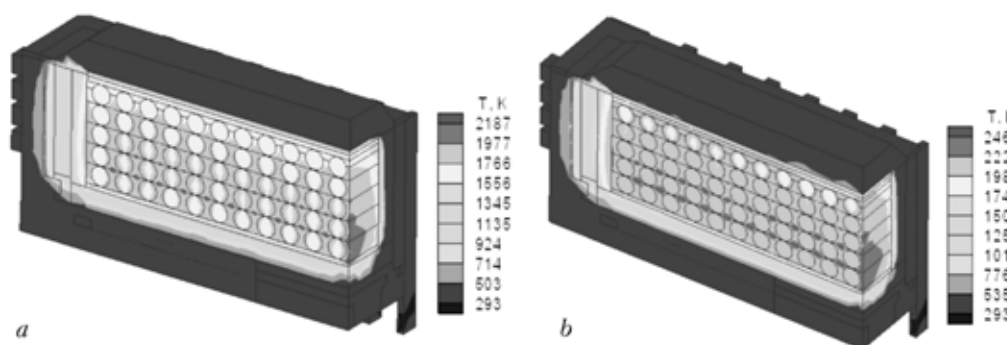


Figure 6. Computer modeling of temperature field of graphitization furnace: a — $T_{\min} = 961$ K, $T_{\max} = 1925$ K; b — $T_{\min} = 1436$ K, $T_{\max} = 2247$ K

leading position on market of electrode products; complex of works for scientific support of rules of the annealing furnace operation were carried out; experimental campaigns were accompanied by computer monitoring of temperature fields, which made it possible to operatively trace adjustment procedure of commissioning of furnace No 10.

Production of new graphitised (PB-5, PB-7) and graphitized (PBG-2) hearth blocks of aluminium electrolytic furnaces with reduced specific electric resistance for electrolytic furnaces working on current up to 320 kA was introduced.

Unique installation for determining thermal-physical properties of bulk materials up to 1750 °C was developed.

Due to introduction of the complex of innovation developments the following results were obtained:

- consumption of electric energy per one campaign of a furnace reduced by 8 % at assigned parameters of the graphitised product quality;
- percentage of graphitised electrodes, specific electric resistance of which corresponds to the world models, has increased (up to 96 %);
- due to intensification of schedule of power supply of the graphitization furnace, fabrication of the products has increased by 15–20 %.



Figure 7. Annealing furnace of new generation (furnace No 7)

It is also necessary to note constant process of intensification of both scientific component of the investigations and technical implementation thereof.

During last year one candidate's thesis was defended and one more was prepared for defending, two monographs and nine articles were published, ten patents were obtained.

So, carried out works and their content prove noticeable scientific and technical prospects, which may be considered as buildup of the national scientific school for ensuring electrode production.

Dear Colleagues and Friends!

Within the period of 75 years OJSC «Ukrainian Graphite», Zaporozhie, Ukraine, passed glorious way, and to-day this is a team of adherents that increase greatly successes, initiated by those, who established the plant and contributed to its development within all these years.

Receive, please, our sincere cordial congratulations with the remarkable date — 75th anniversary of «Ukrainian Graphite»! From the bottom of our heart we wish you prosperity and new creative successes and achievements.

*Editorial Board of Journal
«Advances in Electrometallurgy»*

ELECTROSLAG CASTING OF HOLLOW INGOTS AND BILLETS IN INDUSTRIAL PRODUCTION (Review)

M.L. ZHADKEVICH, V.L. SHEVTSOV and L.G. PUZRIN
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Methods of manufacture of hollow ingots and billets by electroslag casting (ESC), widely distributed in the industry, are considered. Systematization of the ESC methods is made by specifics of mutual movement of external and internal moulds and a billet being melted. Capabilities, advantages and drawbacks of different methods of ESC of hollow billets and principles of the mold movement process control are analyzed. Examples of effective application in industry of hollow ingots and billets, produced by ESC and designed for subsequent deformation or application in a cast form, are given.

Keywords: *electroslag casting, hollow ingot (billet), external mould, internal mould (mandrel), regulation of molten metal level, kinds of hollow billets*

Hollow ingots from steels and alloys are widely used in state-of-the-art industry for production by means of rolling, pressing or radial forging of seamless pipes of different assortment and for manufacturing by hot and cold expanding of different rings and thin-wall shells. Use of such billets allows significant simplifying of technology of production of ready items. The hollow ingots themselves are produced with application of machining, hot upset, or piercing of central part of an ingot of solid section. Hollow billets, designed for expanding, are also produced by centrifugal casting.

Development of electroslag technology caused development of methods for production of hollow billets directly in the process of remelting. These billets were

designed for further processing into items with especially high operation properties. In production of seamless pipes and shells use of a hollow billet excludes operation of piercing of a monolithic electroslag ingot, which compensates cost of electroslag remelting (ESR) and makes it possible to produce pipes from steels and alloys difficult for piercing. In many cases electroslag hollow billets may be used in the cast form without further deformation, because strength of the cast electroslag metal is not inferior to strength of a deformed metal of conventional production, but significantly exceeds it in plasticity and toughness [1, 2].

For formation of a cavity in an electroslag billet inside the mould an additional cooled surface, so called internal mould or a mandrel, is introduced. In this case ESR process is performed in the space between external and internal moulds (Figure 1).

In melting of a hollow ingot area of the molten slag contact with walls of the moulds increases that causes increased loss of heat, which is taken away by the cooling water directly from the slag pool. For compensation of this loss in melting of a hollow ingot specific power, released in the slag, should be higher than in melting of a solid ingot of the same external diameter, whereby the smaller is thickness of the hollow ingot wall, the higher should be increase of the specific power. Relative losses of heat from the slag pool to the cooling water in melting of hollow ingots of any standard sizes may be assessed proceeding from Figure 2. Using dimensionless factor F , equal to ratio of total area of the molten slag contact with cooled walls to area of the metal pool surface, one may determine share of heat, taken away by cooling water directly from the slag, by which supplied power should be increased [3].

In addition to increased heat losses from slag pool in melting of hollow ingots additional heat removal to the mandrel from the remelted metal occurs. Shrinkage of the ingot being melted causes compression by it of the mandrel. That's why character of

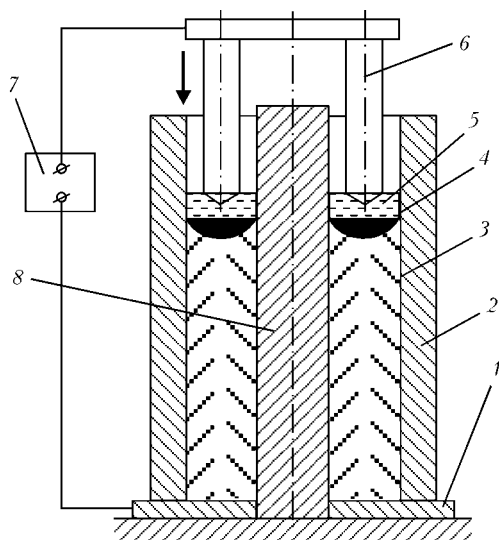


Figure 1. Scheme of melting of hollow billets with immovable internal mould: 1 — pallet; 2 — external mould; 3 — billet; 4 — metal pool; 5 — slag pool; 6 — consumable electrode; 7 — power source; 8 — internal mould (mandrel)



change of heat removal from external and internal surface of the hardening hollow ingot significantly differs. By means of the distance increase from the metal pool surface, heat release of the ingot to the external mould reduces due to increase of gap between them, while heat release to the internal mould increases [3].

In connection with more intensive heat removal metal of the hollow ingot solidifies with higher overcooling than metal of a solid ingot of the same external diameter [4, 5]. This causes production of more fine-grain primary structure and increased and stable values of density of hollow ingots in comparison with solid ones. So, density of metal over thickness of the wall (220 mm) of a hollow ingot of 540 mm diameter from steel of the 35KhN3M grade remains constant and constitutes 7.85 g/cm^3 , while in solid ingot of the same diameter it reduces to center by 0.04 g/cm^3 . As a result metal of a hollow ingot is characterized by higher ductility than of a solid one [6].

The first hollow electroslag ingot was produced in the E.O. Paton Electric Welding Institute as far back as in 1955 [7]. It was melted according to the scheme, presented in Figure 1, just instead of consumable electrodes of big section a welding wire was used. For implementation of such scheme of melting a disposable internal mould was used, which during «undressing» of the ingot was cut and removed. Afterwards development of technology of electroslag casting (ESC) of hollow ingots was directed at search of methods of removal from them of internal moulds without destruction.

In industrial production three different methods of ESC of hollow ingots were mastered, which differed by peculiarities of formation of their external and internal surfaces. According to first method a hollow ingot is melted with internal and external moulds being immovable. According to second method the external mould remains immovable, while the internal one moves relative the ingot being melted. Third method is characterized by the fact that relative movement of both moulds and the ingot being melted takes place.

First method of ESC is mainly used for serial production of cast electroslag billets with semi-closed cavities (Figure 3), which are formed by an immovable reusable mandrel [8]. Such mandrels represent rigid water-cooled rods, made from metal with thermal expansion which significantly differs from expansion of the cast metal. Channels for cooling water are cut on surface of a rod and covered by a thin copper jacket.

For ESC of a hollow ingot from carbon steel a mandrel with a rod from austenite steel is used. After melting the billet with a fixed in it mandrel is heated in a furnace. During heating it is stretched by the rigid mandrel which has higher thermal expansion. After cooling a gap is formed between them, and the mandrel is removed from the billet. In case of melting of a billet from austenite steel a rod from carbon steel

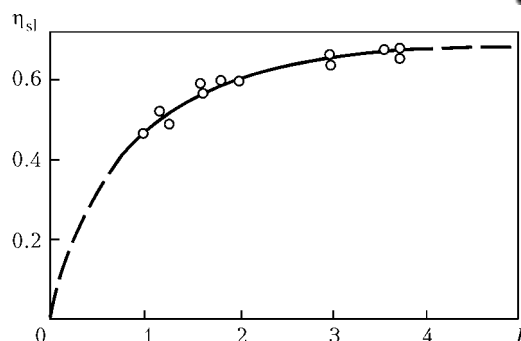


Figure 2. Dependence of relative heat losses from slag pool η_{sl} upon parameter F

is used. In this case during heating in a furnace the cast billet expands more than the mandrel, and the latter is removed in the heated state. As far as mandrels after each melt are insignificantly deformed, they may be repeatedly used [9].

An immovable rigid mandrel prevents from free shrinkage of the metal and causes in it tensile strain, which in the sections, where metal has not sufficiently solidified, may cause formation of hot cracks. Absolute value of tensile strain of a solidifying metal increases with increase of the cavity diameter, that makes higher probability of a crack formation. In this connection a mandrel, made in the form of a rigid water-cooled rod, may be used for formation of internal cavities of a limited diameter (in some cases not more than 200 mm).

Using immovable cooled mandrels the ingots are produced with cavities of even bigger diameter. In this case internal moulds are used, which are able to deform in process of melting under action of the shrinking metal of the casting. These may be water-cooled internal moulds with a disposable jacket, made from a thin carbon steel, or dismountable mandrels. Due to mutual movement of parts of the dismountable mandrel, the latter is not subjected to plastic strain

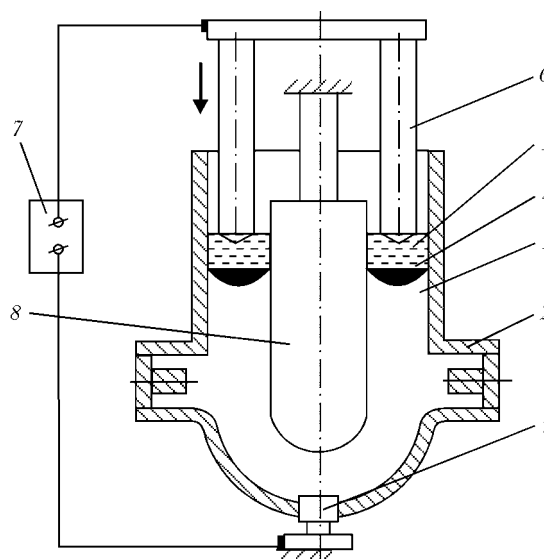


Figure 3. Scheme of ESC of hollow billets of housings of power-producing fittings with immovable reusable mandrel: 1–7 — here and in Figures 4 and 5 are the same as in Figure 1; 8 — immovable reusable mandrel

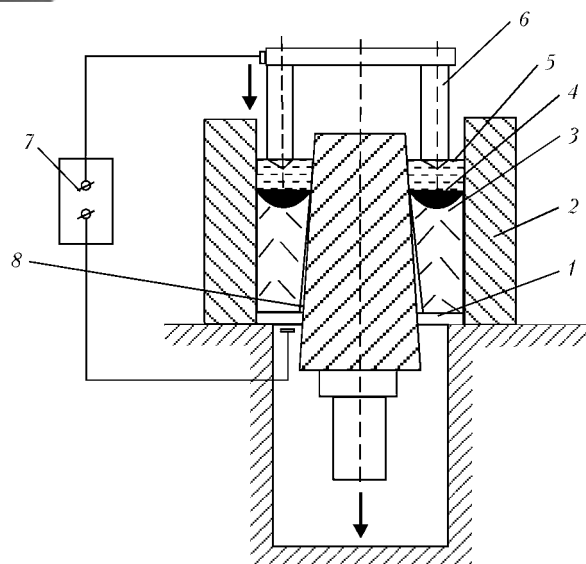


Figure 4. Scheme of ESC of hollow billet with movement of cone mandrel downwards: 8 — movable cone mandrel

in process of shrinkage of a hollow ingot, which allows using it repeatedly [10, 11].

The most widely method of ESC of hollow billets with application of immovable mandrels of different designs is used in manufacturing of parts of the power-producing equipment. So, from steels of the 15Kh1M1F and 0Kh18N10T grades housings of valves are produced with nominal bore from Dn 100 to 400 of 2.2 t mass for thermal and nuclear power plants, and from steel of the 0Kh18N10T grade — connecting pipes of valves with Dn 500 are made [8, 12]. From steel 20 housings of valves with Dn 800 for second circuit of the NPP power units are made [13].

For other branches of industry using such mandrels billets the container bushings from steel of the 5KhNM grade of 690 mm diameter were made, which had wall thickness 185 mm and mass 2.5 t [14], hollow billets of big nuts from steel 45 of 175 kg mass, etc. [10].

For implementation of second method of ESC of hollow billets an internal mould in the form of a truncated cone is used, which is moved in the course of the process relative the part being melted, which allows avoiding its gripping by the cooling metal. Coning of the mandrel is made in such way that during movement of the latter reduction of its diameter corresponds to thermal shrinkage of the billet, whereby the mandrel is placed with its bigger foot in direction of its movement. Depending upon direction of movement, a cavity of different configuration is formed in the casts. When the mandrel moves upwards, the cavity has constant diameter, while during its movement downwards a cavity with a small coning is formed [15].

In serial production only ESC method with a moving downwards internal mould is used. Because of coning of the internal cavity this method of melting is used for production of comparatively short billets with ratio of height to internal diameter close to one. Scheme of this process is presented in Figure 4. As far as electroslag melting is performed according to

the multielectrode scheme in the immovable mould, melted ingots have smooth external surface. Their internal surface is also smooth (without surface tears) because a cone mandrel, when it moves in opposite to growth of the billet direction, compresses crust of the solidifying metal [15].

Peculiarity of cavity formation in such ESC method allows certain squeezing of the mandrel by a cooling billet. Value of the force, necessary for overcoming squeezing of the mandrel, is used as a parameter for regulating speed of drawing [16]. Doubtless advantage of this ESC method of hollow billets is possibility of its performance without application of special sensors that determine position of the metal pool level relative the movable mandrel.

Using this ESC method, different hollow billets are made for subsequent deformation or use in a cast form instead of forged pieces. For hot expanding into rings and cold rolling of pipes hollow billets of 440 mm diameter with wall thickness up to 140 mm and height up to 500 mm from high-alloyed steels of the EI811, EI961, EP57 and Kh16N6 grades are melted [17]. For use in the cast form connection pipes of 10G2, 09G2S and 16GS steels with flanges of 550 mm diameter, wall thickness 100 mm and height up to 600 mm are produced [18]. Using ESC also cast drive gearwheels of powerful industrial tractors of 1180 × 860 × 140 mm size from steel 45G are produced, which were earlier produced from forged pieces. The ESC method allowed drastic reducing volume of machining of wheels due to casting of teeth with minimum profile allowances [19].

For production of long hollow ingots or billets third ESC method is used, in which relative movement of a melted metal and both moulds is performed, whereby a cone internal mould is directed with its expansion upwards. Different options of this method are used: for example, a hollow ingot being melted remains immovable on a pallet, and by means of its growth the moulds are moved upwards (Figure 5, a); the moulds remain immovable, while the billet being melted is moved downwards together with a pallet (Figure 5, b) [20].

For melting of billets using this method the used electrodes are arranged in the form of a paling from round and rectangular rolled stock. The paling of electrodes between the moulds is arranged in such way that elements of the structure that hold the mandrel in necessary position be in interspaces between separate electrodes. The moulds, united into a common block, may have expansion in the upper part. A slag pool is located in it during remelting, and process of melting of consumable electrodes occurs in it [21, 22]. The moulds with expanded melting zone allow using shorter electrodes, cross section of which may exceed wall thickness of a hollow billet being melted, which makes it possible to increase length of the billet without changing height of the electroslag unit [23].

In ESC in an expanded mould the molten metal from flashed ends of consumable electrodes drains

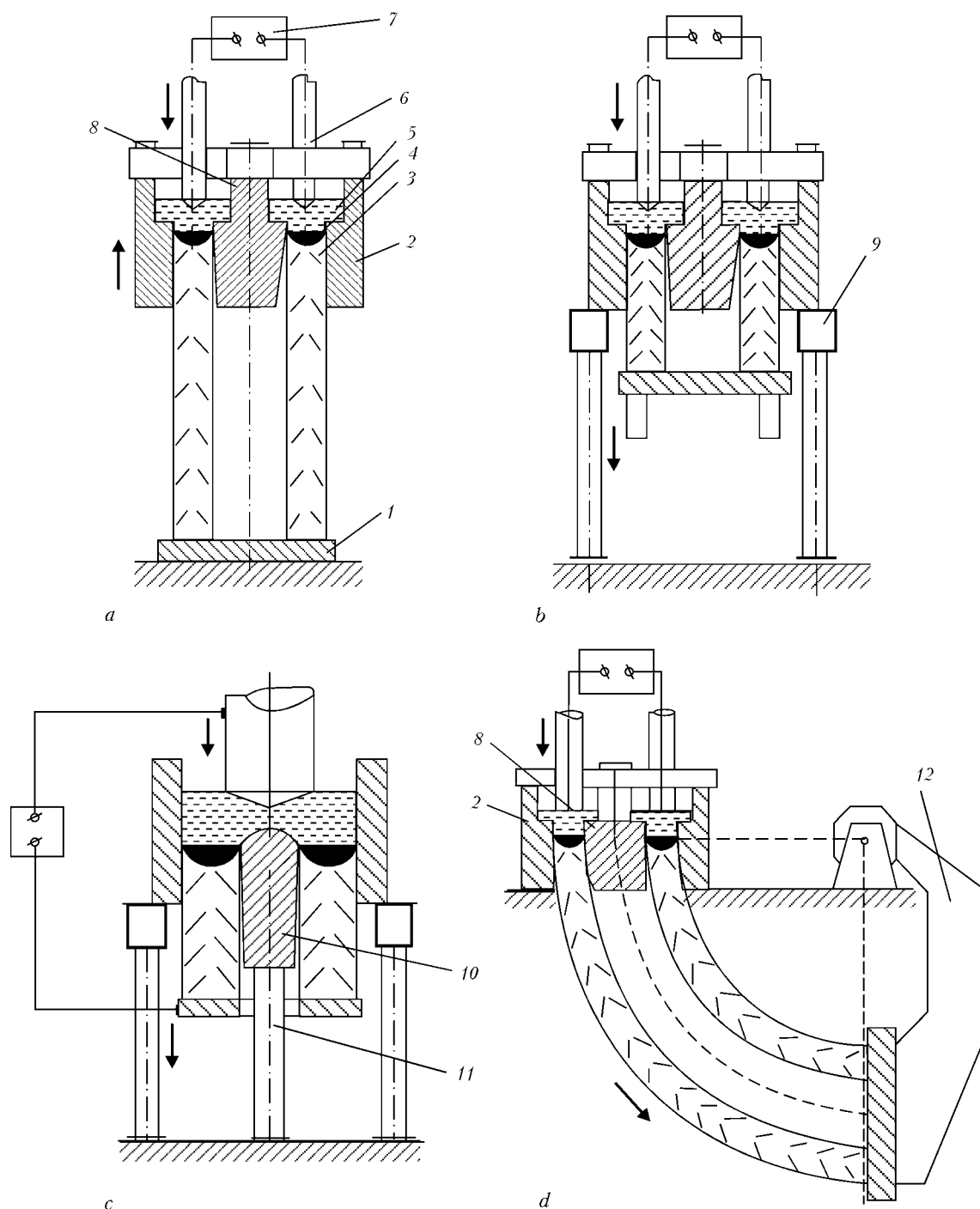


Figure 5. Scheme of ESC with relative movement of moulds and hollow billets: *a* — with immovable billet being melted and moving upwards block of moulds; *b* — with immovable block of moulds and moving downwards billet being melted; *c* — with moving downwards billet being melted and immovable separated external mould and mandrel (electroslag piercing); *d* — with immovable block of moulds and moving over arc of circumference billet being melted; 8 — mandrel connected into block with external mould; 9 — stationary platform for mould; 10 — mandrel for electroslag piercing; 11 — mandrel rod; 12 — mechanism for drawing billet over arc of circumference

into narrow part of the gap, in which a hollow billet is formed. By moving the mould or the ingot at the speed of melting, surface of the metal pool is maintained at the assigned level below the expansion threshold. Surface of the slag pool in expanded part of the mould also remains practically immovable relative its walls. In this case when direct scheme of connection of the electrode–ingot power source is used, local wear of the mould wall occurs in area of the slag pool surface. The wear occurs as a result of

electric erosion of the metal under action of that part of the working current, which goes from the electrode through the slag pool directly to the mould wall [24]. In case of ESC of ingots with filling of an immovable mould, this phenomenon is manifested weakly, because the slag pool moves along the whole surface of the mould walls.

For the purpose of controlling local wear of the walls, consumable electrodes are connected pairwise with source of current according to the bifilar scheme,



whereby share of the working current, which is directed to the mould, and, respectively, local wear significantly reduce [25].

In ESC with relative movement of the hollow ingot being melted and the moulds speed of the movement should correspond to rate of the ingot growth. In case, if speed of movement exceeds rate of the ingot growth, outflow of the molten metal through the formed interspace between the ingot and the cone mandrel will occur, while if speed of movement is below the rate of the ingot growth, squeezing of the mandrel by the hollow ingot will occur, and during its further movement the mould will start to tear from the ingot the metal crust that squeezes it. That's why in this case force of squeezing may not be used for regulation of speed of mutual movement in the same way as in case of melting with drawing of the mandrel downwards. For regulation of speed of mutual movement of the moulds and the ingot in this case special sensors are used which track the metal pool level. Sensors of induction [26], heat [27] and potential [28] types are used, which are installed in the mould wall below the expansion threshold.

Using ESC with relative movement of both moulds long hollow billets with diameters up to 1500 mm and wall thickness from 40 to 350 mm are produced under industrial conditions [23, 29–31]. The most typical examples of using such billets from different classes of steel are presented below.

From carbon steel 20 hollow billets of 680 mm diameter are produced, which have thickness of walls 110 mm and length 1.5 m. Housings of servomotors for hydroelectric power stations are produced from them [12].

From alloyed structural steel of the 38KhM grade wide nomenclature of hollow ingots, which are used for subsequent expanding into rings, are produced [29].

From tool steel of the 9KhF grade billets of 1200 mm diameter are cast with thickness of walls 320 mm, length up to 2.4 m and mass above 16 t for cast sleeves of support rolls of rolling mills [32].

From die steels of the 4KhMFS and 4Kh4M2VFS grades bushings of diameter from 295 to 775 mm and internal diameter from 145 to 365 mm are melted for hydrocontainers of horizontal pipe presses [31]. Experience of operation of cast electroslag bushings showed that their durability exceeds 2 times durability of the forged ones.

From stainless steel of the 07Kh16N6 grade billets of drums of 6 t mass, length 2.5 m, diameter 1460 mm and wall thickness 80 mm are melted [33]. From steel of the 12Kh18N10T grade billets of vessel housings of 2.5 m length, 715 mm diameter with wall thickness 170 mm, which operate at temperature of liquid nitrogen and pressure 7 MPa, are made [34].

There is a version of the ESC technology, according to which the ingot is drawn downwards, and the external mould and the mandrel are not united into a common block. In this case the mandrel is installed on a rigid rod, through which also cooling water is

fed and withdrawn. In process of ESC upper end of the internal mould is maintained below level of the slag in such way that it just a little protrudes above the metal pool, whereby space inside the mould that is above the slag pool level remains free for placement of the consumable electrodes [35, 36]. Scheme of such ESC process is presented in Figure 5, *c*.

Advantage of this ESC version of hollow ingots is possibility of using for remelting one consumable electrode of big diameter. In course of the ESC process as if piecing of solid electrode and formation of a hollow billet occur. This variety of ESC received name — electroslag piercing.

In piercing there is no need to use for remelting thin rolled stock from the required grade of material and produce from it a consumable electrode in the form of a paling of bars. Application of one electrode simplifies process of the ESC preparation and significantly reduces cost of its preparation. Especially efficient is piercing in production of hollow billets from hardly-deformed steels and alloys, from which it is difficult to produce thin bars, whereby for melting of hollow billets cast consumable electrodes may be used, produced by methods of vacuum induction melting and vacuum arc remelting.

Introduction into industry of the piercing method encounters certain difficulties, connected with durability of the technological fitting-out. Firstly, maximum length of a hollow billet, melted in this way, is limited by rigidity of the rod that preserves with necessary accuracy position of the mandrel in relation to the external mould. Secondly, because of a direct scheme of the consumable electrode connection to the power source not just local electroerosion process of the external mould wall occurs, but also intensive destruction of upper part of the mandrel. Wear of the mandrel by the passing current is aggravated by the rain of the overheated metal drops, which get on it from the flashed end of the consumable electrode.

For reduction of these harmful phenomena built-up moulds and mandrels, assembled from separate isolated from each other parts, are used. In addition, using blowing of the slag pool by inert gases through the mandrel, the zone of the drip fall is shifted from upper end of the mandrel to surface of the annular metal pool. These technological methods increase service life of the moulds up to several hundreds melts [37].

Using electroslag piercing, hollow billets of 525 mm diameter with wall thickness 135 mm, length 1.5 m from the 30KhN2M steel and nickel alloy (wt. %: 20 Cr; 20 Fe; 5 Nb; 3 Mo; 1 Ti) were produced. These billets were designed for subsequent deformation [36]. Electroslag cast billets of longitudinal carriages of automatic machines were also serially manufactured from the 20Kh steel. Billets of 1.4 m length with a shape external surface and cavity of 135 mm diameter were melted [35, 37].

Using ESC method with drawing, hollow billets with a curvilinear axis were also produced, whereby forming parts of the moulds were imparted necessary



curvature, and the billet was drawn over arc of the circumference of necessary radius. Scheme of the process is presented in Figure 5, *d*. Using this ESC method pipe knees from high-temperature chrome-nickel steel of 25-20 type [38] and elbows of Dn 350 with wall thickness 60 mm having mass up to 950 kg from steel of the 14KhGS and 30KhMA grades are produced. They are used for production of pipelines and heat exchangers that operate at high temperature and pressure. Produced by this method cast electroslag knees may have turn angle up to 180° [13].

Using scheme with drawing of the billet over circumference only from the external mould, half rings of solid section are cast; after their pairwise welding cast electroslag ring billets are produced. Using this technology, bands of cement kilns of T-shape profile from steel 35 are produced. These rings are welded into body of the kiln and function as supports during rotation of the latter. They have width of the support part 900 mm and general width 1500 mm. Diameter of the support part of the rings is 6 m, internal diameter is 5 m, mass is 65 t. Application of such electroslag bands allowed increasing rigidity of the cement kiln body and significant increasing durability of its lining [39].

For application in cast form without subsequent deformation it is possible to produce not just cylindrical billets with a cavity, located concentrically, but also billets with any other constant over length shape of the cross section. For example, billets of 4 m length with an eccentrically located cavity and a rectangular protrusion outside on the side of the biggest wall thickness [40] and cylindrical billets of the housing of the double-worm granulator of 1.7 m length with the cavity in the form of figure of eight, consisting of two circumferences of 80 mm diameter [41], were produced. Billets in the form of a parallelepiped of $600 \times 540 \times 830$ mm size with a rectangular 190×160 mm hole were also melted [42].

For some machine building parts that operate under conditions of heating long billets with through holes for cooling are needed. Making of long holes by means of machining is rather complex. The ESC method with relative movement of the moulds significantly simplifies manufacturing of such parts. For production of long billets with several isolated from each other longitudinal holes inside the external mould a respective number of cooled conic mandrels are placed. Example of such cast billet is a cooled guide of 3.7 m length in the form of a shape profile

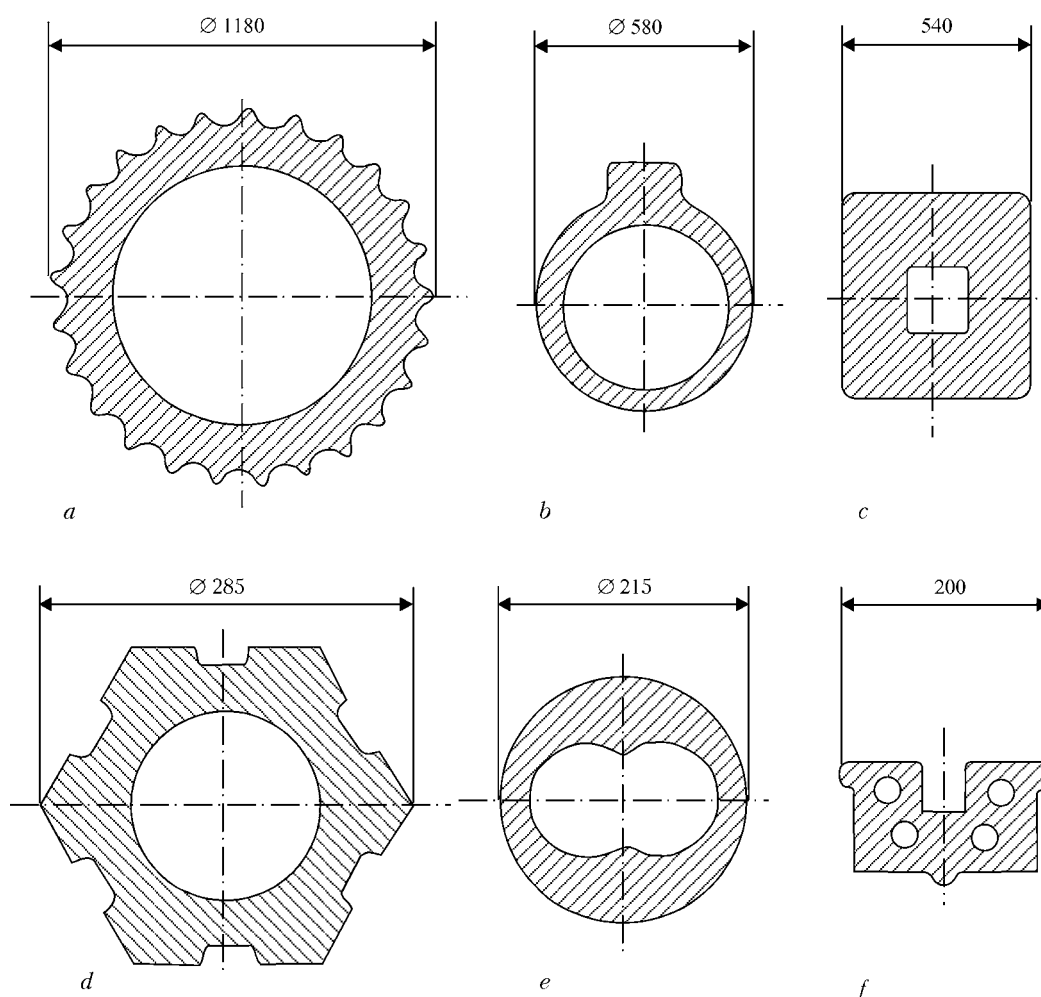


Figure 6. Shapes of cross section of some ESC billets used in cast form: *a* — drive wheel of heavy tractor; *b* — parts with variable wall thickness; *c* — parts with rectangular hole; *d* — longitudinal carriage of automatic machine; *e* — housing of double-worm granulator; *f* — guide with channels for cooling



with four longitudinal through holes of 23 mm diameter from steel of the 3Kh13 grade [43].

In Figure 6 shapes of cross section of some cast shape billets, produced by considered above ESC methods, are shown.

For commercial production of the electroslag hollow ingots and billets of different mass a series of electroslag furnaces was developed [44]. For specific items a water-cooled specialized copper and steel technological fitting-out (moulds, mandrels, pallets) were developed, by means of which it is possible to melt billets of different shape and size [10, 45, 46]. Methodologies of calculation and design of different types of moulds with convective or boiling conditions of cooling were developed [4].

Analysis of possibilities of different methods of production of the hollow cast electroslag billets and experience of their use in industry allowed giving following recommendations:

- it is most rational to perform melting of billets with semi-close cavities using the ESC method with application of immovable external and internal moulds;
- melting of hollow billets of a limited height one may perform by the ESC method with application of an immovable external mould and a movable relative the billet being cast internal mould, whereby external surface of the produced billets may have a complex form;
- for melting of long billets of constant cross section with one or several cavities the ESC technology with relative movement of the billet being melted and the moulds should be used.

CONCLUSIONS

1. Specialists of different countries developed and introduced into industrial production a special version of the electroslag process — ESC of hollow ingots and billets. This technology allows producing directly in the ESC process hollow cast billets, metal of which has higher service properties than the strained one.

2. The electroslag cast billets significantly simplify production from them of many unique parts. The ESC technology also solves the task of production of hollow billets of complex profile from hardly-deformed high-alloyed steels and alloys, which are used on ever growing scale in industry.

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INVESTIGATION OF QUALITY OF THE 20Kh13 STEEL CONE BILLETS PRODUCED BY METHOD OF CENTRIFUGAL ELECTROSLAG CASTING

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Information about chemical composition, structure and mechanical properties of the 20Kh13 electroslag steel in comparison with forged steel of similar composition is given. Possibility of application of the CESC billets from this steel in production of housing parts of gas turbines is substantiated.

Keywords: parts of gas turbines, high-temperature alloys, centrifugal electroslag casting, ductility, impact toughness

A set of billets of 716 and 490 mm diameter, height 500 mm and mass 0.6 t from the 20Kh13 steel was produced according to new technology using method of centrifugal electroslag casting (CESC). In this work quality of metal of the billets of the gas turbine parts, produced by this method from high-temperature steel of martensite class of the 20Kh13 type, was investigated.

BILLETS, which represent a thick-wall truncated cone (Figure 1), were produced in the KTSEShL-1 installation with vertical axis of rotation [3].

Investigation of chemical composition of the CESC billets from the 20Kh13 steel was performed by the quantitative spectral analysis. Weight share of elements in the 20Kh13 casting corresponds to their content in initial metal, except silicon and sulfur, and meets requirements of GOST 5632–72 for this steel (Table 1). Macrostructure of the billets is dense and without defects of shrinkage origin. It consists of two main zones which differ from each other by dispersion

of the crystalline structure — external one having length 5–8 mm with fine-crystalline structure and main one with coarser structure, presented by columnar crystals. Ultrasonic testing did not detect defects of cast character.

For investigation of properties over height of the casting several rings were cut out (Nos. 2–4) of 85 × 85 mm height and wall thickness, and for investigation of macro- and micro-properties one more ring (No 1) was cut out. From produced rings the specimens were made. Longitudinal, tangential and tear specimens were subjected to heat treatment according to the following preliminary conditions: normalization at $T_1 = 950^\circ\text{C}$, cooling in air; double tempering at $T_2 = 680^\circ\text{C}$, cooling in air (twice). Final heat treatment was performed according to the following conditions: normalization at $T_3 = 950^\circ\text{C}$, cooling in air; tempering at $T_4 = 710^\circ\text{C}$, cooling in air. After heat treatment hardness of rings was checked by the ball of diameter $D = 10$ mm under load $P = 27.3$ kN with soaking $t = 10$ s.

Impact toughness, tear ($T = 20^\circ\text{C}$) and tensile investigations at increased temperatures and long-term strength investigations were carried out on tan-

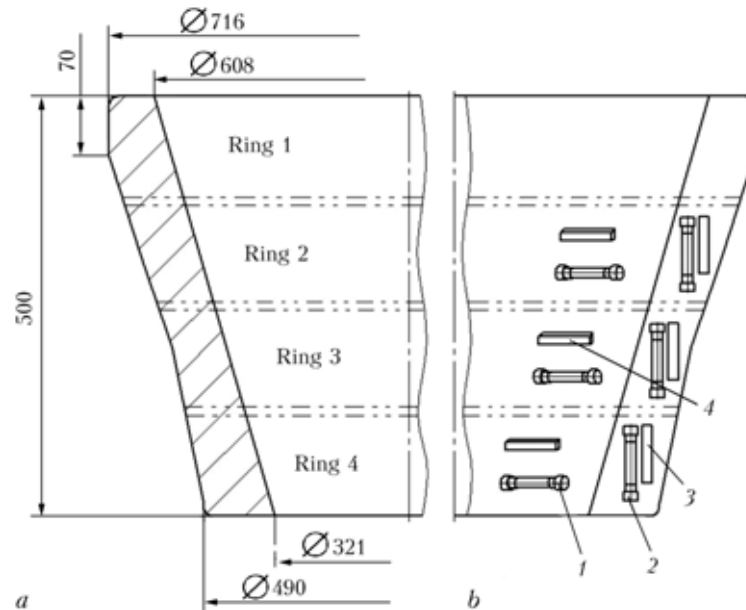


Figure 1. CESC billet (a) and scheme of cutting out of specimens (b): 1 — tangential tear ones; 2 — longitudinal tear ones; 3 — longitudinal impact ones; 4 — tangential impact ones

Table 1. Chemical composition of 20Kh13 steel

Object of investigation	Weight share of elements, %							
	C	Si	Mn	Cr	Fe	Ni	S	P
Initial metal (cast electrodes)	0.16	0.25	0.35	12.0	Base	0.5	0.012	0.021
CESC billet	0.16	0.22	0.35	12.0	Same	0.5	0.008	0.021
Requirements of GOST 5632-72	0.16–0.25	Not more than 0.8	Not more than 0.8	12.0–14.0	»	–	Not more than 0.025	Not more than 0.030

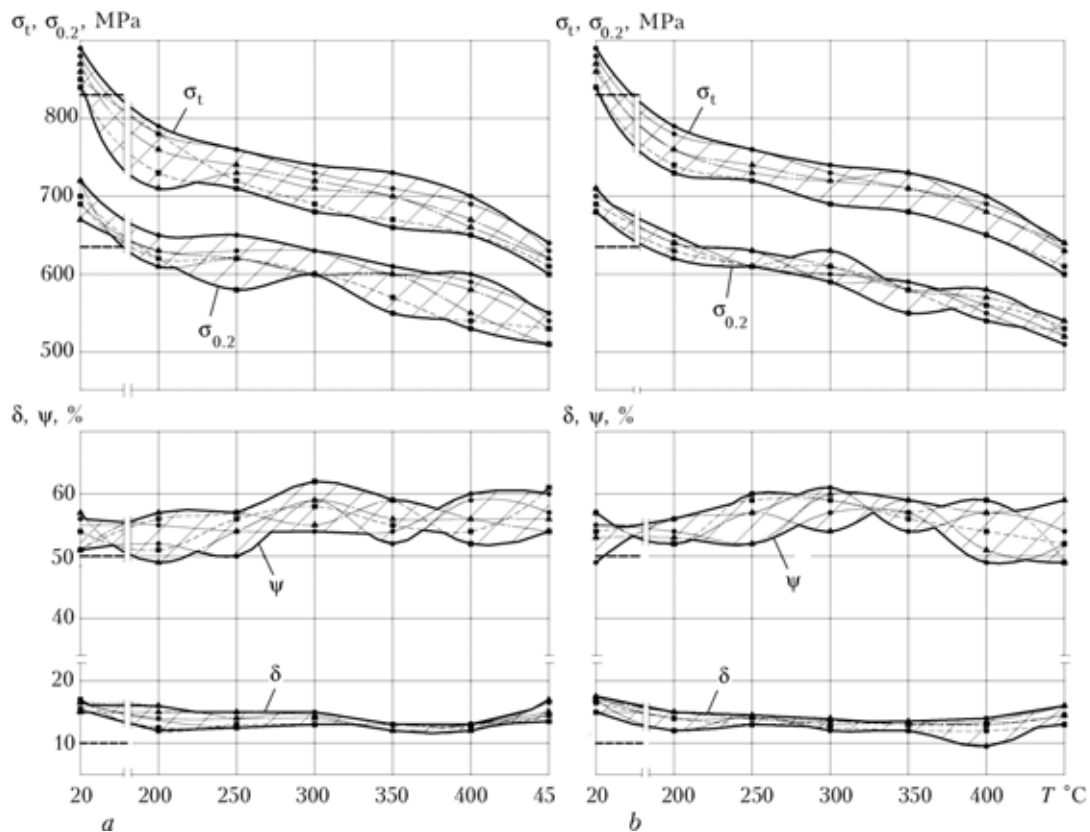


Figure 2. Diagrams of mechanical properties of heat-treated 20Kh13 steel for hardness $HB\ 269\text{--}255$ ($d_{\text{imp}} = 3.7\text{--}3.8\text{ mm}$): a — longitudinal; b — tangential specimens; ● — ring No 2; ▲ — ring No 3; ■ — ring No 4; bold dash lines show values of mechanical properties according to GOST 5362-72



gential and longitudinal specimens, cut out on opposite sides of the rings. Impact toughness tests were carried out on 10 specimens of each kind, tear and tensile tests were carried out on 4 specimens of each kind. Obtained results of tear and impact toughness tests of the rings meet requirements, established for strained metal of open melting (Table 2). Ultimate strength σ_t turned out to be higher of the standard requirements for forged pieces by 30 %, and yield strength $\sigma_{0.2}$ — by 55 %.

In Figure 2 results of tests of mechanical properties within temperature range 20–450 °C, carried out on 6 specimens of each kind, are presented. One may see from the drawing advantage of the 20Kh13 steel in the CESC castings in regard to ductility (δ , ψ) in comparison with the forged metal. So, in regard to relative elongation δ excess constitutes 50 %, and in

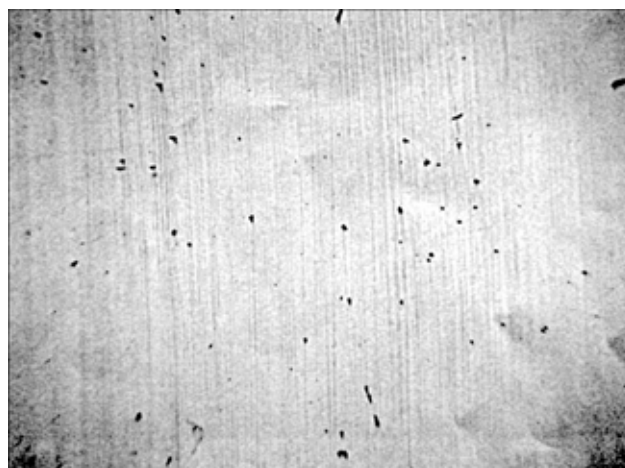


Figure 3. Microstructure of ring (×100)

Table 2. Mechanical properties of 20Kh13 steel in casting after heat treatment

Ring No	Place of specimen cutting out in casting	Direction of specimen cutting out	$T_{\text{test}}, ^\circ\text{C}$	σ_t, MPa	$\sigma_{0.2}, \text{MPa}$	$\delta, \%$	$\psi, \%$	$KCU, \text{J/cm}^2$		$d_{\text{imp}}^*, \text{HB}$
2	Upper part	Tangential	20	890	710	17.0	55	68	63	3.8/255
				890	720	16.0	51	65	75	
				880	690	17.5	49	55	63	
				880	730	15.5	54	65	73	
	Longitudinal	Longitudinal	20	900	710	16.5	56	70	58	3.8/255
				890	720	16.5	56	63	75	
				880	690	16.5	51	68	45	
				890	730	15.0	43	63	56	
3	Medium part	Tangential	20	870	710	14.5	51	55	53	3.8/255
				870	680	18.5	53	63	60	
				860	710	17.0	57	58	50	
				870	720	16.5	56	75	73	
	Longitudinal	Longitudinal	20	860	670	15.0	57	63	63	3.8/255
				860	710	14.0	48	53	53	
				870	710	14.5	51	50	40	
				870	720	16.5	51	60	65	
4	Lower part	Tangential	20	870	710	14.15	51	55	53	3.8/255
				880	730	15.5	54	65	73	
				870	720	16.17	56	75	73	
				880	690	17.5	51	55	63	
	Longitudinal	Longitudinal	20	870	710	14.5	51	53	51	3.8/255
				890	720	16.5	56	63	75	
				860	710	15.0	57	63	63	
				880	730	15.5	54	65	73	
TU U 27.1-00190414-030-2004 on forged pieces (longitudinal ones)			20	>70	>55	>12	>40	>40	4.1-3.7	

* Here d_{imp} is the imprint diameter in millimeters.

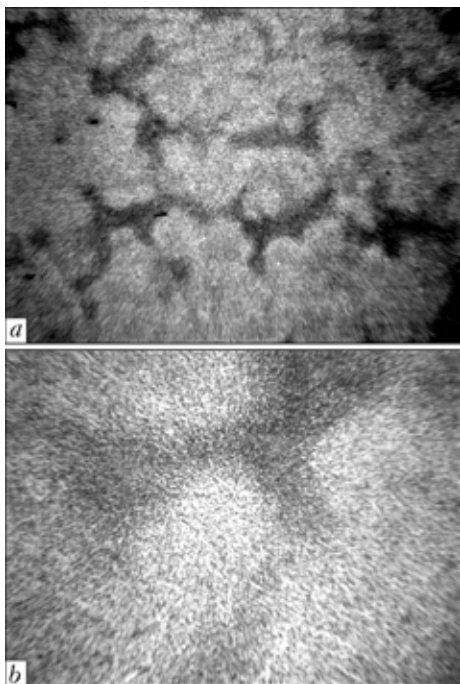


Figure 4. Microstructure of ring after heat treatment for hardness $HB\ 269\text{--}255$: *a* — $\times 100$; *b* — $\times 400$

regard to reduction in area ψ — 5–8 %. One should expect that at higher tempering temperature ductility (δ , ψ) will exceed to greater degree requirements of the standard for forged pieces.

In long-term strength tests under conditions $T_1 = 250\text{ }^\circ\text{C}$, $\sigma = 530\text{ MPa}$; $T_2 = 300\text{ }^\circ\text{C}$, $\sigma = 495\text{ MPa}$; $T_3 = 350\text{ }^\circ\text{C}$, $\sigma = 460\text{ MPa}$; $T_4 = 400\text{ }^\circ\text{C}$, $\sigma = 410\text{ MPa}$ all specimens withstood 200 h without failure which

exceeds more than two times requirements of specifications of Ukraine.

Impact toughness of the 20Kh13 electroslag steel, which was heat treated for hardness $HB\ 269\text{--}255$ ($d_{\text{imp}} = 3.7\text{--}3.8\text{ mm}$), also exceeded requirements of the standard by 50 %.

Microinvestigation showed (Figure 3) presence in structure of the steel of small amount of fine globular non-metal inclusions, uniformly distributed in body of the casting.

Microstructure of steel after heat treatment for hardness ($HB\ 269\text{--}255$) represents tempering sorbite (Figure 4) that stipulates high values of toughness and plastic properties of the steel.

So, carried out investigations of quality of centrifugal electroslag billets from the 20Kh13 steel prove full correspondence (and in regard to some parameters even excess) of the cast metal properties to requirements of the specifications of Ukraine for forged pieces from this steel of open melting. Electroslag castings from the 20Kh13 steel may be recommended for application as billets in parts of gas turbines instead of forged pieces. Works, directed at improvement of the technology, continue.

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TECHNOLOGY AND EQUIPMENT FOR REFINING OF MASTER ALLOYS

Aluminium-thermic reduction from oxides is a traditional technology for production of many types of complex-composition master alloys. Spontaneous occurrence of oxidation-reduction reactions with reduction of metals is caused by high chemical affinity of aluminium for oxygen. Ingots of master alloys produced by this method have such drawbacks as liquation of main elements, contamination of metal with non-metallic inclusions and increased oxygen content. These are the causes of rejection of up to 30 % of master alloys.

The E.O. Paton Electric Welding Institute developed the technology for refining vanadium-containing master alloys (up to 55 % V), based on induction melting in a sectional mould. The technology allows recycling of all wastes of master alloys.

The pilot unit was built for refining of wastes of vanadium-containing master alloys. The unit provides high-quality ingots with a diameter of up to 200 mm and weight of up to 100 kg. Annual output of the unit is up to 50 t.

The developed technology provides for remelting of lumpy scrap in a sectional mould in the inert gas atmosphere. Flux CaF_2 can be used to ensure deeper refining.

Purpose and application. The developed technology and equipment are intended for refining of master alloys with a melting point of 1500–1700 $^\circ\text{C}$. The technology and equipment have passed experimental-industrial verification at the Lelinabad Rare Metal Works (Tadjikistan).

State and level of development. Experimental-industrial verification.

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PHYSICAL MODELING OF SLAG POOL HYDRODYNAMICS IN SLAB CURRENT-LEADING MOULD. Part 2. Cladding

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Hydrodynamics of a slag pool in a slab current-leading mould for the process of cladding has been investigated. It is shown that character of hydrodynamic flows in the slag pool depends upon ratio of parameters of the layer being clad and distance between the current-leading section and the metal pool level in the mould. Distribution of current both along circuit of electrodes of the mould current-leading section and over the whole volume of the pool is investigated.

Keywords: slab current-leading mould, schemes of connection, hydrodynamic flows in process of cladding, spreading of current

As continuation of the works of the slag pool hydrodynamics modeling in a slab current-leading mould, described in [1], hydrodynamic flows occurring in cladding were investigated. For this purpose in the previously used model steel billets were placed on the pallet, cross-section of which was selected in such way that between them and all electrodes of the current-leading section the same spacing be left corresponding to thickness of the clad layer (7.5 and 17.5 mm). The steel billets were reliably fixed on the pallet on two copper rods, which ensured conduction of current. For prevention of possible skew of the billet and ensuring of the assigned spacing uniformity over perimeter of the model, between the electrodes and the steel billets wooden distance bars were installed, placed only over the most upper edge of the current-leading section, while level of saturated solution of calcium chlorine that modeled the slag pool was located lower (Figure 1).

During cladding, as well as during melting of an ingot in the current-leading mould, presence of a break in the current-leading section causes formation of a horizontal flow, directed from place of connection of the cable along circuit of the electrodes over perimeter of the section to the break. However, in this case intensity of rotation of the flow in the spacing between the billet being clad and the mould wall, all other conditions being the same, is significantly lower (in our case approximately two times). Reduction of the spacing also causes lowering of rotation intensity of such flow. It may be increased only due to increase of current in the electrodes-pallet circuit. Location of the pallet (distance to the current-leading section h) does not effect in any way intensity of rotation and practically does not change current in circuit of the electrodes of the current-leading section. Axis of the horizontal flow is located not in the center of the

spacing, but closer to the current-leading section surface (Figure 2).

Reduction of the rotation intensity is, evidently, connected with concentration of the magnetic field lines of force in the steel core — the billet being clad. The smaller is the spacing (the clad layer) the smaller number of lines of force pass through the solution and, therefore, the lower is intensity of the magnetic field H in the spacing (Figure 3). As a result the force, which acts on the electrically charged particles of the solution that model the slag pool, gets lower, and intensity of the solution rotation reduces.

Vertical flows, registered in modeling of the ingot melting process [1], depend to a great degree in the course of cladding upon position of the pallet. Under conditions of the experiment at distance from the pallet to the current-leading section more than 50 mm vertical flows for any schemes of the current-leading section connection were not detected. They appear in case of bringing of the pallet closer to the dividing section and are most noticeable when distance to the current-leading section gets smaller than spacing between the billet and the mould. So, for the case, when spacing equaled 17.5 mm and distance to the current-leading section was 12 mm, vertical flows were registered (Figure 4), which form near electrodes, are directed downwards along walls of the mould to the pallet, shifted according to the scheme of connection by the horizontal flow, and ascend to surface near edges of the billet being clad (see Figure 4, dash lines). In case of presence of one break in circuit of the electrodes vertical flows on side of connection of the cable have somewhat bigger length. In case of two breaks in circuit of the electrodes of the current-leading section pattern of the flows is symmetrical (Figure 4, *b*).

It should be noted that formation of descending flows near electrodes of the current-leading section occurs during cladding not in the area of transition from the current-leading to the middle (dividing) section near lower boundary of the electrodes, as in modeling of the ingot melting process, but at a certain

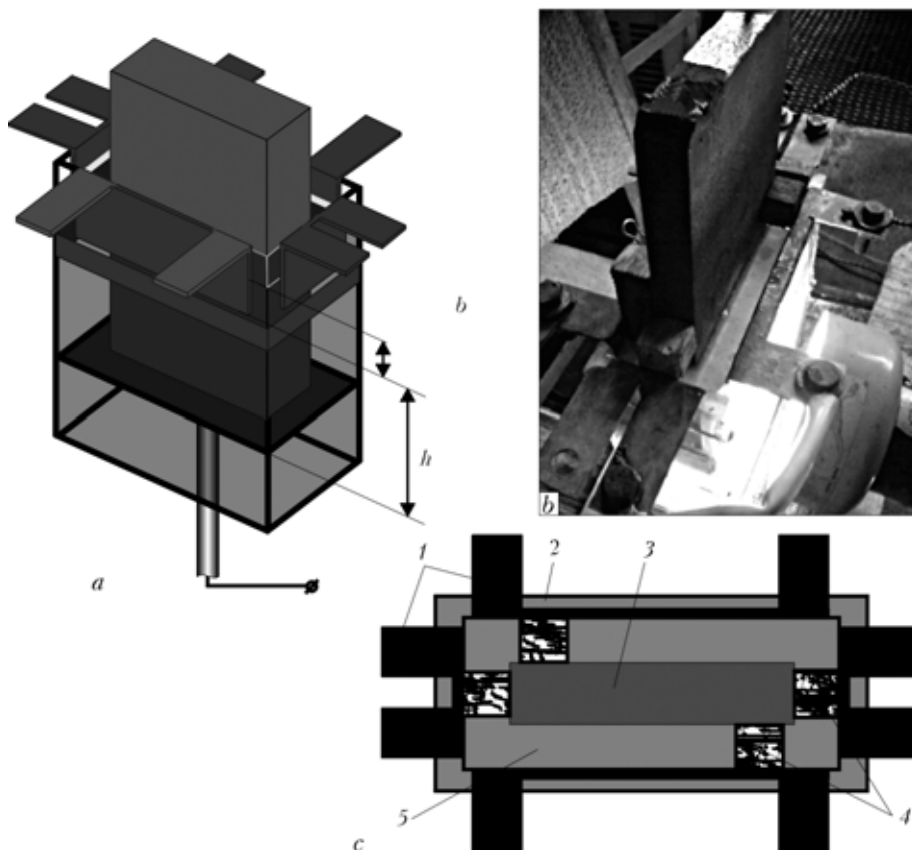


Figure 1. General view of current-leading slab mould model (*a, b*) and location of distance bars (*c*) for centering of billets for cladding: 1 — contacts of current-leading section electrodes; 2 — mould body; 3 — billet being clad; 4 — wooden distance bars; 5 — liquid modeling slag in spacing; *b* — depth of dipping of electrodes

distance from surface of the solution. Such phenomenon is, possibly, connected with change of electric resistance of the electrode–pallet circuit area and free convection forces of the solution.

It was established in modeling of the ingot melting process that area of the highest heat release was lower boundary of the electrodes of the current-leading section. In course of cladding, when resistance in area

of the current-leading electrode–billet being clad circuit is lower than in the current-leading electrode–pallet area (to be more precise the electrode–metal pool surface), such area should be, evidently, considered zone near the slag pool surface adjacent to the electrodes. However, heating of the slag (the modeling solution) occurs over whole contact surface of the electrode. A portion of heated in this place solution expands, gets lighter, and tries to come to the surface, counteracting the flow which occurs under action of



Figure 2. Rotation of horizontal flow in cladding in current-leading mould (view from above): 1 — walls of mould body; 2 — electrodes of current-leading section; 3 — flow of solution which models slag; 4 — spacing (17.5 mm); 5 — billet being clad; 6 — wooden distance bar

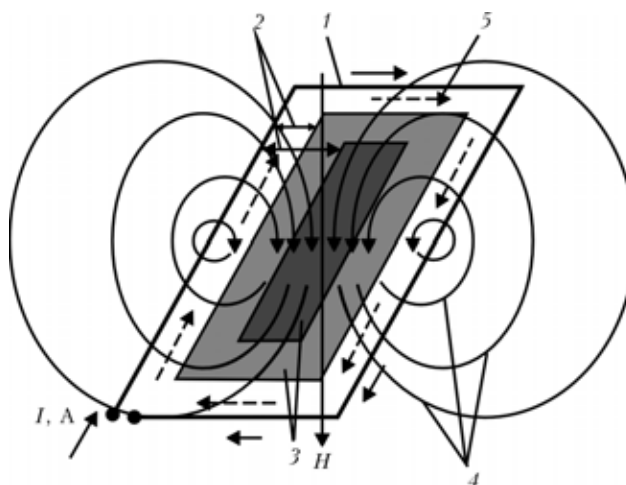


Figure 3. Rotation of solution which models slag and concentration of portion of magnetic field lines of force in billets being clad: 1 — current-leading circuit; 2 — spacing; 3 — billets being clad; 4 — magnetic field lines of force; 5 — direction of solution rotation



electromagnetic forces. Counteraction of the free convection forces to electromagnetic forces in this area causes origination of descending flows not from the surface of the solution modeling the slag pool, but at certain distance from it. At further bringing closer of the pallet to the current-leading electrodes visible origination of the descending flows shifted to lower boundary of the electrodes.

In electroslag processes in the current-leading mould spreading of the current from the current-leading area both along the electrodes (see Figure 4, figures near copper buses that connect adjacent electrodes) and over the whole volume of the slag pool occurs. In order to assess pattern of spreading of the current in the solution that models the slag a number of experiments were carried out. As a measuring instrument for assessing level of current in the selected direction a small current transformer in the form of a ferrite ring with copper winding was used. External diameter of the transformer was 10.5 mm and thickness — 7 mm. Current, passing through the ring in the solution, excites magnetic flow in core of ferrite which, in its turn, induces EMF in winding of the current transformer. Produced voltage was registered by means of the microvoltmeter.

Factor of proportionality between measured voltage and registered in the solution current was preliminarily determined by means of the measurement system calibration.

In Figure 5, *a* scheme of the experiment is presented. Measurements were carried out both in direction from the electrodes to the billet and along horizontal flow in different areas over perimeter of the mould and over height of the pool from the surface to the pallet. Registered current corresponded to the current that flew in the solution in selected direction through the section equal to internal diameter (4 mm) of the current transformer. As a whole (both for

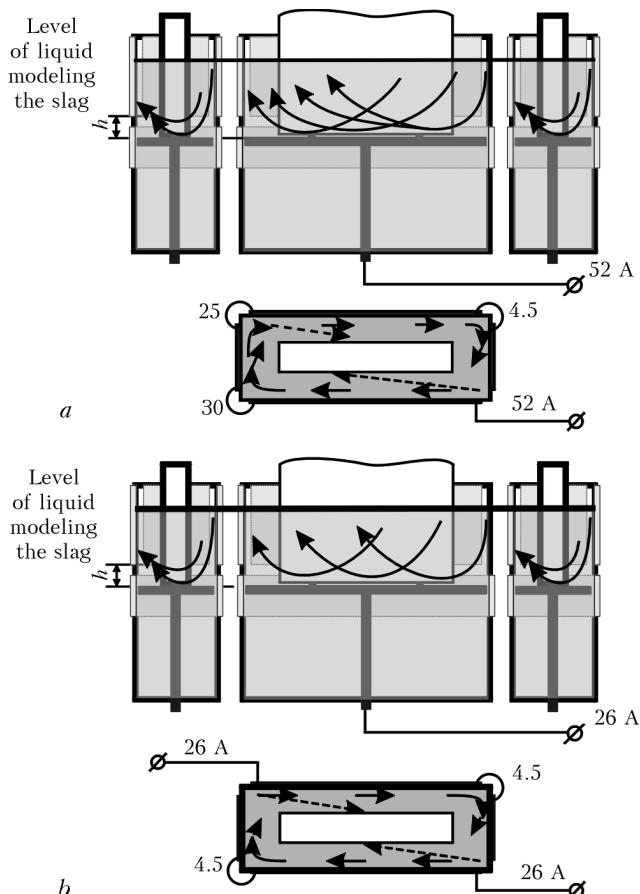


Figure 4. Hydrodynamic flows of liquid modeling the slag in cladding in flat current-leading mould with one (*a*) and two (*b*) breaks in upper section: $h = 12$ mm

scheme with one and with two breaks in circuit of the electrodes) reduction of current in the solution modeling the slag was registered by means of advancement along circuit of the electrodes and moving away from the place of connection of the current-leading cables. Similar character of change of the current was

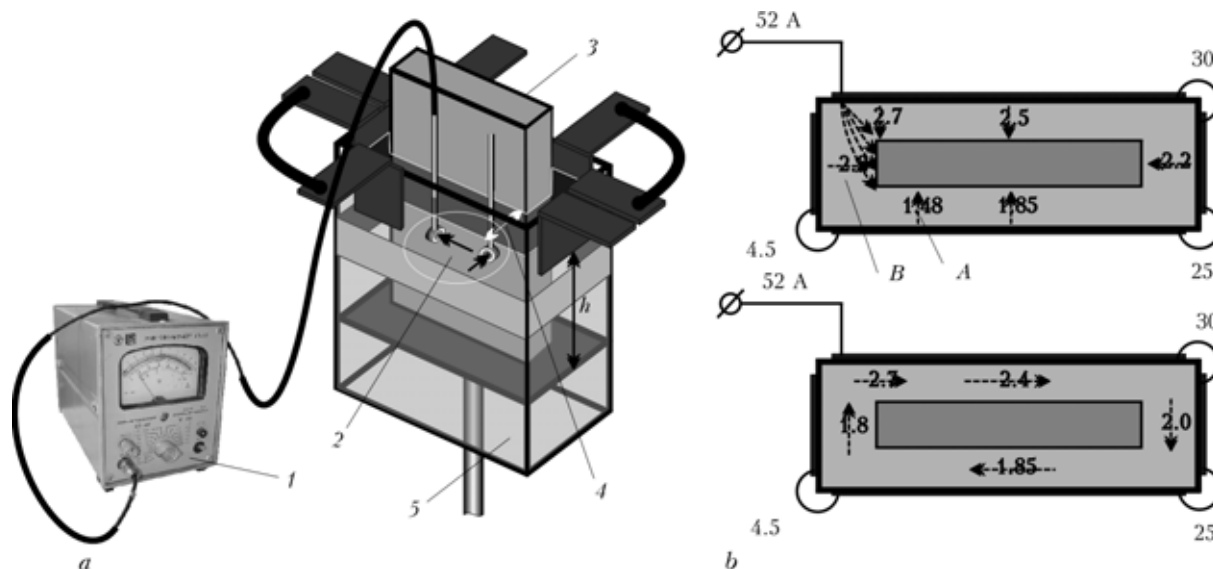


Figure 5. Distribution of current in solution modeling the slag in cladding in flat current-leading mould: *a* — scheme of experiment; *b* — obtained values of current in horizontal plane near lower end of current-leading electrodes; 1 — measuring instrument; 2 — position of measuring sensor in spacing and direction of measured currents in model solution; 3 — billet being clad; 4 — spacing between billet and wall of model; 5 — model of flat current-leading mould

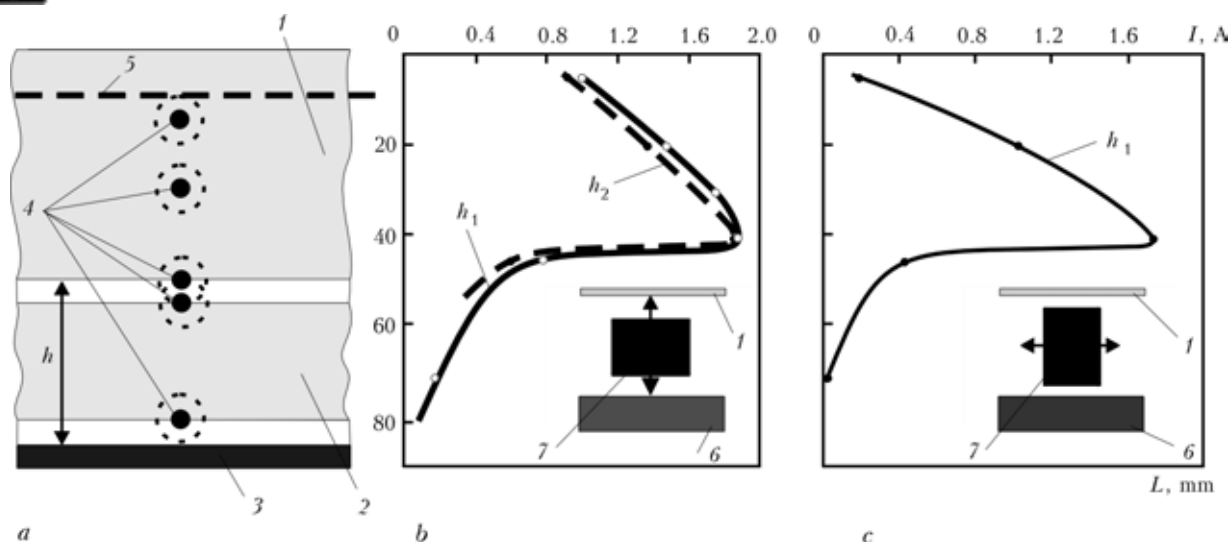


Figure 6. Distribution of current over depth of solution modeling the slag during cladding in flat current-leading mould: *a* — fragment of mould with areas of measurement; *b, c* — radial and horizontal components; 1 — current-leading electrode; 2 — copper contour of intermediate section; 3 — pallet; 4 — areas of measurement of current; 5 — level of solution modeling the slag in mould; 6 — billet for cladding; 7 — position in spacing of measurement current transformer; $h_1 = 50$ mm; $h_2 = 12$ mm; L — depth of submersion of measurement current transformer

also detected in circuit of the current-leading electrodes (in our case 52 A–30 A–25 A–4.5 A). Measurement of the current that flows in direction from the electrodes to the billet showed the highest value (2.7 A) in area of the solution immediately adjacent to the areas of connection of the current-leading cables, and the lowest value (1.48 A) — in the area, located near opposite wall of the model (Figure 5, *b*, area *A*). Increase of the radial component (from the electrode to the billet) of the current in area *B* is, evidently, connected with branching of a portion of the current from the place of the cable connection to the end of the billet being clad.

Investigation of distribution of the current over depth of the solution showed that the highest values of the current for both radial and horizontal (over perimeter along circuit of the electrodes) component were at the level of the lower end of the current-leading electrodes (Figure 6). Immediately near surface of the solution the radial component exceeded approximately 5 times the horizontal component. At increase of depth of dipping up to the level of lower end of the current-leading electrodes a smooth increase and then (in the spacing between the current-leading section of the electrodes and the middle intermediate section) sharp reduction of current were registered. In the area of the intermediate section smooth reduction of current was registered. Change of distance h from the pallet to the current-leading electrodes from 50 to 12 mm enabled certain reduction of radial component of the current, while horizontal component practically did not change (Figure 6, *b*,

c). Such character of change of the current is, evidently, connected with the fact that if distance to the current-leading section gets smaller than spacing between the billet and the mould, then determining role in distribution of the current over volume of the solution that models the slag pool starts to play vertical component of the current.

CONCLUSIONS

1. It was established that in cladding in the current-leading mould character of hydrodynamic flows in the slag pool depended upon ratio of values of the layer being clad and distance between the current-leading section as well as level of the metal pool in the mould. If this ratio was more than 1, then both, vertical and horizontal flows were detected. By means of reduction of this ratio intensity of vertical flows reduced, and prevailing influence exerted horizontal flow that rotated around the billet being clad.

2. It was shown that intensity of the horizontal flow rotation got higher by means of increase of current in the current-leading sections—pallet circuit and thickness of the clad layer.

3. It was determined that spreading of current in the slag pool was not uniform. The highest values of current for both radial and horizontal (over perimeter along circuit of the electrodes) component were at the level of the lower end of the current-leading electrodes.

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DEVELOPMENT OF ELECTRON BEAM MELTING OF TITANIUM IN THE E.O. PATON ELECTRIC WELDING INSTITUTE

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Production of titanium ingots from uncrushed blocks of spongy titanium using method of electron beam melting is described. Values of melting efficiency for 1200 and 850 mm diameter ingots are determined at which depth of the molten pool does not exceed radius of the ingot, that ensures a satisfactory result from the viewpoint of theory of crystallization. High quality of produced ingots of 1100 mm diameter is shown.

Keywords: block of spongy titanium, titanium ingot, electron beam cold hearth melting, electron beam installation, mathematical modeling

Wide use of titanium alloys brings to the foreground production cost of titanium products, including ingots [1]. Significant reduction of price of the ingots is enabled by putting into operation of powerful installations for electron beam cold hearth remelting that produce large-size ingots with application of uncrushed blocks of spongy titanium as initial material [2].

On basis of more than 30-year experience of the E.O. Paton Electric Welding Institute in the field of electron beam welding of metals the State Enterprise «Scientific-Industrial Center «Titan» was established.

At present SE «SIC «Titan» includes a mini-plant which produces ingots of round and rectangular sections (six electron beam installations with annual productivity 3–5 thou t, depending upon the rolled stock) (Figure 1).



Figure 1. EBR workshop

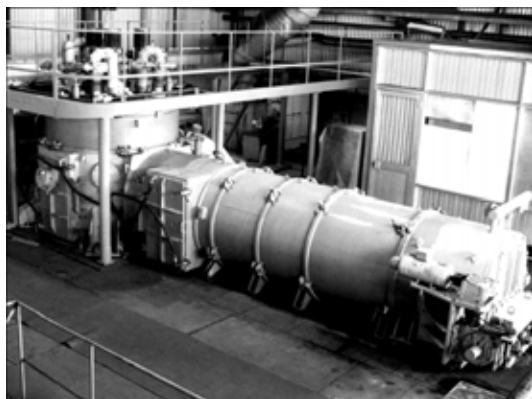


Figure 2. UE5812 electron beam installation

For production of large-size ingots from uncrushed blocks of spongy titanium [3] a «SIC «Titan» operate the UE5810 and UE5812 electron beam installations.

The UE5812 (Figure 2) [4] installation allows producing from blocks of spongy titanium of up to 1 t mass each ingots of up to 850 mm diameter and up to 4500 mm length (Figure 3), and the UE5810 electron beam installation (Figure 4) makes it possible to produce from blocks of up to 4 t mass ingots of up to 1200 mm diameter and up to 4500 mm length (Figure 5).

It is also possible to flash on this installation side surface of ingots (Figure 6) for exclusion of machining.



Figure 3. Flashed ingot of 850 mm diameter

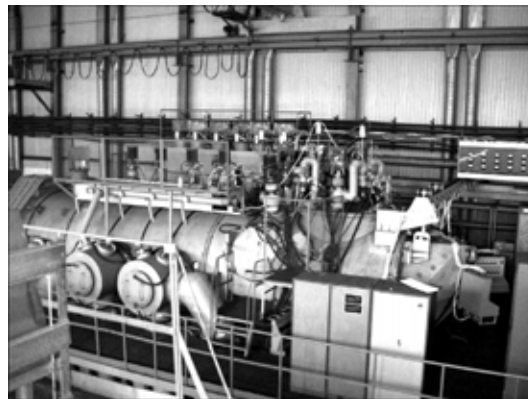


Figure 4. UE5810 electron beam installation



Figure 5. Ingot of 1100 mm diameter

At the same time scale factor exerts significant influence on structure and properties of the metal of ingots. As note nowadays the researchers, for classical process of vacuum-arc melting exist different sizes of the ingots, above which it is impossible to produce ingots of satisfactory quality.

For determining conditions of crystallization of large-size ingots calculations within a framework of the mathematical model of heat transfer in a cylindrical ingot were carried out (Figure 7) [5].

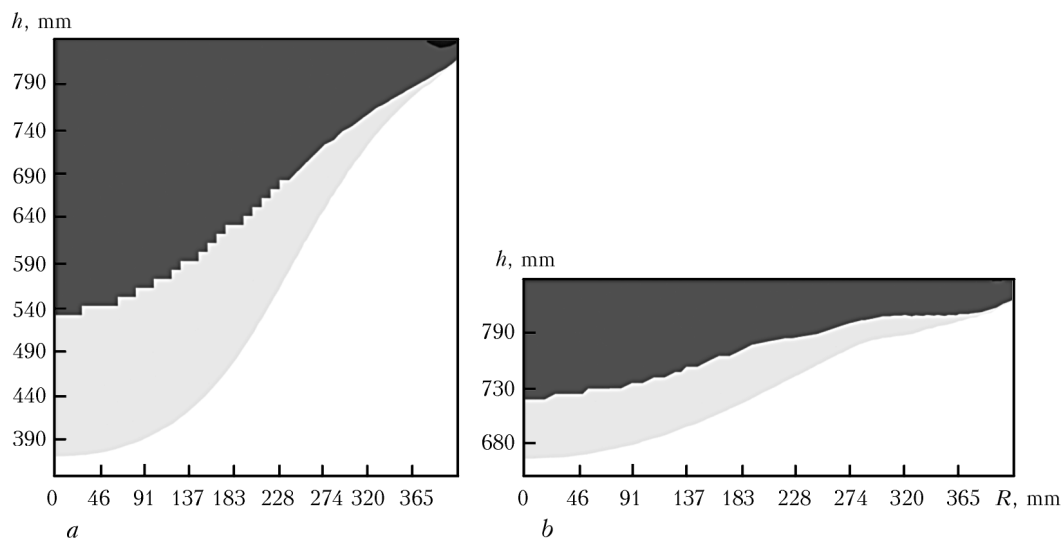


Figure 7. Dependence of molten pool configuration of ingot of 850 mm diameter upon rate of melting, kg/h: *a* — 600; *b* — 400

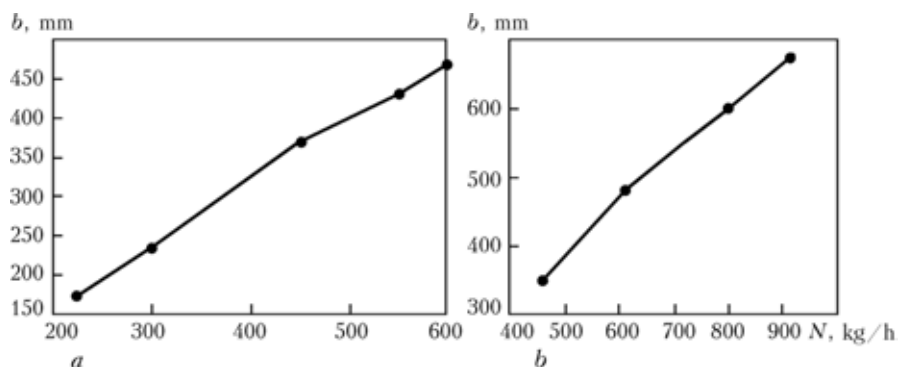


Figure 8. Dependence of molten pool depth upon melting productivity *N*: *a* — ingot of 850 mm diameter; *b* — 1200 mm

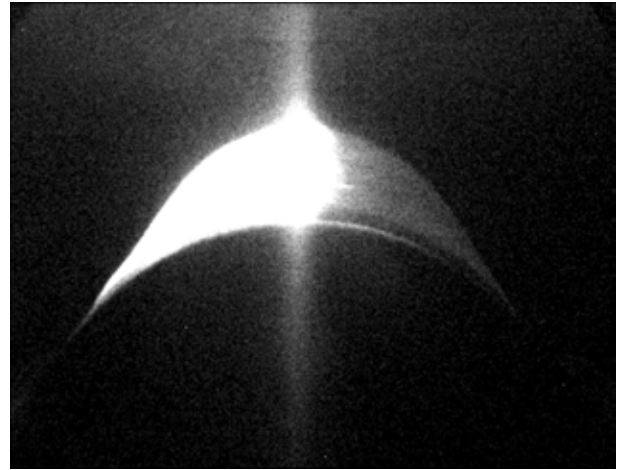


Figure 6. Process of flashing of ingot of 1100 mm diameter

The investigations were carried out by changing rate of melting up to 1000 kg/h. One may see from the drawings that dependence of the molten pool depth is directly proportional to productivity of the process (Figure 8). It was established that depth of the molten pool did not exceed radius of the ingot (which, from the viewpoint of theory of crystallization, is a satisfactory result) at following values of productivity of the melting: for 850 mm diameter — 550 kg/h, 1200 mm diameter — 800 kg/h.

Investigations of chemical composition of ingots of 1100 mm diameter (Figure 9) showed that content

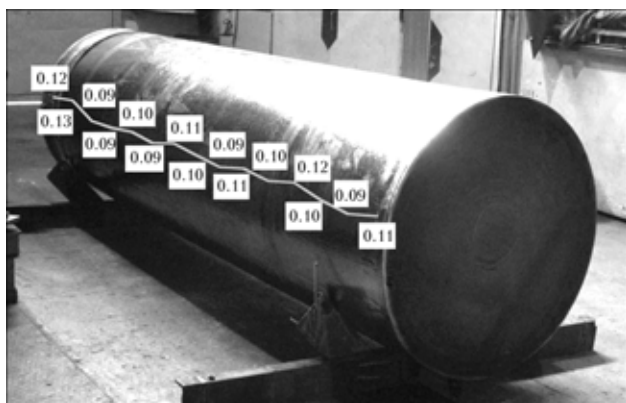


Figure 9. Distribution of oxygen in ingot of 1100 mm diameter



Figure 10. Pipe ingot of 600/400x2000 mm size

of impurities in the ingot corresponded to the ASTM B348-00 standard, whereby the admixtures, despite application as an initial material of single-piece blocks of spongy titanium, were practically uniformly distributed over length of the ingot.

Ultrasonic testing of the ingots showed that echoic discontinuities — shrinkage cavities and pores, structural non-uniformity and inclusions — were absent in them. In addition, absence of a significant structural non-uniformity of the ingot proves correctness of mathematical calculations of technological parameters of melting and stability of its process. Technology of production of hollow ingots was mastered (Figure 10), which allowed excluding operation of piercing in production of a pipe billet and, as a result, reducing losses of the metal and cost of production of seamless pipes [6]. Titanium rings of up to 2000 mm diameter were produced from the pipe billet (Figure 11).



Figure 11. Expanded rings of 1850 and 1415 mm diameter

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2. Paton, B.E., Trigub, N.P., Akhonin, S.V. (2005) Production of titanium ingots from uncrushed spongy titanium blocks. *Ibid.*, **2**, 23–26.

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AUTOMATIC CONTROL OF CURRENT OF GAS-DISCHARGE ELECTRON GUN WITH COLD CATHODE

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Issues of automatic control of current of automatic electron guns on basis of high-voltage glow discharge with cold cathode by change of pressure in the gun at its continuous pump-down and regulated bleeding-in using low-inertia electromagnetic leak are considered. Mathematical model of automatic control of the gas-discharge gun current and its solution on a computer are presented. Influence of the gas-dynamic characteristics of the gas pump-down and bleeding-in systems on process of control is shown, and comparison of calculated and experimental transient characteristics of current control of the gas-discharge electron gun for spraying is made.

Keywords: gas-discharge electron gun, leak, discharge, control system, mathematical model

At present electron guns on basis of high-voltage glow discharge (HVGD) with cold cathode are used for electron beam melting and welding of thin-wall items on ever growing scale. Despite comparatively low specific power in the beam, such guns have a number of advantages in comparison with widely used in the electron beam technologies guns with thermionic emitters. They are characterized by long service life of cold cathode with developed emission surface, may stably operate in atmosphere of different gases within wide range of pressure values, ensure formation of electron beams of different shape, and are relatively simple and reliable in operation. Their application allows simplifying technological equipment [1]. In industry gas-discharge guns are used, having power from several up to hundreds kilowatts. Depending upon their designation they are characterized by design, electron-optic, and energy parameters. Control of current of the gas-discharge guns is performed by change of pressure in area of burning of the discharge using regulated bleeding-in of gas into the gun at continuous pump-down of the latter. Such method of control is stipulated by strong dependence of the gas-discharge gun current upon pressure in the discharge gap [2]. If in process of operation bleeding-in of gas

into the gun is regulated by change of pressure in it and invariable acceleration voltage is maintained, one may control discharge current and therefore power of the beam within the whole working range of the gun [3]. Regulated bleeding-in of gas into the gun is performed using the leaks. For majority of technological processes, in which gas-discharge electron guns (GDEG) are used, automatic control of their parameters with high accuracy and short time of adjustment is required. In separate cases, especially at starting of high-power guns, when frequent arc break-downs are possible, the gas bleeding-in system should ensure operation in the mode of gas pressure stabilization in the gun or in the manual control mode, whereby the leaks, used in systems of the gun current control, should have high stability of parameters and low inductance of the electrically controlled drive.

Physical model of a typical system for automatic current control of GDEG with electromagnetic leak of gas consists of a gas-discharge electron gun 2 with a beam duct 7, a source of high voltage power supply of the gun 3, the gun current sensor 4, an electron regulator 12, a leak of gas with electromagnetic drive 11, a dosing device 9 and a gas chamber 10, a channel for bleeding-in gas 1 that connects the leak with the gun, a vacuum chamber 8, and a vacuum duct 6 that connects the vacuum chamber with the vacuum pump 5 (Figure 1). Sensor of the gun current is a low-impedance resistance, serially connected into low-voltage section of the discharge circuit, or sensor on basis of Hall effect, connected to high-voltage section of the discharge circuit and having high-voltage galvanic isolation. The electromagnetic leak is equipped with an advancing electromagnetic drive which is mechanically rigidly connected with stock of the dosing device and operates in analogue mode. Continuous pump-down of the gun is performed through the beam duct jointly with the vacuum chamber.

In process of the gun operation a signal from the discharge current sensor is fed to the electronic control unit where it is compared with a preset reference

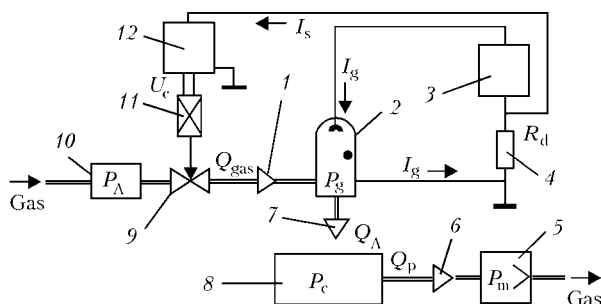


Figure 1. System of automatic current control of GDEG with electromagnetic leak (for designations see the text)



voltage, set depending upon required value of the discharge current, amplified by the PID-amplifier, and sent to winding of the leak electric magnet. Depending upon force of the control signal, the leak directs flow of gas into the gun that is continuously pumped-down, due to which pressure in it is established at such level, at which current of the discharge corresponds to the preset one. Inertance of actuators and gas-dynamic processes of gas pump-down and bleeding-in limit time characteristics of the GDEG current control, whereby significant improvement of characteristics of the gun current control system is achieved by choice of optimum values of parameters of the gas pump-down and bleeding-in systems at the stage of the electron gun, the vacuum installation, and the actuator design. Such task is connected with big volume of experimental investigations. It is significantly simplified due to computer modeling of the GDEG automatic current control systems.

In [3] mathematical model of the electron gun automatic current control system on basis of HVGD is presented, in which an electromagnetic leak with a dosing device is used, made in the form of an axially symmetrically located seat with a flat compacting surface and a hole for flow of gas in the center, and a movable stock with a flat end surface on the side of the seat. This design of the dosing pair is characteristic of the fact that working stroke of the stock is determined by flow capacity of the hole in the seal and limited by position of a stop of the advancing electromagnetic drive of the leak.

In real structures of the electromagnetic leaks with a mentioned dosing pair working stroke of the stock is 0.01–0.02 mm, that's why at change of temperature conditions of the leak because of difference of values of thermal expansion factors of the materials of its structure changes the gap between the stock and the seat of the dosing pair up to closure of the leak. This causes disturbance of operation of the gun current control system both in manual and automatic modes. Besides, characteristic of dependence of the gas flow upon position of the stock in mentioned dosing system has essentially non-linear character in initial area, that complicates the gun current regulation in manual mode.

In this work system of the GDEG automatic current control with the electromagnetic leak is investigated, in which design of the dosing pair is changed, due to which non-linearity of the characteristic of its productivity is reduced and practically influence of temperature conditions of the leak on stability of its operation is absent. It allowed its efficient using both in automatic and in manual modes of the gun current control. Mathematical model of the system of the GDEG automatic current control and its solution on a computer are presented, influence of gas-dynamic characteristics of the gas pump-down and bleeding-in systems on characteristics of control is investigated, influence of dynamic characteristics of the leak electromagnetic drive on process of the gun current control is shown, and comparison of calculated and experimental transient characteristics of the process of automatic current control of the spraying GDEG is made.

Mathematical model of gun current automatic control system. When developing mathematical model, the gun gas-dynamic system with the pump-down system was considered as a system with concentrated parameters, in which volumes of vacuum ducts and gas release from their surfaces and gas flows which did not exert significant influence on dynamics of pressure change in GDEG in process of its operation, i.e. bleeding-in of gas into the gun and vacuum chamber of the technological installation, sorption processes on surface of the gun discharge chamber and vacuum chamber of the installation, etc. were not taken into account. It was assumed that pump-down of the vacuum chamber and the gas-discharge gun is performed by a vacuum pump, rapidity of action of which is to a significant degree constant within a wide range of pressure values, which is characteristic of the most widely used in electron beam installations diffusion, rotational, and other pumps [4].

Mathematical model of the system of the GDEG automatic current control may be presented as a system of differential equations that describe dynamics of the leak drive and dependence of its gas flow capacity upon force of the control signal and conditions of balance of the gas flows in discharge chamber of the gun and vacuum chamber of the electron beam installation, whereby input parameter of the model is the control voltage on the leak U_l and output parameter is the signal from the gun current sensor I_g .

Dynamics of the advancing electromagnetic drive of the leak that operates in analogue mode is described by equation of voltage balance in the electromagnet power supply circuit and condition of equilibrium of forces of its mechanical part, which at minor deviations have the form

$$R_c \Delta i_l + L_c \frac{d\Delta i_l}{dt} = \Delta U_l,$$

$$m_l \frac{d^2 \Delta l_l}{dt^2} = \sum_{i=1}^n \Delta F_i = \Delta F_e - \Delta F_s - \Delta F_f,$$

where R_c , L_c , i_l and U_l are respectively the active resistance, inductivity, current and voltage in winding of the leak electric magnet; m_l is the mass of movable part of the leak; l_l is the coordinate that determines position of the armature with the stock relative the valve seat; F_e is the pulling force of the electromagnet; F_s is the elastic force of the spring; F_f is the force of friction.

$$\Delta F_e = C_e \Delta i_l, \quad \Delta F_s = C_s \Delta l_l,$$

$$\Delta F_f = C_c \frac{dl_l}{dt},$$

where C_e is the slope of the electromagnet pulling characteristic; C_s is the coefficient of rigidity of the spring; C_c is the coefficient of force of friction.

For reduction of influence of temperature conditions on stability of operation of the leak structure of its dosing pair is made in the form a stock 1, on

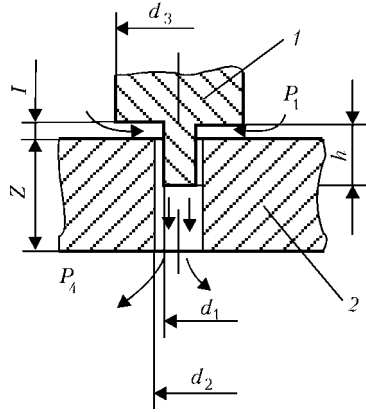


Figure 2. Schematic image of design of dosing pair of leak (for designations see the text)

end surface of which a cylindrical protrusion of smaller diameter is made, and a seat 2 in the form of a hollow cylinder, inside of which protrusion of the stock 2 moves (Figure 2). In close state of the leak the sealing surfaces of the dosing pair are flat surfaces of the stock end and of the hollow cylindrical seat. During displacement of the stock in the process of adjustment flow capacity of the leak S_d is determined by flow capacity of the gaps, formed by surfaces of the seal S_{d1} and cylindrical surfaces of the seat surfaces and the stock protrusion S_{d2} , and flow capacity of cylindrical hole of the seat S_{d3} , which are functions of axial movement of the stock relative seat l_1 . In such structure stroke of the stock at the distance up to several millimeters is ensured, which practically excludes influence of temperature change of the leak on its gas flow capacity.

Expression for determining flow capacity of the leak S_d may be written in the form of a total of serially connected conductivities S_{d1} , S_{d2} , S_{d3} :

$$\frac{1}{S_d} = \frac{1}{S_{d1}} + \frac{1}{S_{d2}} + \frac{1}{S_{d3}}.$$

Flow capacity S_{d1} , formed by flat sealing surfaces of the stock and the seat, may be considered as flow capacity of a rectangular pipeline with section $a_1 \times b_1$ and length c_1 , determined from the following expressions:

$$a_1 = p(d_3 - d_2); \quad b_1 = \frac{h}{2}; \quad c_1 = \frac{d_3 - d_2}{2}.$$

Then, according to [4], gas flow capacity of this area of the vacuum duct for air in a laminar flow will have the form

$$S_{d1} = A_1 \bar{p}_1 l^2,$$

where $A_1 = 5.8 \cdot 10^8 k_1 d_2^2 (d^3 - d^2)^{-1}$; k_1 is the empirical coefficient, value of which depends upon the ratio a_1/b_1 ; p_1 is the mean value of gas pressure in this area of the vacuum duct.

Flow capacity S_{d2} of second area, formed by two cylindrical surfaces of the stock protrusion and a hole in the dosing pair seat, may be also calculated as a

rectangular vacuum duct with section $a_2 \times b_2$ and length c_2 , which are calculated from the ratios

$$a_2 = p(d_2 - d_1); \quad b_2 = \frac{d_2 - d_1}{2}; \quad c_2 = \frac{h - l}{2}.$$

Then gas flow capacity S_{d2} for air in a laminar flow will be determined from equation

$$S_{d2} = \frac{A_2 \bar{p}_2}{h - l},$$

where $A_2 = 488 k_2 p^2 (d_2 - d_1)^2$; k_2 is the empirical coefficient, value of which depends upon the ratio a/b_1 ; $\bar{p}_2$ is the mean value of pressure in area of the vacuum duct with gas flow capacity S_{d2} .

Flow capacity S_{d3} , formed by a cylindrical hole in the dosing pair seat with diameter $d_s = d_2$ and $H_s = z - h - l$, is determined according to formula

$$S_{d3} = \frac{a_3 \bar{p}_3}{z - h - l},$$

where $A_3 = 1360 d_2^4$ (for air); $\bar{p}_3$ is the mean value of pressure in area of the vacuum duct with gas flow capacity S_{d3} .

Then general capacity of dosing pair of the leak will be determined by the expression

$$S_d = p_1 l^2 + \frac{A_2 p_2}{h l} + \frac{A_3 p_3}{z - h - l}.$$

Flow capacity of gas channel S_c , located between the leak and the gun, is significantly higher than flow capacity of the leak S_d and when calculating total flow capacity of the channel for bleeding-in gas into the gun S_g it may be neglected. Transport lag of gas, stipulated by movement of gas molecules over the channel from the leak to the gun, exerts significant influence on characteristics of regulation. Without taking into account effect of blurring of the gas flow fronts in the pipeline, the channel for bleeding-in gas may be considered as a link with a net time delay τ_d in circuit of regulation. Then expression for total flow capacity of the gas channel, taking into account time delay, will have the form

$$S_g(t) = \left(p_1 l^2 + \frac{A_2 p_2}{h l} + \frac{A_3 p_3}{z - h - l} \right) (t - \tau_d).$$

Model of gas-dynamic system of the gun with a pump-down system may be presented in the form of a system of differential equations which describe conditions of balance of gas flows in the gun discharge chamber and vacuum chamber of the electron beam installation. Main flows, which determine pressure in discharge chamber of the gun, are a regulated gas flow Q_{gas} that is fed into GDEG through the leak and the vacuum duct that connects the leaks with the discharge chamber of the gun, and gas flow, pumped down from the gun through the beam duct Q_b . Equation of balance of the gas flows in the GDEG discharge chamber may be written in the form



$$V_g \frac{dp_g}{dt} = Q_{\text{gas}} - Q_b,$$

where V_g is volume of the gun discharge chamber; p_g is the gas pressure in the gun.

Regulated gas flow Q_{gas} is determined by flow capacity S_g and difference of pressures in the leak p_A and the gun p_g :

$$Q_{\text{gas}} = S_g (p_A - p_g).$$

Flow of the gas, pumped-down from the gun through the beam duct Q_b , is determined by flow capacity of the beam duct and difference of pressures in the gun and the vacuum chamber of the electron beam installation.

$$Q_b = S_b (p_g - p_c),$$

where S_b is the flow capacity of the beam duct; p_c is the pressure in vacuum chamber of the electron beam installation.

Main flows that determine pressure in vacuum chamber of the electron beam installation in GDEG are flow of the gas, which is fed from the gun into the vacuum chamber Q_b , and flow of the gas, pumped down from the vacuum chamber by the vacuum pump Q_0 . Equation of balance of the gas flows in vacuum chamber of the electron beam installation may be written in the form

$$V_c \frac{dp_c}{dt} = Q_b - Q_p,$$

where V_c is the vacuum chamber volume.

Flow of the gas, pumped down from the vacuum chamber, is proportional to rate of the chamber pump-down S_p and pressure in it p_c , $Q_p = S_p p_c$.

Rapidity of the chamber pump-down is determined by rapidity of action of the vacuum pump S_p and flow capacity of the vacuum duct S_v that connects the vacuum chamber and the vacuum pump

$$\frac{1}{S_p} = \frac{1}{S_p} + \frac{1}{S_v}.$$

Flow capacity S_v is determined by geometry of the vacuum duct, depends upon pressure in the vacuum duct, and may be calculated using equations of the discharged gas dynamics.

Rapidity of the vacuum pump action, according to [4], is determined by formula

$$S_p = S_c \left(1 - \frac{p_m}{p_c} \right),$$

where S_c and p_m are the calculated rapidity of the pump action and the limit pressure in the pump (parameters, which are given by the manufacturer-plant in technical certificate of the pump).

Then expression for determination of flow of pumped down gas from the vacuum chamber will have form

$$Q_p = \frac{1}{\frac{1}{S_v} + \frac{1}{S_c}} \left(1 - \frac{p_m}{p_c} \right) p_c = \frac{S_v S_c}{S_v + S_c} (p_c - p_m).$$

Dependence of the gun current upon pressure is described by empiric ratio

$$I_g = a p_g^m U_g^n, \quad (1)$$

where a , m , n are the constants, depending upon kind of the gas, material of the cathode and geometry of the electrodes, whereby m may vary within 2–4.

Output parameters of the control object is voltage of the feedback signal U_{fb} fed to the electron regulator from the gun current sensor:

$$U_{fb} = K_s I_g.$$

Mathematical model for GDEG as the object, in which discharge current is stabilized by means of pressure change in the discharge gap using automatically controlled electromagnetic leak, may be written as

$$\begin{cases} R_1 i_1 + L_c \frac{di_1}{dt} = U_1, \\ m_1 \frac{d^2 l_1}{dt^2} = C_e i - C_g l_1 \quad C_c \frac{dl_1}{dt}, \\ S_g(t) = \left(p_1 l^2 + \frac{A_2 p_2}{hl} + \frac{A_3 p_3}{(z-h-l)} \right) (t - \tau_d), \\ V_g \frac{dp_g}{dt} = S_g(p_A - p_g) - S_b(p_g - p_c), \\ V_c \frac{dp_c}{dt} = S_b(p_g - p_c) - \frac{S_v S_c}{S_v + S_c} (p_c - p_m), \\ I_g = a p_g^m U^n; \quad U_{fb} = k_d I_g. \end{cases} \quad (2)$$

Obtained system of equations is non-linear one. For its solution a program was developed that allows modeling dynamics of a separately taken object or an object in composition of a close system and takes into account influence of non-linearity and delay in the gas bleeding-in channel. In the close system the PID-regulator with a transfer function was used

$$W_{tr}(p) = k_{tr} \left(1 + \frac{1}{T_{pr} p} + T_{pred} p \right),$$

where k_{tr} is the transfer coefficient of the regulator; T_{pr} is the time of the proportional-plus-integral element; T_{pred} is the time of prediction.

Numeric solution of mathematical model of the gun automatic current control system. Solution of the system of equations in non-linear form was performed on a computer using Euler method [5, 6]. For implementation of the Euler method system of differential equations

$$\frac{dY(t)}{dt} = F(t, Y)$$

was presented in the following form:

$$\frac{Y_{n+1} - Y_n}{\tau} - F(t_n, Y_n) = 0,$$

where n is the number of the step of solution; t is the step in time; Y is the vector of solution of the system; F is the function of time of current state of the investigation object.

According to this the system of equations (2) has at transition to the finite-difference equations, without taking into account change of the integration step in time, the following form:



$$\begin{cases}
i_g^n = f(p_g^{n-1}, U_g); \\
i_l^{n+1} = i_l^n + \frac{U_l - R_y i_l^n}{L_c} \tau; \\
l_l^{n+1} = l_l^n + \tau y; \\
y^{n+1} = y + \left[\frac{c_e}{m_l} i_l^n - \frac{c_g}{m_l} l_l^n - \frac{c_c}{m_l} y^n \right] \tau; \\
S_d^n = C_l l_l^n; \\
p_g^{n+1} = p_g^n + \frac{S_d^{n+1} p_A^{n-Z} S_b (p_g^n - p_c^n)}{V_g} \tau; \\
p_c^{n+1} = p_c^n + \frac{S_b (p_g^{n+1} - p_c^n) - \frac{S_v S_p}{S_v + S_p} (p_c^n - p_m)}{V_c} \tau;
\end{cases}$$

where $y = \frac{dl_l}{dt}$; Z is the delay in number of steps t in time. Upper indexes of the variables indicate the number of the step in time.

In the program possibility of change of coefficients of the system of equations in process of fulfillment of the programs and modification of non-linearities, which enter into these equations, by means of change of respective subprograms-functions is envisaged.

For determining flow capacity of dosing pair of the leak S_d , which was conditionally divided by us into three characteristic areas, approximate methods of calculation were used, because in case of laminar flow of gases into formulas of calculation of flow capacity of each area of the vacuum duct mean value of gas pressure in this area was included, which, in its turn, depended upon flow capacity of the latter.

For determining gas pressure in the singled out areas of the vacuum duct, created by dosing pair of the leak, they were divided into bigger number of pressure increments dp . Values dp depend upon difference of pressures at inlet and outlet of the vacuum duct and number of increments dp . The higher is number of increments, the more accurate is obtained result; however, in this cases increases volume of calculations and time necessary for the calculation. In our case the number of calculations $kd = 50$. Proceeding from the fact that calculated vacuum duct was conditionally divided into three characteristic areas, mean value in each of them was determined as follows:

$$\bar{p}_1 = \frac{p_1 + p_2}{2}; \quad \bar{p}_2 = \frac{p_2 + p_3}{2}; \quad \bar{p}_3 = \frac{p_3 + p_4}{2},$$

where $p_1 = p_{in}$ and $p_4 = p_{out}$ are the levels of gas pressure respectively at inlet and outlet of the leak, values of which are known; p_2, p_3 are the gas pressures at boundary of conditional division of the vacuum duct areas, values of which are unknown. Pressure values p_2 and p_3 were determined in each cycle: $p_2 = p_1 - sdp$, where s is the counter of a cycle and for first iteration $s = 1$; $p_3 = p_1 - zdp$, where z is also the counter of the cycle $z = s + 1$. Pressure values, with which condition of continuity of flow is fulfilled with highest authenticity, were assumed valid. For this purpose in the program a certain value ek was calculated that characterized error of calculation of the true pressure and the flow capacity values. Mathematically it looks as follows:

$$\begin{aligned}
ek = & ((p_1 - p_2)S_{d1} - (p_2 - p_3)S_{d2})^2 + \\
& + (p_2 - p_3)S_{d2} - (p_3 - p_4)S_{d3})^2.
\end{aligned}$$

In this expression difference of flows in first and second and in second and third vacuum ducts is calculated. Values, for which ek is the smallest, are assumed valid. Differences of flows were squared in order to avoid situation at which appearance of big negative values ek and, respectively, significant increase of the calculation error would be possible.

The developed program allows bringing result of solution of the system of equations on screen of a computer in the form of a graph of the transient characteristic and superimposing versions of solution in the selected system of coordinates. Graphs or series thereof are stored in the form of separate files which allows comparing on screen of a computer versions of solutions and optimizing parameters of the gun automatic current control system.

Analysis of the process of the gun automatic current control on a computer. Purpose of the modeling consisted in investigation of influence of parameters of the control channel elements and links on transient characteristics of the GDEG current control process and choice of values of coefficients of the system movement equations and parameters of the electron regulator adjustment, ensuring required characteristics of control.

Values of coefficients of movement equations were selected for conditions of operation of the automatic current control system with GDEG of up to 7 kW power, installed on the URM027 commercial vacuum installation for spraying thin films. Values of the pre-set coefficients were determined from the equipment certificates, and of unknown ones --- by calculation.

Calculation of the coefficients was performed as follows. From family of the gun volt-ampere characteristics $I_g = f(U_g, p_g)$ the required mode of the gun operation was selected $I_g = 0.4$ A, $U_g = 10$ kV, and pressure in the gun for the given mode of operation $p_g = 1.3$ Pa was determined. Constant coefficients a and m from dependence (1) for this mode of the gun operation were calculated using method of least squares. Then conditions of gas flow through beam duct of the gun and the vacuum duct, connecting the vacuum chamber with the vacuum pump, and values of flow capacities S_b and S_v were determined. For the assigned design of the leak dosing unit flow capacity S_d was established.

Initial values of constant coefficients $R_l, L_c, m_l, C_e, C_l, C_c$, which characterize dynamics of the leak, were determined using formulas for calculation of dynamic characteristics of electromagnet mechanisms, presented in [7] and other works, and then in process of modeling they were corrected for obtaining necessary form of the transient control characteristic.

Selected analogue mode of the leak operation was ensured by matching slope of the electromagnet pull characteristic and rigidity of the spring in working area of the leak.

Influence of parameters of the system elements and links on characteristics of control was determined by response of the system to the stepwise input action



at different values of coefficients of the equations. Investigations were carried out at close circuit of regulation with the PID-regulator.

In Figure 3 transient characteristics of the process of the gun current automatic control at time of its switching at different values of the leak parameters are presented.

By means of reduction of the coil inductance L_c , mass of the electromagnet armature m_l (Figure 3, *a*, *b*), increase of the spring rigidity C_s , and slope of the electromagnet pulling characteristic C_e rate of the control system response to a disturbance action was increased. When developing mechanical part of the leak, it is very important to correctly select ratio of the parameters m_l , C_e , C_s , C_c . Increase of the armature mass up to a certain value transfers the electromagnet into the mode of self-oscillation (Figure 3, *b*), i.e. in this case mass of a movable part of the leak m_l is the factor which builds up oscillations, while coefficient of force of friction C_c is a useful damping factor that quiets oscillations.

It was also established that by means of reduction of the gun gas-discharge chamber volume V_g and increase of gas flow capacity of the beam duct S_b (Figure 3, *c*) time constant of gas bleeding-in and pump-down from the gun reduces, which improves dynamic characteristics of regulation. However, by means of increase of the flow capacity S_b , consumption of working gas in the gun and pressure in vacuum chamber of the electron beam installation p_c increase at the assigned mode of the gun operation. Reduction of flow capacity of the vacuum duct between the vacuum chamber and the vacuum pump exerts damping action on process of regulation, however in this case reduces rapidity of pump-down of the installation vacuum chamber. Sharp worsening of the system stability and quality of regulation causes increase of the lag time τ_d in the gas bleeding-in channel that connects the leak with the gun (Figure 3, *d*). Influence of the lag on quality of regulation increases by means of reduction of the volume V_g and the flow capacity S_b .

As a result of the carried out on a personal computer modeling it was established that in case of application of a low-inertia electromagnetic leak, characteristics of the GDEG current control process are determined by gas-dynamic characteristics of the gun and gas pump-down and bleeding-in systems, whereby minimum time of regulation may constitute dozens and hundreds milliseconds.

Experimental investigation of the gun current automatic control system. On basis of results of the investigations automatic current control system of a spraying GDEG with a low-inertia electromagnetic leak was developed. Experimental investigation of the leak characteristics and transient characteristics of the automatic current control system of a spraying gun under real conditions was carried out, which allowed carrying out verification of the modeling results with obtained experimental data.

It was established that graphs of dependence of the flow capacity of the leak upon position of the dosing pair stock, obtained experimentally and from calculations (Figure 4), do not have significantly non-

linear areas. Insignificant discrepancy of the curves is explained by errors in determination of gas pressure in the areas of gas channel of the leak dosing pair and empiric values of coefficient k that depends upon ratio of characteristic geometric sizes of the vacuum duct and influence of elastic deformation of the sealant from plastic floor, not taken into account during de-

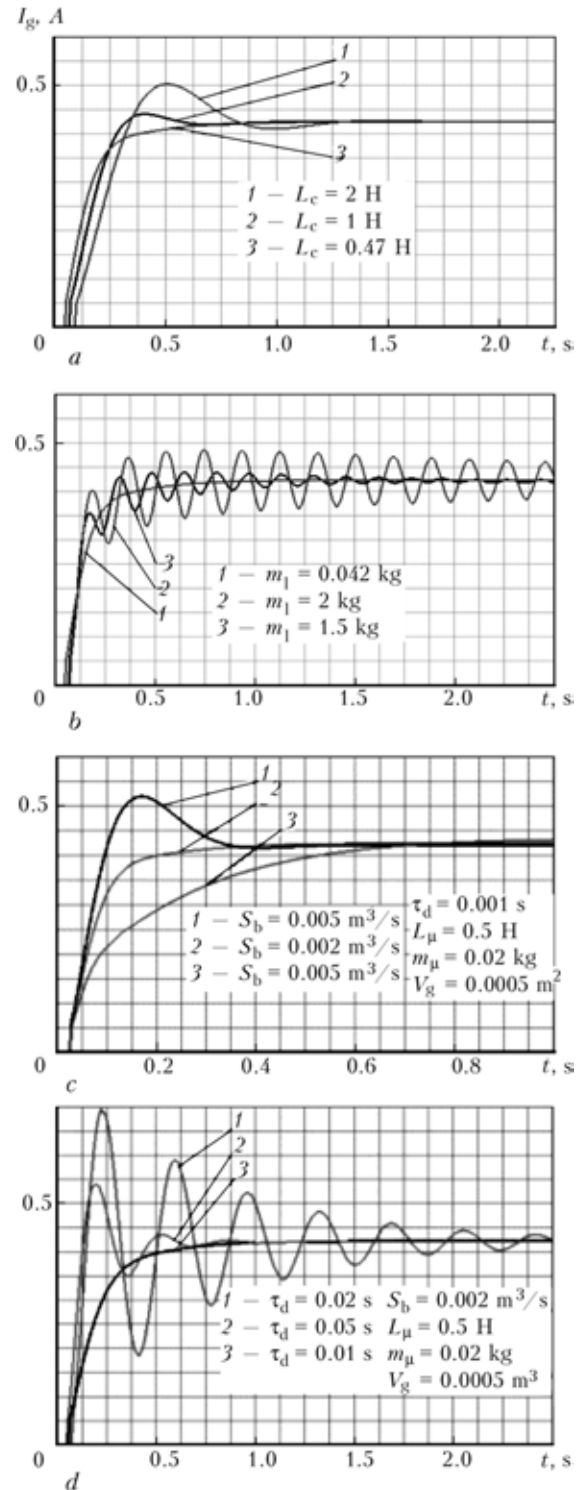


Figure 3. Calculated transient characteristics that illustrate influence of parameters of gas-dynamic system of gun on transient characteristics of adjustment: *a* — inductance of electromagnet coil of leak L_c ; *b* — mass of electromagnet armature of leak m_l ; *c* — gas flow capacity of beam duct S_b ; *d* — delay time τ_d in gas bleeding-in channel

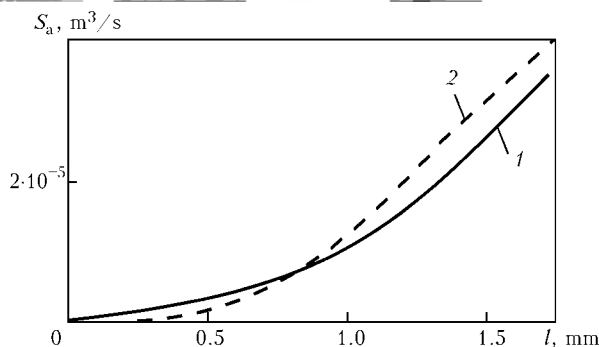


Figure 4. Dependence of flow capacity of dosing unit of leak upon stock stroke: 1 — calculation; 2 — experiment

velopment of the mathematical model and exerting significant influence in initial area of the curves. In addition, in the developed leak the main static parameters practically do not depend upon change of its temperature which allows efficient using of the leak as an actuator in the GDEG current control systems in automatic and manual modes of operation.

In Figure 5 experimental transient characteristics of the automatic current control process of a spraying GDEG at time of its switching at different values of flow capacity of beam duct of the gun, through which pump-down of the latter is performed, are presented. In case of optimization of the leak parameters for operation with a spraying gun, flow capacity of the beam duct in which constituted $0.002 \text{ m}^3/\text{h}$, time of achievement by the gun of optimum mode constituted approximately 300 ms at aperiodic character of the transient process. In case of reduction of the beam duct flow capacity down to $0.0005 \text{ m}^3/\text{s}$, which ensures more efficient isolation of the gun and the technological chamber in regard to pressure, transient characteristic of the gun current control process had oscillation character with attenuation, whereby re-adjustment equaled not more than 25 % and time of regulation — about 500 ms. Increase of the transient characteristic aperiodicity in this case, other parameters being invariable, was achieved experimentally by selection of optimal values of integral and differential components of the electron regulator transfer characteristic, whereby attempt to reduce time of achievement by the gun of operation mode failed. Necessary aperiodicity of transient characteristic of the gun current control process and short time of regulation were achieved by selection through calculation and subsequent experimental operational development of optimal values of the leak parameters and gas-dynamic characteristics of the gun and the pump-down system.

Comparison of the experimental transient characteristics with the calculated ones (Figure 3, c, Figure 5) showed that their difference in regard to level of re-adjustment and time of achievement of the working mode constitutes 15–20 %, which is explained by influence of errors in determining of gas-dynamic characteristics of the gas pump-down and bleeding-in system, parameters of the electromagnetic leak, etc.

CONCLUSIONS

1. It was shown that suggested mathematical model of the process of gas-dynamic gun current control and

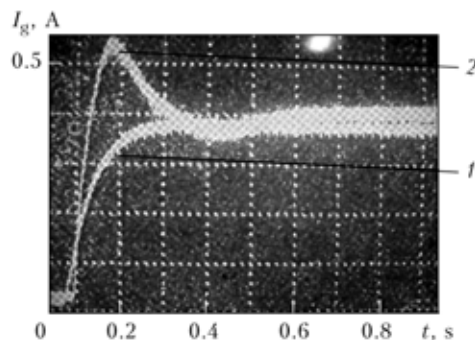


Figure 5. Oscillograms of transient characteristics of process of automatic current control of spraying GDEG at S_b , m^3/s : 1 — 0.002; 2 — 0.005

implementation of its solution on a personal computer allow using computer modeling in designing of automatic systems of current control of GDEG with cold cathode and other gas-discharge sources of charged particles operating under conditions of continuous pump-down of gas.

2. It was established that transient characteristics, obtained in calculation and experimental ways, correlate well, and this confirms correctness of this model of the process of automatic GDEG current control using gas-dynamic method.

3. It was determined that minimum time of regulation of the gas-discharge gun current by means of pressure change in the discharge gap, limited by inertance of gas-dynamic processes in the gun and gas pump-down and bleeding-in systems, may constitute in real systems dozens and hundreds of milliseconds, which allows efficient controlling current of guns and performing programmed control of the electron beam power in time according to requirements of a specific technological process.

4. Using computer modeling low-inertia electromagnetic leaks and systems of automatic discharge current control by means of change of pressure were developed, which ensure efficient work of GDEG of different designation under conditions of carried out technological processes, whereby minimum time of the current adjustment depends upon gas-dynamic characteristics of the gun and the vacuum installation and constitutes hundreds of milliseconds, and error of the adjustment does not exceed 2–3 %.

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CONDENSATION EROSION-RESISTANT COATINGS ON BASIS OF BORON CARBIDE

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Feasibility of using commercially produced boron carbide for production of erosion-resistant coatings by method of electron beam evaporation in vacuum is demonstrated. Results of investigation of chemical composition of the material on basis of boron carbide, structures and some properties of erosion-resistant B₄C-base coatings, deposited from vapor phase, are presented.

Keywords: *electron beam deposition, boron carbide, erosion-resistant coatings, structure*

Good prospects of using boron carbide as a material of erosion-resistant coatings for protection of parts of state-of-the-art machinery are stipulated by its high hardness, high-temperature strength, chemical inactivity and low density (2.52 g/cm³) in combination with high abrasive wear resistance [1]. In [1] possibilities of using method of electron beam evaporation and condensation in vacuum for deposition of the erosion-resistant coatings on basis of boron carbide are shown.

Goal of this work consisted in investigation of influence of chemical composition of evaporated materials on structure and properties of deposited coatings and investigation of chemical composition of boron carbide (ingots being evaporated) of different producers, residues of ingots (pools) after evaporation of these materials in vacuum, structure, chemical composition, and properties of the produced coatings.

Initial materials were powders of boron carbide, produced at Zaporozhie Abrasive Plant (ZAP), Donetsk Plant of Chemical Reactives (DPCR) and the «Starck» company (Germany).

The coatings were produced by method of direct electron beam evaporation in vacuum of boron carbide pellets and deposition of the vapor flow on a stationary substrate. For this purpose pellets of the B₄C boron carbide of 35 mm diameter were used, produced by cold (DPCR and «Starck») and hot (ZAP) pressing. In first case initial powder of boron carbide was compacted into a pellet in a mould of a respective size at room temperature, in second case process of compacting of the powder was performed at about 1700 °C in atmosphere of inert gas. Electron beam evaporation of the B₄C pellet was performed from surface of a copper water-cooled stock of 70 mm diameter. Substrates of 20.0 × 14.0 × 2.4 mm size were made from steel of the following chemical composition, wt. %: 24 Ni, 14.9 Cr, 2.4 Ti, 1 Mo; Fe — the rest. Roughness of surface of the substrates R_a equaled 1.8–2.2 μm. Blocks of substrates of 90 × 14 mm size (specimens)

were fixed in an immovable fixture and installed above evaporators at the distance 300 mm. Temperature of the specimens in process of the coating deposition was 480–540 °C, rate of condensation — approximately 1 μm/min, thickness of the boron carbide coating — 14–18 μm.

For better adhesion of the coating to a steel, substrate surface of the latter was preliminarily treated by ions of argon [1]. For the purpose of matching temperature coefficients of linear expansion of the steel and the substrates on surface of the latter a binding layer of titanium of 5–8 μm thickness was applied by means of the titanium ingot evaporation, using method of electron beam remelting from copper water-cooled crucible of 50 mm diameter.

Structure and chemical composition of the materials were investigated using the CamScan 4D scanning electron microscope in the mode of secondary and elastically repelled electrons, the INCA-200 Energy energy-dispersion system of X-ray spectral microanalysis, and the Philips X-ray-fluorescent analyzer «X'Unique II». Microhardness of the coatings in cross section and on surface was measured using attachment of the Duromat 4000E microhardness gauge to the Polyvar Met optical microscope at loads from 0.2 to 2.0 N. Adhesion tests were carried out by means of bending the specimens with application of a three-point scheme of loading according to the methodology, presented in [1].

Kinetics of oxidation of the materials was investigated in atmosphere using the «Perkin Elmer» high-sensitivity (up to 0.1 μg) thermogravimetric analyzer TGA7 at rate of heating/cooling 10 °C/min within the range of 20–1000 °C. Spoon for loading of the specimen was made from platinum. Temperature was determined using chromel-aluminium thermocouple, preliminarily calibrated by ferromagnetic transition by two Curie points. Calibration of weighs was performed using standard specimen of 100 mg mass. The instrument was controlled by means of a computer and specialized software, whereby it was possible to record process of oxidation and processing of graphic data.

Content of main components and impurities in pellets of boron carbide of different producers

Producer	Weight share of elements, %										
	B	C	Fe	Si	Ti	Ca	Mg	Al	S	W	O
DPCR	69.3	29.2	0.50	0.15	0.29	0.15	0.10	0.08	0.10	–	+
ZAP	64.2	32.7	0.13	0.63	0.57	–	–	0.05	–	1.33	+
«Starck»	69.2	30.5	0.14	0.20	0.03	0.03	–	0.04	–	–	+

Note. Sign + shows presence of oxygen.

A fragment of the B_4C pellet of hot extrusion, the B_4C powders of 40–50 and $\leq 1 \mu m$ dispersity, a separated from the substrate B_4C coating (condensate) of 15 μm thickness, and graphite of the MG1 grade were used as the specimens. The investigated specimen of up to 50 mg mass was placed into the platinum spoon, heated up to 150 °C at rate 10 °C/min, and soaked within 30 min for removal of moisture. Kinetics of

oxidation of the specimens was studied in the process of further uniform heating up to 900 °C.

Erosion resistance of the coatings was assessed in abrasive wear tests in a flow of solid particles using the TsUK-3M installation according to the methodology, presented in [2], by comparison of loss of their mass by means of wear of the standard specimens. Quartz sand (size of the grains was 100–300 μm , speed of flow of the abrasive particles equaled 30 m/s) was used as the abrasive. Diameter of flow of the abrasive particles was 3.5 mm, its flow rate equaled 500 g/min; inspection and weighing of the specimens were performed after consumption of 1–2 kg of the abrasive. Amount of the abrasive, used in one cycle of tests, equaled 26 kg. Abrasive test with application of quartz sand was performed at angle of attack $\alpha = 90^\circ$.

Concentrations of chemical elements were determined in analysis of local areas of the microsection surface, made on spalling of the B_4C pellet, using the INCA-200 ENERGY X-ray spectral analyzer. Chemical composition of material of the pellets (boron, carbon, impurities) from every producer of the powder was different (Table).

Stoichiometric composition of the B_4C boron carbide constitutes 78.26 % B and 21.74 % C. It is evident that in initial pellets in addition to carbide also free carbon (up to 8 %) is contained.

In Figure 1, *a* characteristic microstructure of the boron carbide coating in cross section is shown. Results of the investigations prove uniform distribution of chemical elements over thickness of the coating (Figure 1, *b*). Mean concentration of boron and carbon in all investigated coatings was as follows, wt. %: 69.5–70.3 B, 29.1–30.3 C. In the coatings also impurities of a number of elements were discovered (from 0.3 to 0.8 %), mainly of iron, titanium, silicon and oxygen.

Investigations of surfaces of the pellets (solidified pools) after evaporation allowed establishing presence of separate local zones, containing 97–100 % of graphite.

In Figure 2 diagram of boron–carbon state is presented with singled out on it range of the concentrations (it is shown by arrows), corresponding to chemical composition of the investigated powders on basis of boron carbide. Composition of powders (pellets) of boron carbide and produced coatings correspond to the area B_4C + carbide of the diagram boron–carbon, i.e. they contain non-equilibrium boron carbide and free carbon. Presented results prove that concen-

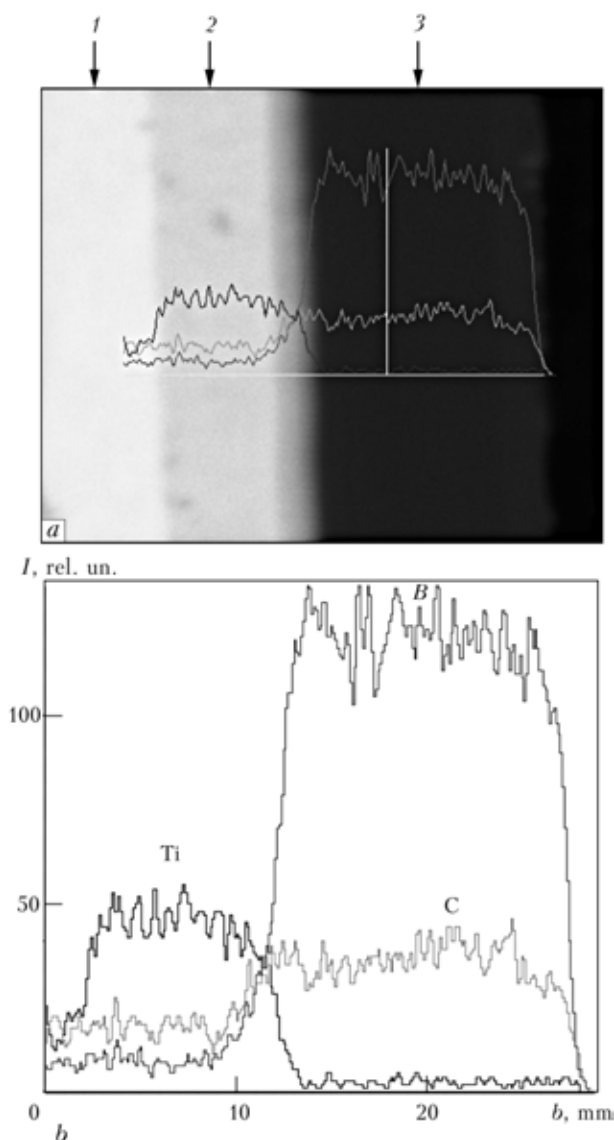


Figure 1. Microstructure of coating on basis of boron carbide (*a* — $\times 3500$) and distribution of chemical elements over thickness *b* of coating (*b*): 1 — substrate; 2 — binding titanium layer; 3 — coating on basis of boron carbide; *I* — intensity of signal

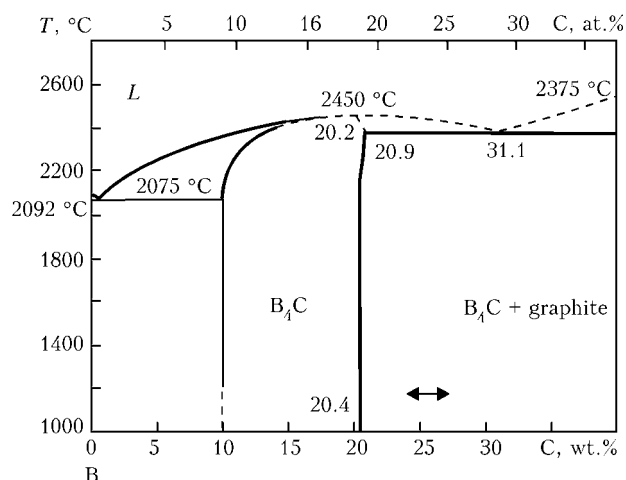


Figure 2. Boron-carbon constitutional diagram with singled out (by arrows) range of compositions of investigated materials on basis of boron carbide

tration of boron and carbon in the coatings are practically close to their content in material of the pellets being evaporated. This proves possibility of variation of composition of the coatings of the boron-carbon system by change of composition of the initial materials, which, in its turn, allows controlling service characteristics of the produced coatings (hardness, erosion resistance and fracture toughness).

Adhesion tests showed that B_4C -base coatings, produced within condensation temperature range 480–540 °C at bending of the specimens at 38–45° do not laminate, just their cracking was registered; further increase of bend angle of the specimens with the coating caused their failure. First cracks in the coating, located perpendicular to longitudinal axis of the specimen and caused by deformation of the substrate surface layer, were visually detected at bend angles 3–4°. The results obtained qualitatively prove satisfactory adhesion of the coatings to steel substrates with transient layer of titanium.

Microhardness of coatings in cross section, deposited at $T_s \approx 500$ °C and load on the indenter $P = 0.5$ N, was $HV = 26$ –28 GPa.

Fracture toughness of the coatings at load on the indenter from 0.5 to 2.0 N was determined according to the methodology, consisting in obtaining of a set of imprints of a diamond pyramid at different loads with assessment of quantity and character of occurring in this case cracks and other defects. The measurements were carried out on surface of the coatings ($T_s \approx 500$ °C), produced from powders of DPCR, ZAP and the «Starck» company. Characteristic peculiarity of the coatings was absence of cracks around imprints of the indenter at mentioned loads. Mean values of microhardness of the coatings at loads 0.5, 1.0, 1.5 and 2.0 N constituted respectively 31.5; 30.0, 29.0 and 27.0 GPa. Chemical composition in regard to boron and carbon was practically the same, wt.%: 69.5–70.3 B and 29.1–30.3 C. In Figure 3 obtained dependence of microhardness of the coatings on basis of boron carbide upon substrate temperature within the range of 370–670 °C is shown.

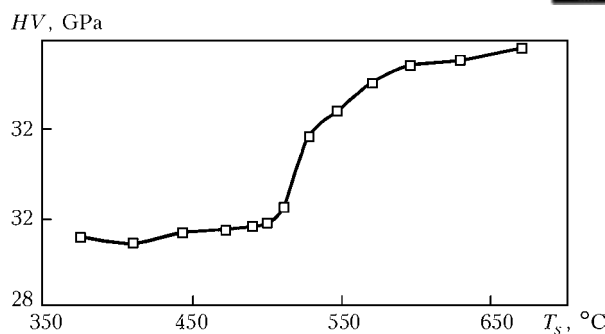


Figure 3. Dependence of microhardness of coating on basis of boron carbide upon temperature of substrate ($P = 0.5$ N)

Fine structure of the coating in the plane, parallel to its surface, was investigated using method of translucent electron microscopy on the Hitachi microscope H-800 at acceleration voltage 200 kV. Preparation of the specimens was performed according to standard methodology with application of instruments Polyfinn (England), Gatan-656 (USA), Microslice-4 (England) and Ion Tech (England).

Surface (Figure 4, *a*) and translucent (Figure 4, *b*) structures of the coating on basis of boron carbide are presented. The translucent structure represents high-dispersion chaotically oriented crystals. Because of small size of the coherent dissipation areas (3–5 nm), the electron diffraction pattern, obtained from them in the diffraction mode, had significantly blurred rings (Figure 4, *c*), which confirmed nanosize structure of the coating. Blurring of the rings on the radiograms complicates identification of phases in the coating, and strong background on the electron diffraction patterns proves presence of amorphous phases of boron carbide and carbon.

So, at non-equilibrium condensation of vapor phase of boron carbide and substrate temperature $T_s = 480$ –540 °C a nanostructural coating is formed.

In Figure 5 data on kinetics of oxidation (M/M_0 is the ratio of the specimen mass after oxidation to mass of the initial specimen) of the investigated materials are presented. Process of boron carbide oxidation starts within temperature range 600–700 °C, whereby boron carbide of hot extrusion is oxidized with the least intensity (Figure 5, curve 1), which is stipulated by its high density and minimum specific surface. Ultradispersed powder of boron carbide (the «Starck» company, Figure 5, curve 4) is most of all subjected to oxidation because of its high specific surface, presence of free carbon, and, probably, defective structure. Bend on the curve of its oxidation at 700 °C is consequence of two competing processes: oxidation of boron and intensive at this temperature process of oxidation of carbon.

Kinetics of oxidation of coatings on basis of boron carbide was investigated on flaked from the substrate condensates. These condensates (Figure 5, curve 3) are in regard to high-temperature strength inferior to boron carbide of hot extrusion, approaching powder of boron carbide with dispersity of the particles about 40–50 μm (Figure 5, curve 2), and start to oxidize at temperature about 600 °C.

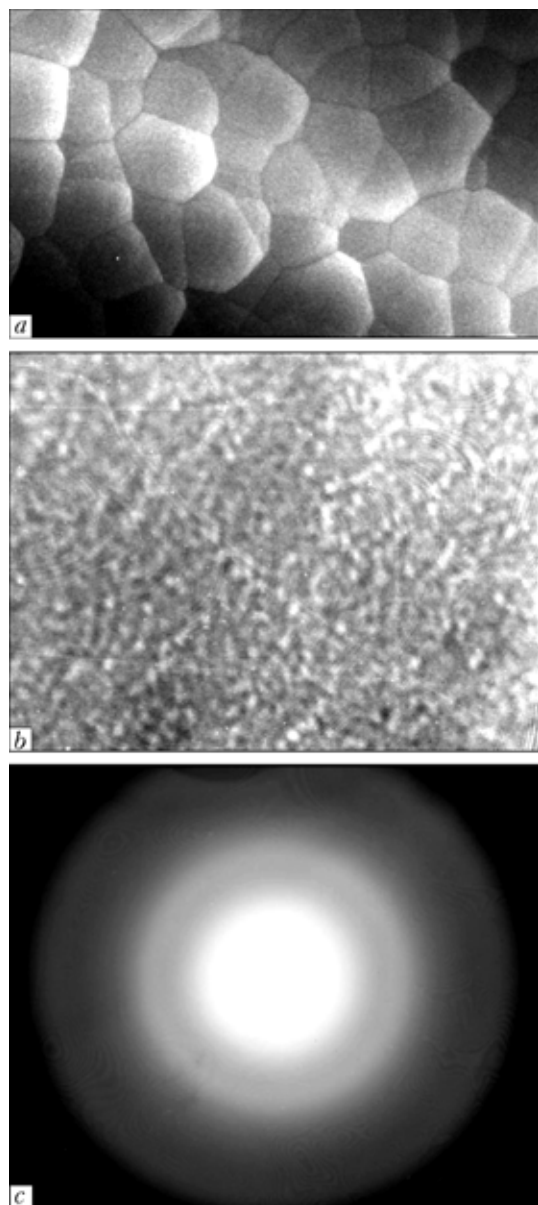


Figure 4. Structure of surface of coating on basis of boron carbide (*a* — $\times 100,000$), electron-microscopic image of fine structure (*b* — $\times 2,000,000$), and electron diffraction pattern of coating (*c*)

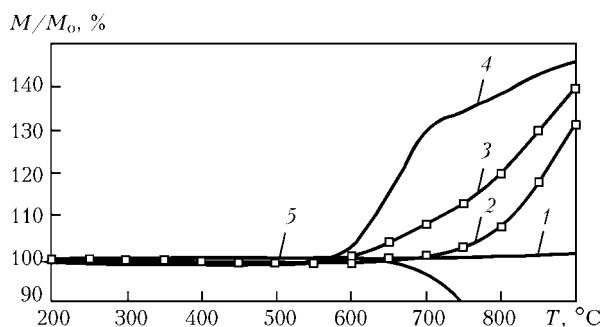


Figure 5. Kinetics of oxidation in air of materials and coatings on basis of boron carbide: 1 — B_4C of hot extrusion; 2 — B_4C powder of 40–50 μm diameter; 3 — B_4C condensate, $\delta = 15 \mu m$; 4 — B_4C powder of $\leq 1 \mu m$ diameter; 5 — carbon (graphite MG1)

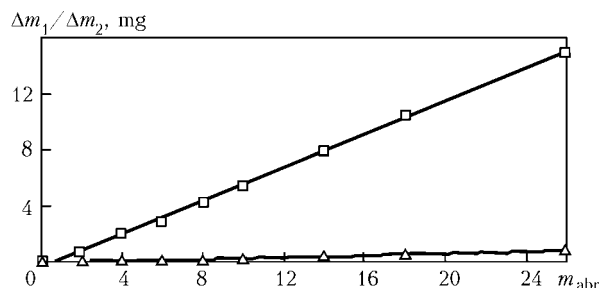


Figure 6. Change of mass of steel specimens without (standard) and with coating on basis of boron carbide of 15 μm thickness in process of abrasive testing using quartz sand at angle of attack 90°: 1 — without coating; 2 — with coating on basis of boron carbide

The results obtained match well literature data, according to which boron carbide [3] or boron-carbon alloys [4] start to be oxidized at temperature 600 °C with full oxidation at temperature 1200–1300 °C.

Erosion resistance of coating on basis of boron carbide of 15 μm thickness with a sublayer of titanium of 4 μm thickness, deposited on steel plates of 20 $\times$ 14 mm size and thickness 2.4 mm at temperature $T_s = 500$ –520 °C, was investigated. Rate of condensation constituted 1 $\mu m/min$, microhardness of the coating — 26–28 GPa. As far as chemical composition of the coatings, applied with application of initial materials of different producers, was practically the same (see the Table), the coating for investigation of erosion resistance was produced by means of evaporation of the cold extrusion pellets from the B_4C powder, produced at DPCR.

In Figure 6 graphic dependence of loss of the mass upon amount of the consumed abrasive for standard steel specimens without the coating and steel specimens with the coatings is shown. As it follows from the drawing, standard specimens demonstrate practically uniform (proportional) loss of mass depending upon mass of the consumed abrasive at angle of attack 90°. Specimens with the coating are subjected to smaller loss of mass.

According to data of metallographic investigation of the coating surface structure before and after processing using the abrasive (Figure 7), loss of the coating mass occurs partially because of ablation of separate defects of the coating (microdrops), located on the coating surface, and then progresses due to increase and deepening of dimensions of the «craters» in the place of removal of the drops. Interaction of the abrasive particles with microdrops on the coating surface causes their active erosion ablation, which causes smoothing of roughness and general leveling of the coating surface relief, i.e. as a rule cutting or knocking-out of the drops with formation of craters occurs. As a result of difference in roughness of initial surface of the coatings (in regard to size and number of microdrops), at the beginning of the process of abrasive wear significant difference in loss of the coating material mass is noticeable. Afterwards intensity of abrasive wear of the coating reduces. In initial period of the test (after consumption of 10 kg abrasive) on the coating surface preserved cone-like frag-

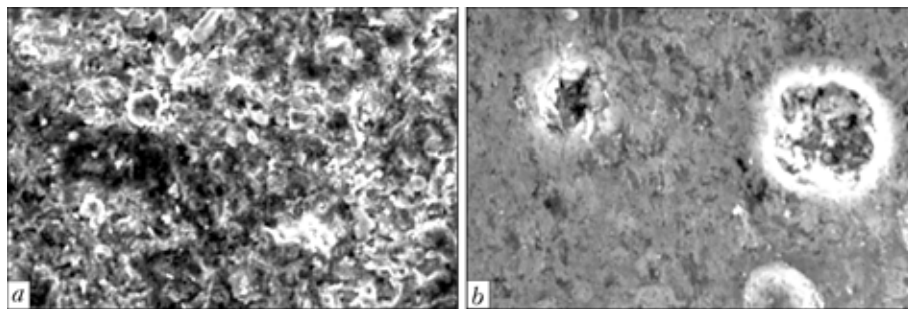


Figure 7. Structure of standard specimen surface (a) and coating after abrasive test (b); abrasive — quartz sand, angle of attack of 90° (×1500)

ments or traces of their presence. Later (after consumption of 26 kg abrasive) number of small cones sharply reduced over the whole surface of the coating, mainly all big drops were removed, and practically the whole surface was leveled (Figure 7, b).

After consumption of 26 kg abrasive erosion ablation of the coating material on basis of B₄C equaled approximately 0.26 mg, while loss of mass of the standard specimen was 14.9 mg. Calculation of relative loss of the standard specimen mass Δm_1 to coating mass loss Δm_2 ($\Delta m_1 / \Delta m_2$) gives the following (approximate) result: abrasive (quartz sand) $\alpha = 90^\circ$; $\Delta m_1 / \Delta m_2 \approx 57$.

CONCLUSIONS

1. Powders of the B₄C boron carbide of commercial production (ZAP, DPCR and the «Starck» company, Germany) and manufactured from them ingots for electron beam evaporation contain free carbon and impurities of a number of elements with increased, in comparison with boron carbide, vapor pressure (iron, silicon, titanium, calcium, magnesium).

2. Chemical composition of the coatings in regard to boron and carbon corresponds to that of initial evaporated pellets of boron carbide and corresponds to the area B₄C + graphite of the boron-carbon constitutional diagram. Full identification of the coating phases is difficult because of blurring of rings on the electron diffraction pattern.

3. The B₄C-base coatings, produced by method of electron beam evaporation and condensation in vac-

uum at substrate temperature about 500 °C, are nanostructural and characterized by high adhesion to the basis, density and homogeneity of chemical composition; they have microhardness about 30 GPa.

4. Microhardness (measured on microsections, taken from surface) of the B₄C-base coatings, produced within deposition temperature range 450–650 °C, increases from 31 to approximately 40 GPa.

5. Oxidation of materials and coatings of the boron-carbon system in air starts at temperature 600 °C, whereby by means of increase of dispersity of the materials oxidation resistance of the latter reduces.

6. Erosion resistance of specimens with a coating on basis of boron carbide is more than 50 times higher than that of steel specimens without the coating in tests with application of quartz sand at angle of attack 90°. Further increase of erosion resistance of the coating assumes optimization of both composition and structure of the coating and thermo-physical conditions of evaporation and condensation of the boron carbide pellets.

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ELECTRON BEAM REFINING OF PLATINUM AND PLATINUM-BASE ALLOYS

Information 2. Electron beam refining of platinum-base alloys

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Detailed investigation of refining of platinum-base alloys was carried out. Industrial electron beam technology for production of platinum-base alloys has been developed.

Keywords: *electron beam remelting, platinum metals and alloys, impurity elements, melting conditions*

In [1] results of high-purity platinum (not less than 99.99 wt.%) production are presented. This work is devoted to the problem of production of platinum-base alloys.

Scrap of platinum metals and alloys (mainly scrap of glass-making equipment, spinneret feeders and chemical utensils) contains significant amount of glass and a number of metal impurities. The glass consists of the following oxides, wt. %: 50–60 SiO₂, 8–17 CaO, 7–15 Al₂O₃, 3–10 B₂O₃, 1–2 Fe₂O₃.

Content of impurities in the platinum metals and platinum-base alloys depends to a great degree upon methods of their production. Several methods are used in the industry:

- hydrometallurgical refining with production of the platinum sponge and rhodium powder and subsequent induction remelting in a ceramic crucible;
- induction melting in a ceramic crucible in air and vacuum-induction remelting in a ceramic crucible;
- induction melting in a ceramic crucible in air and vacuum-arc remelting in a copper sectional water-cooled crucible;
- induction melting in a ceramic crucible in air and vacuum-arc remelting with a non-consumable electrode;
- induction melting in a ceramic crucible in air and vacuum-arc remelting with consumable electrode;
- induction melting in a ceramic crucible in air and electron beam remelting;
- induction melting in a ceramic crucible in air and zone electron beam melting.

Despite application of a big number of long technological operations and chemical reagents, hydrometallurgical process allows producing separately (element by element) platinum metals.

Induction melting in a ceramic crucible in air makes it possible to mix well and blend alloys, oxidize part of their impurities, and assimilate them into the crucible material. In oxidizing melting practically does not change concentration of such metals as pal-

ladium, gold and copper. At the same time in the induction melting process it is impossible to reach required purity of the metal in regard to a number of metal and gas impurities. Weight share of oxygen achieves 0.05 %. Disadvantage of this kind of melting consists in contamination of the melt by the crucible material particles.

Intrinsic to induction melting in a sectional water-cooled crucible (a cold crucible) are advantages of the induction crucible melting, whereby the melt is not contaminated with material of the crucible. This method allows performing melting of metals at any pressure and producing ingots of high quality, but it has rather low energy efficiency because of high heat losses in copper walls of the crucible [2].

Vacuum-arc remelting with a non-consumable electrode causes unavoidable contamination of the melt by tungsten. Vacuum-arc remelting of platinum and platinum alloys with a consumable electrode allows reducing content of oxygen 5 times, carbon and nitrogen 9 times, fluorine, magnesium, chlorine, sulfur, calcium, iron, zinc, bromine, arsenic, antimony, barium and lead by one order and more, but content of copper remains high. In electric arc vacuum melting refining of the alloy occurs not just due to removal of the impurities into gas phase, but also due to their pushing aside to the upper (lost head) part of the ingot.

For preparation of the electrode the initial materials are pressed or welded using tungsten-electrode argon-arc welding, which is disadvantage of this method of melting and causes additional expenses. In this method the metal is for a limited time in a molten state and, therefore, refining process does not proceed sufficiently fully. Efficient ingot yield equals 41 % [3].

For deeper refining from impurities method of electron beam melting (EBM) is used, which allows reducing content of gaseous impurities by one order and significant reducing amount of metal impurities due to vacuum distillation — transition of the impurities into gas phase of the substances with higher than in the base metal partial pressure. In EBM non-metal inclusions are pushed aside on side surface of the ingot

**Table 1.** Chemical composition of platinum-rhodium alloy after oxidation induction melting in periclase crucible and subsequent EBM

Product name	Weight share of elements, %														
	Pt	Rh	Pd	Ir	Fe	Cu	Ni	Pb	Al	Mg	Si	Sn	Zn	B	Ca
Initial scrap of platinum-rhodium alloy	92.64	6.68	0.08	0.0012	0.034	0.08	0.007	0.065	0.040	0.040	0.160	0.009	0.070	0.070	0.020
Ingot of platinum-rhodium alloy after oxidation induction remelting	92.89	6.85	0.082	0.0014	0.012	0.077	0.002	0.009	0.005	0.030	0.007	0.002	0.008	0.001	0.004
Ingot of platinum-rhodium alloy after EBM	92.95	6.99	0.012	0.0015	0.010	0.004	0.0005	0.0005	0.001	0.004	0.001	0.0005	0.0005	0.0004	0.0005
TU 48-1-169-83	93±0.3	7±0.3	Σ 0.15		0.025	Σ 0.025		0.005	0.005	0.005	0.005	Σ 0.02		Not regulated	

and then are fully removed by turning of its surface layer.

In the ESM process upper part of the metal, which in the course of melting moves over height of the billet being remelted, is in a molten state. As a result redistribution of metal impurities occurs in EBM on the metal-melt interface, which is characteristic of zone purification. Combination of processes of vacuum distillation and zone purification allows intensifying refining. It should be noted that this process is rather expensive, because up to 4 % of precious metal transits into vapor.

At SE «Pridneprovsky Plant of Non-Ferrous Metals» (PPNFM) a combined technological scheme is used for full refining of the initial scrap of platinum metals:

- hydrometallurgical refining;
- oxidation induction melting;
- EBM.

Hydrometallurgical refining is used for purification and separation of platinum metals. Oxidation induction melting is performed in the ILT-0.02 furnace in the periclase crucible, whereby impurities in oxide form, which are present in initial feedstock, interact with the crucible material — periclase, forming complex oxide compounds on basis of MgO-spinel that are in solid-liquid state at values of the process temperature up to 2000 °C. Refining effect of induction melting in a ceramic crucible is achieved due to assimilation of oxide inclusions by the crucible walls. Results of purification of the glass-making equipment scrap after oxidation induction melting are presented in Table 1.

Analysis of the Table 1 results shows that this method allows significant reducing content in the metal of aluminium, silicon, calcium and boron in comparison with the initial one. However, insignificant amount of a number of metal impurities transits into the melt from components of the glass (aluminium, calcium, iron, and silicon). In addition, particles of periclase are present in the metal. That's why at next

stage of processing EBM is performed in the UE-178 furnace.

The UE-178M electron beam installation is equipped with the P-103 flat-beam gun, designed at the E.O. Paton EWI, which is located above the mould and the billet being melted. The gun has a programmed sweep of the beam. The billet is fed into the melting zone using a side feeding mechanism through the guiding chute. Melting is performed directly into the mould in the drop mode at residual pressure in the working chamber $5 \cdot 10^{-2}$ Pa [1]. Optimum conditions of melting were determined, at which necessary level of refining is achieved and losses of platinum materials, constituting base of the alloy, are minimum.

Important positive feature in EBM is preservation to a significant degree of rhodium content in the alloy and its rather homogeneous distribution in the ingot (Table 2). For investigation of the rhodium distribution character in volume of the ingot the latter was cut into two halves and chip samples were taken from different areas: a cylindrical surface (point 1), middle (point 2), and half of the ingot radius (point 3).

Table 2. Distribution of rhodium in volume of platinum-rhodium ingot

Ingot	Sampling points	Weight share of rhodium in alloy, %
P-311-4	1	9.81
	2	9.75
	3	9.75
P-323-16	1	10.03
	2	10.10
	3	10.07
P-294-7	1	9.92
	2	9.89
	3	9.87

Table 3. Technological parameters of platinum-rhodium alloy refining from palladium under different conditions of EBM

Weight share of palladium, %		Coefficient of refining	Rate of melting, kg/h	Beam current, A	Yield into ingot in EBM, %
In initial feedstock	After EBM				
0.99	0.160	6.2	6.8	1.7	97.70
0.92	0.100	9.2	5.2	1.7	96.40
0.24	0.035	6.9	6.0	1.7	97.10
0.24	0.060	4.0	6.7	1.7	99.20
0.84	0.110	7.6	6.9	1.9	98.30
0.69	0.200	3.4	7.3	1.8	99.50
0.92	0.170	5.4	5.6	1.6	99.00
1.16	0.060	19.3	4.2	1.8	95.30
1.04	0.120	8.6	4.2	1.7	97.71
3.00	0.180	16.6*	3.1	1.7	96.80
2.92	0.120	24.3*	2.8	1.7	96.60
3.00	0.110	27.3*	2.6	1.7	96.20
3.00	0.150	20.0*	2.9	1.7	96.70
3.00	0.140	21.4*	2.9	1.7	96.80

* Double EBM.

Content of rhodium in sampling points is presented in Table 2.

Distribution of rhodium in ingots after EBM is rather uniform.

Main attention in the investigation was concentrated on determination of optimum conditions of electron beam refining of the Pt–Rh alloy from palladium that is present in the glass-making equipment scrap (Table 3).

Coefficient of refining in the presented experimental melts varied from 3.4 to 27.3; optimum current of the beam in refining of the Pt–Rh alloy from palladium equaled 1.7 A, at which heat specific power was 0.54 kW/cm². Analysis of influence of the melting rate on degree of refining was performed under conditions of provision of the same power of heating, i.e. at the electron beam current 1.7 A. In case of reduction of the melting rate, duration of the metal soaking in

molten state and evaporation of the metals increase and, therefore, degree of refining gets higher (see Table 3).

At reduction of rate of melting below 4.5 kg/h total percent of metal yield into ingot gets lower, because main evaporating components (platinum and rhodium) partially transit into the condensate.

For deep purification it is advisable to perform double refining. By means of increase of the number of remelting operations degree of refining increases more intensively than parameters of rate of remelting and efficient alloy yield.

Palladium and other low-melting metals are removed significantly below the level, established by TU 48-1-169–83. Content of iridium in the alloy practically does not change and accumulates in the process of multiple use. If it is necessary to separate platinum metals, hydrometallurgical refining is used. Iron is

Table 4. Chemical composition of platinum-rhodium alloy after induction melting in atmosphere of chlorine in periclase crucible and subsequent EBM

Product name	Weight share of elements, %														
	Pt	Rh	Pd	Ir	Fe	Cu	Ni	Pb	Al	Mg	Si	Sn	Zn	B	Ca
Initial scrap of platinum-rhodium alloy	92.07	6.47	0.050	0.0012	1.250	0.060	0.007	0.015	0.040	0.008	0.060	0.009	0.005	0.070	0.010
Ingot of platinum-rhodium alloy after induction remelting with feeding of chlorine into reaction zone	92.89	6.85	0.082	0.0014	0.012	0.077	0.002	0.009	0.005	0.030	0.007	0.002	0.008	0.001	0.004
Ingot of platinum-rhodium alloy after EBM	92.95	6.99	0.012	0.0015	0.010	0.004	0.0005	0.0005	0.001	0.004	0.001	0.0005	0.0005	0.0004	0.0005
TU 48-1-169–83	93±0.3	7±0.3	Σ 0.15		0.025	Σ 0.025		0.005	0.005	0.005	0.005	Σ 0.02		Not regulated	



removed poorly, which is explained by presence of rather strong chemical bond in the Fe–Pt system. Gibbs energy at atomic share of iron in the Fe–Pt system from 0.1 and more equals approximately 73.6 J/mol [4].

Experimental melts for refining of platinum and platinum-rhodium alloy from iron with content of the latter from 0.1 to 1.5 % showed low efficiency of using EBM. That's why double-stage method of pyrometallurgical refining of such feedstock was developed at SE PPNFM, which envisaged at first stage induction melting of platinum metals with feeding of chlorine into the reaction zone, and at second stage — EBM [5]. Results of double-stage remelting of the spinneret feeder scrap, used for production of basalt fiber, are presented in Table 4.

Using the same method the EBM condensate is refined up to sufficient purity and retuned into production of glass-making units. Analysis of the EBM results (see Tables 1–4) showed that the metal corresponded to requirements of TU 48-1-169-83. Losses of noble metals in remelting of the glass-making equipment scrap constituted less than 0.5 wt.%.

In experimental melts ingots of the Pt–Rh alloys were produced, from which glass-making equipment (GME) was manufactured. At average service life of such GME, equal to 160–180 days, the equipment, produced from experimental ingots of the Pt–Rh alloy at SE PPNFM, worked more than 300 days. At SE PPNFM was mastered production of ingots of noble metals and alloys on their basis, chemical utensils, thermoelectric converters, and other items from platinum metals.

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- video control unit.

The EB gun can slide transversely relative to the upper work chamber shifting the beam axis to the respective positions when welding seams of different diameters.

The entire working sequence, including evacuating, rotating the workpiece, welding and changing the workpiece is carried out automatically according to a preset program and with a high degree of reproducibility of the set welding parameters.



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<http://www.nas.gov.ua/pwj/beam>

<http://paton.kiev.ua/eng/inst/ntkstructure/deplist/571.html>

THERMAL STATE OF DRUM-COOLER OF PLASMA-ARC INSTALLATION IN PROCESS OF SUPERFAST MELT HARDENING

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Mathematical model of thermal state of the drum-cooler is suggested. Influence of its geometric dimensions on rate of hardening of a strip of amorphous structure was studied.

Keywords: spinning, superfast hardening, drum-cooler, mathematical model, boundary conditions

By now methods of production of alloys with amorphous and microcrystalline structure with application of superfast hardening have been singled out into a separate direction in metallurgical production [1]. Quickly hardened alloys, especially produced by method of spinning in the form of strips, are used on ever growing scale in different fields of production. Most widely strips of amorphous structure are used in the fields of brazing, electronics and chemistry [2].

However, a number of technological and theoretical issues of production of such materials are not solved, which is stipulated by rapidity of the process, poor control of casting and solidification of the melt, and complexities, connected with significant dependence of their propensity to amorphicity upon chemical composition. Big number of works is devoted to modeling of this technological process, but main bulk of them describes processes of the melt solidification and formation of amorphous structure, while attention to

investigation of the drum-cooler operation practically was not paid. That's why it is necessary to study preliminarily thermal state of the drum-cooler, which will allow assessing volume of the metal that may be amorphised on existing equipment, and use these data in designing of a new one. All investigations were carried out on plasma-arc installation for production of alloys with amorphous and microcrystalline structure using spinning method, developed in the E.O. Paton Electric Welding Institute, NASU [2].

Statement of the problem. In superfast hardening of a thin metal strip (50–100 μm) main cooling of the melt is performed due to the contact heat exchange with the drum-cooler. That's why such parameter as temperature gradient in the drum body plays determining part in the process of amorphicity. The drum-cooler has a form of a hollow cylinder, inside which water is filled as a cooling agent. In Figure 1 scheme of a melting unit with a ceramic drain nozzle, a drum-cooler and a solidifying on it strip is presented.

Goal of this work consisted in modeling of thermal state of the drum-cooler in process of cooling of the melt in the form of a strip and investigation of influence of its geometrical dimensions on rate of hardening of the strip of amorphous structure.

Calculation scheme. Let us build mathematical model of heating of the drum-cooler body in process of cooling of a strip of thickness d on surface of a rotating cylindrical drum, thickness of contact wall of which $\delta = \frac{D_1 - D_2}{2}$, where D_1, D_2 are respectively the external and the internal diameters; $2b$ is the drum width. Origin of the spatial coordinate is on external surface of the strip, axis y is directed to center of the drum, and axis x — along generatrix of the cylinder. Let us consider design of the drum, in which wall thickness δ that contacts with the melt is less than the drum width $2b$, and width $2b$ is less than diameter of the drum D_1 . It is interesting to investigate process of heat distribution over width and height of the wall, taking into account high speed of the drum rotation (with the period $n = 0.04$ s); distribution of heat along the wall may be neglected. In this case thermal state of the drum wall is described by 2D model of

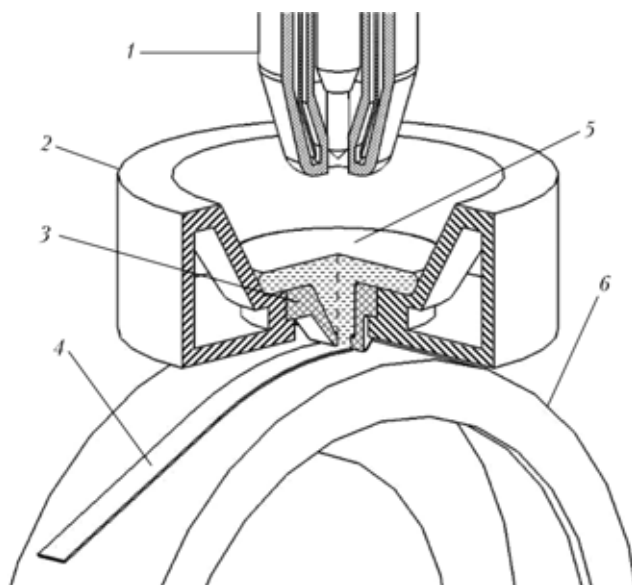


Figure 1. Scheme of melting unit and drum-cooler: 1 — plasmatron; 2 — water-cooled crucible; 3 — drain nozzle; 4 — strip; 5 — melt; 6 — drum-cooler

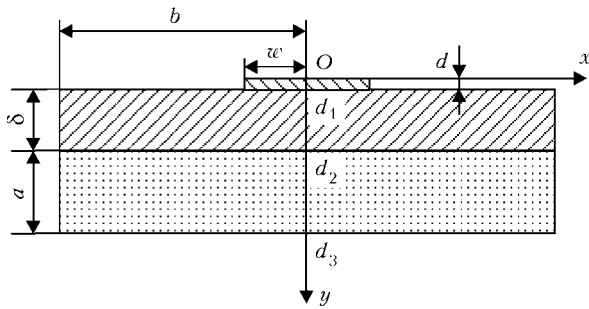


Figure 2. Scheme of calculation section

heat conductivity. Schematically section of the drum and the strip is given in Figure 2.

Influence of curvature of the wall on curve of the temperature change inside it may be described by coefficient of curvature ϕ [3]. Its value is determined by ratio of diameters $\phi = f(D_1/D_2)$ (Figure 3). That's why if thickness of the cylinder wall in comparison with the diameter is small and ratio D_1/D_2 is close to one, influence of the wall curvature may be also neglected. In our case ratio of the diameters equals 1.056, which makes $\phi = 1$. That's why this problem may be described by elementary 2D equation in rectangular Cartesian coordinates.

In the calculation the section being investigated sequentially passes over the whole length of the drum-cooler circumference, by the end of the period it comes into initial point, and the process repeats. In each new period distribution of temperature in initial position of the calculation section equals final distribution of temperature in last point of the previous period.

Neglecting convective mixing of water and considering liquid medium immovable relative the drum, we will describe distribution of heat over the section by the following 2D equation of heat conductivity:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right)$$

where $T(x, y)$ is the temperature in point (x, y) ; $\lambda(x, y, T)$ is the coefficient of heat conductivity in point (x, y) at temperature T ; c_p is the heat capacity; ρ is the density of the substance.

Calculation area for the strip is as follows: $0 \leq x \leq w$; $0 \leq y \leq d_1$; for the drum: $0 \leq x \leq b$; $d_1 \leq y \leq d_2$; for water: $0 \leq x \leq b$; $d_2 \leq y \leq d_3$.

As far as we consider the task that is symmetrical relative axis Oy , area of consideration is limited by the rectangle $0 \leq x \leq b$; $d_1 \leq y \leq d_3$.

Let us formulate the following boundary conditions:

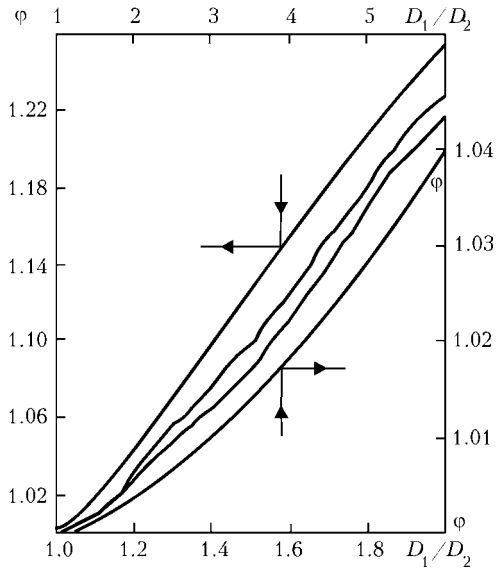
heat flow in the plane of symmetry is absent

$$\lambda \frac{\partial T}{\partial x} \Big|_{x=0} = 0;$$

plane $x = w$

$$-\lambda_s \frac{\partial T}{\partial x} \Big|_{x=w, y \leq d_1} = \alpha_{sa} (T(W, y, t) - T_{air}) - q_{rad};$$

plane $y = 0$


 Figure 3. Dependence of curvature coefficient $\phi = f(D_1/D_2)$ [3]

$$\lambda_s \frac{\partial T}{\partial x} \Big|_{0 \leq x \leq w, y=0} = \alpha_{sa} (T(x, 0, t) - T_{air}) - q_{rad};$$

plane $y = d_1$

$$\begin{cases} \lambda_s(x, y, T) \frac{\partial T}{\partial y} \Big|_{0 \leq x \leq w, y=d_1} = \\ = \alpha_{sc} (T(x, d_1 + 0, t) - T(x, d_1 - 0, t)) \text{ at } T_S \geq T_{fin}; \\ \lambda_c(x, y, T) \frac{\partial T}{\partial y} \Big|_{0 \leq x \leq w, y=d_1} = \\ = \alpha_{ca} (T(x, d_1 + 0, t) - T_{air}) \text{ at } T_S \leq T_{fin}; \\ \lambda_c(x, y, T) \frac{\partial T}{\partial y} \Big|_{0 \leq x \leq b, y=d_1} = \\ = \alpha_{ca} (T(x, d_1 + 0, t) - T_{air}); \end{cases}$$

plane $x = b$

$$-\lambda_c(x, y, T) \frac{\partial T}{\partial x} \Big|_{x=b, d_1 \leq y \leq d_2} = \alpha_{sa} (T(b, y, t) - T_{air});$$

$$-\lambda_c(x, y, T) \frac{\partial T}{\partial x} \Big|_{x=b, d_2 \leq y \leq d_3} = \alpha_{wa} (T(b, y, t) - T_{air});$$

plane $y = d_2$

$$\begin{aligned} \lambda_c(x, y, T) \frac{\partial T}{\partial y} \Big|_{0 \leq x \leq b, y=d_2} = \\ = \alpha_{cw} (T(x, d_2 + 0, t) - T(x, d_2 - 0, t)); \end{aligned}$$

plane $y = d_3$

$$\begin{aligned} -\lambda_{cw}(x, y, T) \frac{\partial T}{\partial y} \Big|_{0 \leq x \leq b, y=d_3} = \\ = \alpha_{wa} (T(x, d_3 + 0, t) - T_{air}), \end{aligned}$$

where α_{sa} , α_{sc} , α_{ca} , α_{cw} , α_{wa} are respectively the strip-air, strip-drum, drum-air, drum-water and water-air heat transfer coefficients; λ_s , λ_c , λ_w are respectively the heat conductivity coefficients of the strip, drum and water.

Process of heat transfer between heat exchange surfaces and ambient environment is described by

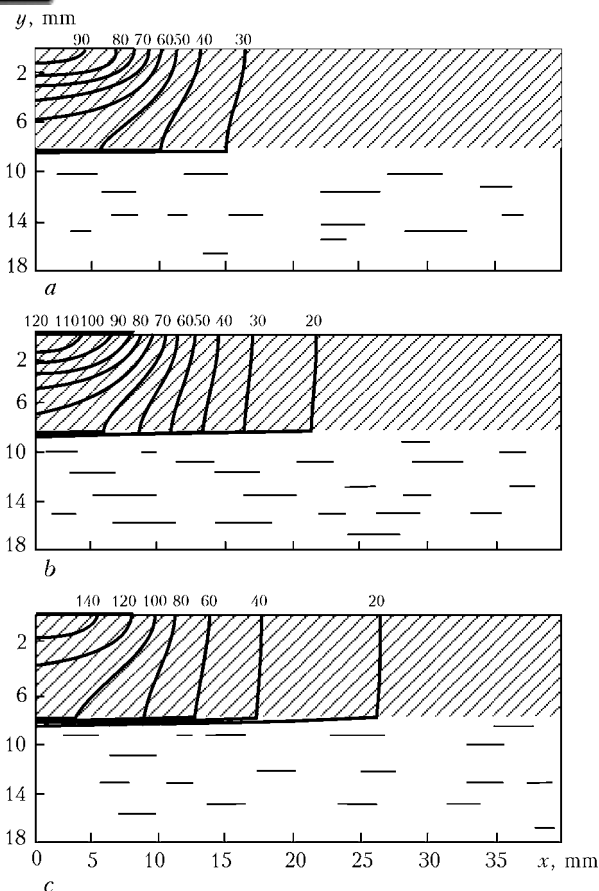


Figure 4. Isotherms of calculation section at t, s : a — 1; b — 2; c — 3

Newton–Richman law [4]. At the strip–air boundary to convective heat exchange radiant heat exchange is added, which obeys Stefan–Boltzmann’s law and is described by boundary conditions of second kind.

$q_{\text{rad}} = \epsilon \sigma \left(\frac{T}{100} \right)^4$ is the heat flow, stipulated by radiation, where ϵ is the degree of blackness; σ is the Stefan–Boltzmann’s constant.

Significant part is played by radiation only at the strip–air boundary, because only at high temperatures

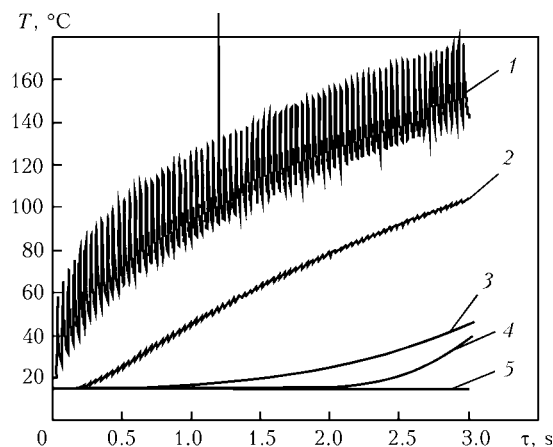


Figure 5. Change of drum temperature in process of melt hardening: 1 — on external surface of drum d_1 ; 2 — on internal surface d_2 ; 3 — water at distance 0.4 mm from point d_2 ; 4 — experimentally obtained dependence; 5 — temperature of water at boundary with air d_3

radiant component is comparable with the convective one. For example, for a strip from nickel alloy convective component of heat flow at temperature 1000 °C achieves $7 \cdot 10^4$, radiant component — about $1 \cdot 10^4 \text{ W/m}^2$ ($\epsilon(T)$ was selected as for pure nickel [5]). At the same time convective component of heat emission from internal wall of copper drum equaled $7 \cdot 10^3 \text{ W/m}^2$ (the drum was not heated above 100 °C in the experiment), and radiant component of heat emission equaled just about $0.5 \cdot 10^2 \text{ W/m}^2$ (for the assessment $\epsilon \approx 0.1$ was taken [5]). So, in all boundaries, except the strip–air one, radiation may be neglected.

For solution of 2D equation of heat conductivity Krank–Nickolson scheme was selected [6, 7]. The calculations were carried out using MATLAB 7 package.

For comparison of results of the modeling and practical data the process of hardening of the Ni–Si–B system alloy on a copper drum was selected. According to the results of X-ray diffraction analysis, the strip was produced in the experiments in amorphous state. High-temperature differential analysis showed that first endothermic reactions during heating of a strip of amorphous structure appeared at 400 °C (673 K) [8]. So, one may draw conclusion that temperature of the strip at its separation from the drum equals ≤ 400 °C (673 K). Technological parameters and physical data of materials for the calculation are as follows [5]:

Thickness of strip d , m	$1 \cdot 10^{-4}$
Thickness of drum wall δ , m	$8 \cdot 10^{-3}$
Strip width $2w$, m	$1.6 \cdot 10^{-2}$
Drum width $2b$, m	$8 \cdot 10^{-2}$
Thickness of water layer a , m	$1 \cdot 10^{-2}$
External diameter of drum D_1 , m	0.3
Internal diameter of drum D_2 , m	0.284
Period of drum rotation n , s	0.04
Air temperature T_{air} , °C	14
Initial drum temperature $T = T_{\text{water}}$, °C	14
Initial strip temperature T_0 , °C	1050
Strip temperature at its separation from drum T_{fin} , °C	400
Initial water temperature T_{water} , °C	14
Heat exchange coefficients, $\text{W}/(\text{m}^2 \cdot \text{K})$:	
strip–air α_{sa}	70
strip–drum α_{sc}	$5 \cdot 10^6$
drum–water α_{cw}	$8 \cdot 10^4$
drum–air α_{ca}	70
water–air α_{wa}	10
Heat conductivity coefficients, $\text{W}/(\text{m} \cdot \text{K})$:	
strip λ_s	93
drum λ_c	389
water λ_w	0.6

Discussion of the results. The modeling allowed obtaining distribution of temperatures in the calculation section (Figure 4). As one could expect, the highest temperature gradient is directly under the point of the drum contact with the strip; direction over width of the section also plays significant part in distribution of the temperature. Water in this scheme practically does not exert significant influence on distribution of temperature. So, main heat, released from the melt, is absorbed by the drum–cooler body.

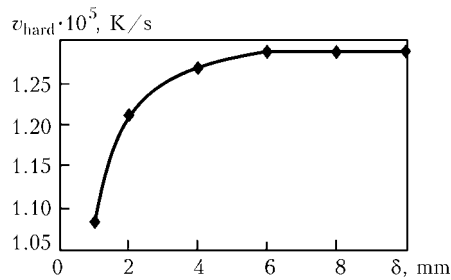


Figure 6. Dependence of hardening rate v_{hard} (2nd second) upon thickness of drum contact wall

Obtained results of modeling were estimated by rate of the strip hardening, equal to $\frac{T_0 - T_{\text{fin}}}{t_c}$, where t_c is the duration of the contact and cooling of the strip on the drum surface. Investigations of the range of heat exchange coefficient values showed that at initial period of hardening change of coefficient of heat exchange between the melt and the drum within $5 \cdot 10^2 - 5 \cdot 10^6 \text{ W}/(\text{m}^2 \cdot \text{K})$ causes change of the hardening rate $(1.0 - 6.5) \cdot 10^5 \text{ K/s}$. Change of coefficient of heat exchange between the drum and water within $8 \cdot 10^2 - 8 \cdot 10^8 \text{ W}/(\text{m}^2 \cdot \text{K})$ showed its insignificant influence on rate of hardening, which is connected with immovability of liquid medium relative the drum.

Time dependences of temperature in reference points showed that the results obtained matched experimental data (Figure 5). Carried out full-scale experiments for measurement of temperature inside a rotating drum-cooler directly under the point of contact with the melt demonstrated that within time of pouring (about 2.8 s) temperature changed from 14°C (287 K) to 39°C (312 K) [9]. Taking into account design peculiarities of the measuring sensor, the obtained curve corresponds to water temperature at the distance 0.3–0.5 mm from point d_2 . As far as investigations were carried out on small volumes of metal, pouring process was short, within this time temperature of the drum constantly increased, i.e. the process was characterized as a transient one. Calculation of temperature dependence of the drum-cooler demonstrated good match with experimental curve, which had the same angle of inclination of temperature change dependence upon time. Certain difference is explained by inertance of measurements and simplified mathematical model.

For determining criterion of the drum design optimization the modeling was carried out with change of geometric dimensions of the drum-cooler. Investigation of influence of the drum contact wall thickness (2nd second of pouring) on rate of hardening (Figure 6) showed that thinning of the wall caused fall of the latter, and increase of thickness by more than 6–10 mm did not enable its quality changes and stopped at the value $1.3 \cdot 10^5 \text{ K/s}$.

Influence of the drum-cooler diameter on rate of the melt hardening in time (Figure 7) showed falling characteristic. By means of the diameter increase angle of inclination reduces.

At modeling of a longer hardening process temperature of the drum asymptotically approaches a cer-

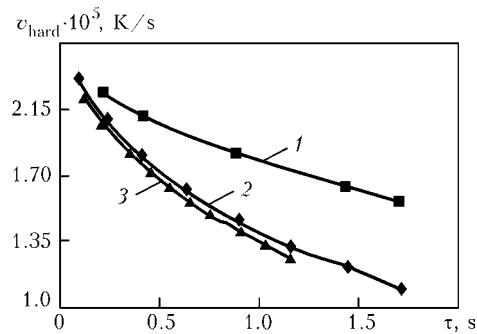


Figure 7. Change of hardening rate of melt at different diameters of drum-cooler, cm: 1 — 100; 2 — 30; 3 — 15

tain constant temperature that depends upon physical properties of materials. This is connected with the fact that heat dissipation is actually performed only due to convective heat exchange with ambient environment by means of blowing of the drum by air, which is incommensurable with amount of heat brought from the melt. However, there is no possibility to compare obtained dependences with the experiment. For producing strips of bigger length (on commercial equipment) it is necessary to ensure quality heat dissipation, constant circulation of the cooling agent and increase of the drum-cooler diameter.

CONCLUSIONS

1. Mathematical model of thermal state of a drum-cooler in process of superfast hardening of melt by spinning method was developed.

2. As a result of modeling influence of coefficients of heat exchange between strip-drum and drum-water surfaces, external diameter and thickness of the drum contact wall on rate of hardening of a strip was established.

3. It was shown that for the purpose of the drum design optimization its external diameter should be maximum possible, and thickness of the contact wall should exceed 10 mm.

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DEVELOPMENT AND MASTERING OF DEOXIDATION AND ALLOYING TECHNOLOGY OF ShKh15SG-V BEARING STEEL USING MnS25 FERROMANGANESE SILICON

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Results of experimental-industrial mastering of the ShKh15SG-V bearing steel melting by application of the MnS25 ferromanganese silicon (DSTU 3548–97) with weight share of calcium not more than 0.1 % instead of the FMn78A (DSTU 3547–97) ferromanganese and the FS65 (DSTU 4127–2002) ferrosilicon with high (up to 0.5 %) and unstable content of calcium are presented. Use of national ferroalloys instead of imported ferrosilicon according to the developed innovation technology of melting and ladle treatment of steel ensures significant increase of efficient metal yield and enables reduction of contamination of the billets and sectioned rolled stock by globular and oxide inclusions.

Keywords: bearing steel ShKh15SG-V, arc reduction electric furnace, steel melting technology, alloying and deoxidation of steel by ferromanganese silicon, ladle treatment, solid slag-forming materials, ladle-furnace, ladle vacuumator, quality of billet and sectioned rolled stock, globular and oxide inclusions, saving of ferroalloys

Statement of the problem. One of directions of the OJSC «Dneprospeetsstal» marketing strategy is increase of the bearing steel production for OJSC «Kharkovsky Bearing Plant» (KhBP). The latter plans to organize supply of their products to a number of leading automobile concerns (Toyota, Nissan, Volkswagen), which open their branches in Russia, and master production of high-precision large-size bearings for mobile stock of Ministries of Railways of CIS countries.

Production of steel for large-size bearings with increased calcination capacity, ensured in the ShKh15SG-V steel (GOST 3756–73) by weight share of manganese 0.90–1.20 and silicon 0.40–0.65 % and in the ShKh15 steel respectively by 0.20–0.40 and 0.17–0.37 %, is more complex than production of other kinds of bearing steels concerning technical-economic parameters of through technology of melting and ladle treatment of the metal.

In [1] results of the technology of melting and ladle treatment of the ShKh15SG-V steel with application of imported 75 % ferrosilicon ($\text{Ca} \leq 0.1$ %) instead of national FS65 ferrosilicon (DSTU 4127–2002), containing 0.3–0.5 % Ca [2, 3], are presented. It was established that application in the experimental campaign of the imported ferrosilicon and ferromanganese of the FMn78A grade (DSTU 3547097) with ladle treatment of the metal according to the used at the Dneprospeetsstal through technology of the ShKh15SG-V steel production did not allow improv-

ing steel quality with stably low parameters concerning globular and oxide inclusions. Assessment of the metal quality (GOST 801–78 and ASTM E45, method A) relative globular kinds of inclusions showed that certain reduction of contamination of the billets and sectioned rolled stock was accompanied by increase of the oxide inclusions. So, assumed significant increase of yield of the efficient sectioned rolled stock of comparable geometric size was not achieved [1].

It should be especially noted that constantly increasing requirements of the bearing metal consumers to quality of the metal products stipulate the need to continue scientific researches and development of new technologies for increasing degree of the steel purity from non-metal inclusions. Multiple investigations [2, 3] of micro- and macrostructure of the bearing steel and bench tests of the metal quality showed dangerous influence of non-metal inclusions on operation characteristics of bearings. Occurring in zone of contact of the roller with the bearing rings volumetric stress state of the metal that causes change of metal-physic properties up to structural change of the steels in the contact zone in the pair system ball (roller)–ring causes incoherence of elastic-plastic properties of the inclusions–metal matrix interphase boundary with subsequent development of pitting (chunk-out of the metal).

In [4] interaction between the hazard parameter and dimensions of different chemical-mineralogical inclusions are presented (Figure 1). The highest hazard in regard to reduction of service life of a bearing cause large-size difficultly formed in the process of rolling of the metal inclusions, which preserve in ready metal products shape of globules. Non-metal



inclusions represent calcium aluminates of homogeneous structure, heterophase complexes, which include compounds (solutions) of the $\text{CaO-Al}_2\text{O}_3$ system, and spinel-like $(\text{Mg}, \text{Fe}^{2+})\text{O}(\text{Al}, \text{Cr}^{3+}, \text{Fe}^{3+})_2\text{O}_3$ phases. As a rule, in analysis of conditions of formation of inclusions priority of absolute contents of dissolved in the metal oxygen and an element-deoxidizer is established. At the same time special significance acquires ratio of activities of both elements-deoxidizers (a_{Mn} , a_{Si} , a_{Al}) and non-controlled by standards in the course of melting and ladle treatment elements (a_{Mg} , a_{Ca}) [5–7]. By means of change of activities of the deoxidizers in course of deoxidation of molten steel and during solidification of the metal, crystallization and solid-phase reactions of formation of oxide phases occur in certain areas of phase equilibriums of the $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ system.

Content, chemical-mineralogical composition, and dimensions of non-metal inclusions depend upon a number of the following priority factors: thermodynamic activity of used deoxidizers and their composition, temperature-time conditions of deoxidation and ladle treatment of the metal, methods of steel casting, limitation of secondary oxidation, quality of bottom-pouring refractories (high heat resistance and low erosion), weight of the ingots (duration of the metal crystallization), and geometrical dimensions of sectioned rolled stock, which effects deformability of inclusions.

Physical-chemical audit of used technology of melting and refining of steel. Physical-chemical audit of melting processes and ladle treatment of the ShKh15SG-V steel, carried out according to the used technology with application of national FS65 ferrosilicon and experimental technology with application of imported low-calcium 75 % ferrosilicon allowed detecting shortcomings of through technology at stages of the molten steel alloying and deoxidation and stipulating the innovation through technology of the ShKh15SG-V steel production under conditions of Dneprospetsstal [8, 9].

Theoretical analysis of the processes and material balance of the steel deoxidizers (calcium and aluminium) at all stages of ladle treatment showed that although «excessive» amount of calcium during casting and crystallization of metal in the mould (weight of the ingot equaled 3.6 t) ensures with residual (dissolved) aluminium a relatively low content of the dissolved (active) oxygen, at the same time it is to a significant degree responsible for formation of increased amounts and dimensions of both globular inclusions in steel on basis of $\text{CaO-Al}_2\text{O}_3$ and heterogeneous inclusions on basis of $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$ (Figure 2, Table 1).

Investigations, carried out at the Dneprospetsstal plant, showed that because of a relatively high content in the FS65 ferrosilicon of calcium, its concentration in molten steel after addition of ferrosilicon into the metal during treatment in the ladle-furnace increased up to the values, exceeding critical ones. This became the basis for performance of experimental melts of

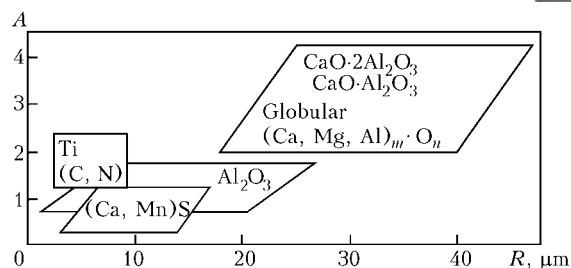


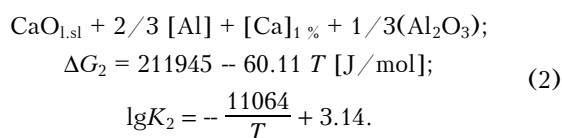
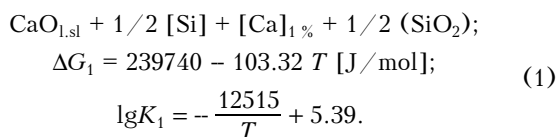
Figure 1. Influence of chemical-mineralogical nature and size of inclusions R on operation characteristics of bearings [4]; A — index of hazard

the ShKh15SG-V steel according to different options of deoxidation using aluminium and additions of the FS65 ferrosilicon into the metal (into a furnace, a ladle-furnace, a vacuumator, or addition by parts of the general amount at different stages of melting and ladle refining of the molten metal). Averaged values of chemical composition of the metal and the slag according to used technologies at different stages of melting and ladle treatment of the ShKh15SG-V steel are presented in Tables 2 and 3.

As far as heat load on surface of the slag melt (q of disintegration of electrodes on the ladle-furnace) is almost 50 % higher in comparison with arc furnace of equivalent capacity ($q_{\text{ladle}} = 0.4$; $q_{\text{DSP-60}} = 0.22$) and occupies practically whole surface of the slag melt, in case of overheating of the slag in zone of operation of electric arcs and at higher integral temperature of the slag in the ladle-furnace installation mass-exchange processes in the slag-metal system are developed, initiated by reduction reactions with participation of the metal pool and oxide-fluoride slag components.

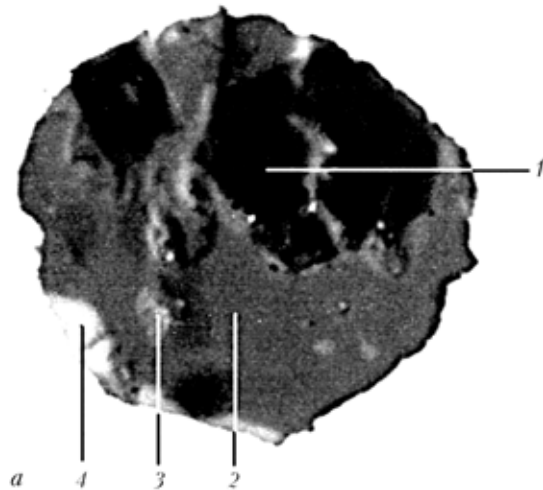
Source of influx of «excessive» calcium into the metal are processes of calcium reduction from the CaO-CaF_2 melt by silicon of the FS65 ferrosilicon, aluminium in composition of FS65 (1.5–2.0 %), and aluminium powder during deoxidation of the slag in course of degassing of the metal.

Reduction of calcium at the stage of ladle treatment may be presented in generalized form by the following reactions:



Thermodynamic characteristics of reactions (1) and (2) are calculated, taking into account heat of dissolution and transition of the components from the standard «pure substance» state into ideal infinitely diluted 1 % solution in iron [10].

Determining according to method of A.G. Ponomarenko [10] activity of the metal and slag components (Table 3) as phases with collectivized state



of the electrons, it was established that values of activity of oxides at 1600 °C equal 0.345 for 50 % CaO; 0.137 for 10 % SiO₂, and 0.048 for 10 % Al₂O₃.

Then chemical potential $\left(\mu_i = \frac{\Delta G_{T,i}}{d_{in}}\right)$ of formation of calcium solutions with content 10 ppm according to reactions (1) and (2), provided chemical potentials of the elements diluted in the metal and the flag phase are equal, acquires the following values:

<i>T</i> , K	1600	1700	2000	2200
$\mu_{Ca}^{(1)}$, J	1.31	1.32	0.17	−0.55
$\mu_{Ca}^{(2)}$, J	3.60	3.38	2.73	2.29

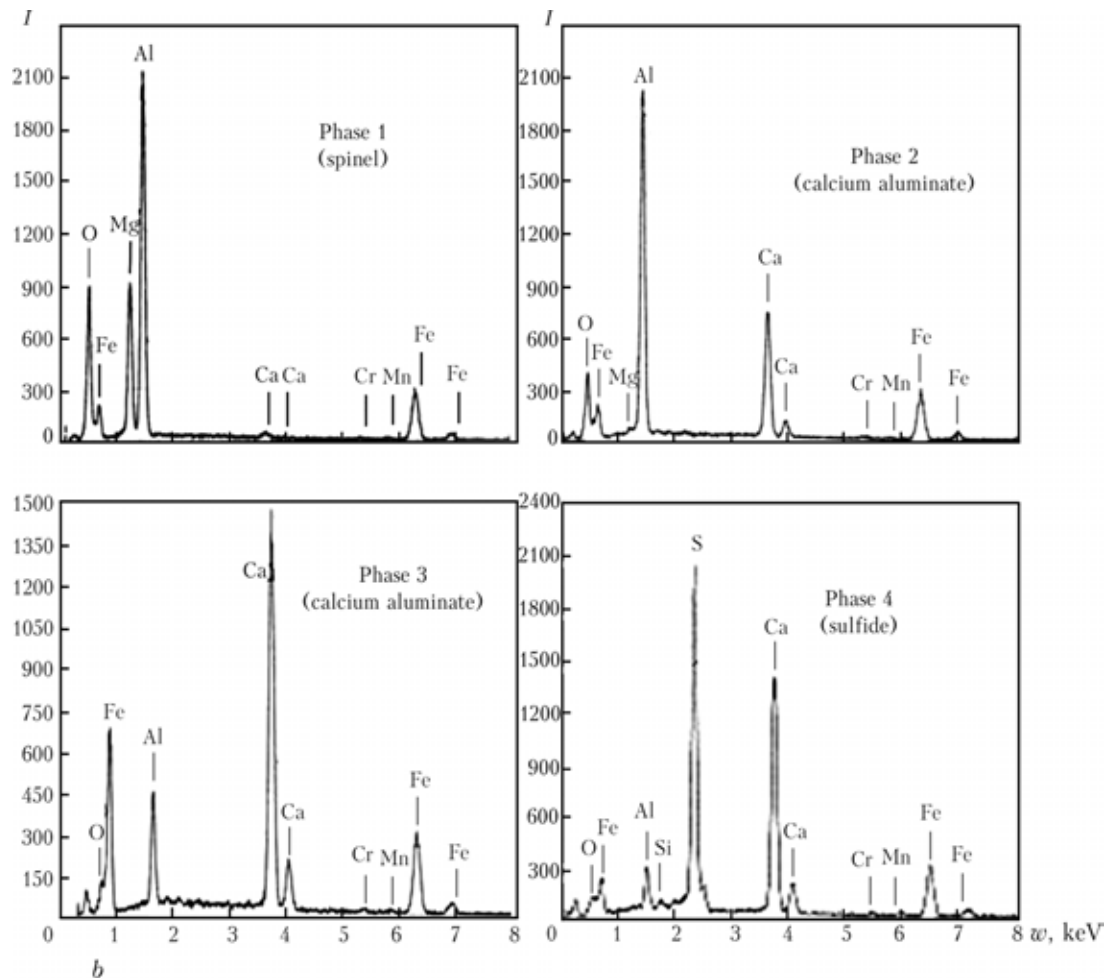


Figure 2. Globular heterophase inclusions in ShKh15SG-V steel: *a* — optical image (×1500); *b* — energy spectra of elements *w* in *K*_α-radiation: 1–4 — analyzed phases; *I* — pulse

Table 1. Chemical composition of analyzed phases (Figure 2) [1]

Phase	Weight share of elements, %							
	Mg	Al	Ca	Si	Cr	Mn	Fe	O
1	11.34	24.89	0.52	—	0.26	0.32	25.37	37.29
2	0.33	22.41	18.71	—	0.36	—	23.63	34.56
3	—	5.57	37.62	—	0.78	—	27.76	28.28
4	—	1.76	23.54	0.21	0.32	S	17.28	40.63
						16.26		

**Table 2.** Chemical composition of ShKh15SG-V steel at stages of melting and ladle treatment in ladle-furnace and ladle vacuumator

Technology stage	Weight share of elements, %							
	C	Mn	Si	Cr	P	S	Al	Ca, ppm
Before tapping from ASF*	0.75	0.15	0.13	1.200	0.011	0.045	0.004	4.0
At beginning of treatment in ladle-furnace (after addition of FS65)	0.95	0.17	0.20	0.014	0.018	0.040	0.040	5.0
At end of treatment in ladle-furnace	0.99	1.00	0.48	1.430	0.014	0.009	0.045	13.8
At end of treatment in vacuumator	0.99	1.00	0.48	1.430	0.014	0.005	0.033	10.6

* Arc steel furnace.

Table 3. Chemical composition of slag at different stages of ShKh15SG-V steel production technology

Period of melting	Weight share of elements, %				
	CaO	MgO	Al ₂ O ₃	SiO ₂	FeO
Before tapping from ASF	45	15	3	7	2.5
At beginning of treatment in ladle-furnace (after addition of FS65)	50	9	13	8	1.0
At end of treatment in ladle-furnace	55	7	9	10	0.3
At end of treatment in vacuumator	55	7	10	15	0.3

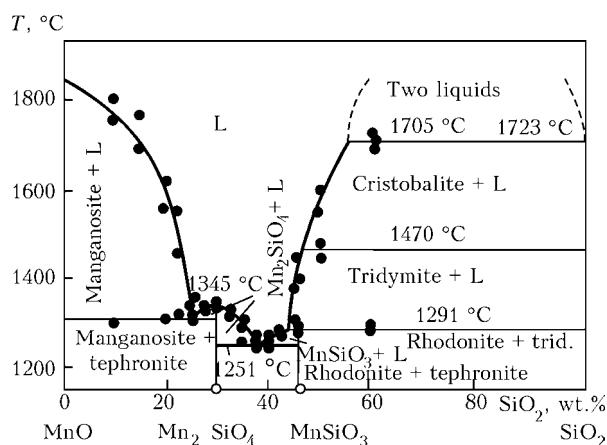
Analysis of thermodynamic data and theoretical calculations confirms prevailing influence of silicon on the calcium reduction processes and indicates technological factors for limitation of this process by reduction of the slag basicity and increase of the Al₂O₃ content.

It should be specially noted that observance of steel production conditions with rational content of calcium in molten metal is necessary, but not sufficient condition for production of sectioned rolled stock with specified index of the metal contamination with globular and oxide inclusions, corresponding to top groups of quality. That's why it is very important to ensure the most favorable state of the metal, preceding to alloying, deoxidation, and ladle treatment of the steel intermediate product in DSP-60, ladle-furnace, and vacuumator for formation of primary in molten steel and secondary non-metal inclusions within liquidus-solidus range during crystallization of metal in the mould.

Thermodynamic analysis and experimental investigations showed that at separated deoxidation of molten iron by manganese (ferromanganese) the oxides (Mn, Fe)O or pure manganese oxide are formed with melting point 1850 °C. In the Fe-Mn-O system at content of manganese in the melt 0.02 % mole share (1.9 % wt.%) equilibrium concentration of manganese oxide in slag phase achieves 89.8 wt.% [11]. In case of deoxidation of iron by silicon (ferrosilicon), product of the reaction is SiO₂ with melting point 1720 °C. Combined alloying and preliminary deoxidation with application of complex alloy of ferromanganese silicon are accompanied by formation (at certain weight shares of manganese and silicon in ferroalloy and molten iron) of low-melting reaction products of the MnO-SiO₂ system (Figure 3) of eutectic composition with melting point 1320 °C [12]. This situation is

thermodynamically substantiated and experimentally confirmed in monography [13] and then in work [14], whereby according to the monography molten non-metal inclusions form at temperatures of steel production in case of ratio in the metal of [% Mn] and [% Si] 3 to 8 (Figure 4).

So, if alloying and preliminary deoxidation of the metal-intermediary product as basis of the ShKh15SG-V steel is performed using ferromanganese silicon with a certain ratio of manganese and silicon, in which dissolved calcium is practically absent, it is possible to create prerequisites for formation and removal of greater part of primary non-metal inclusions and production of metal with reduced content of dissolved oxygen. Later, during introduction of aluminium at the stage of the metal treatment in the ladle-furnace and in the ladle vacuumator, thermodynamically more stable conditions should be ensured for production of steel with reduced content of globular and oxide inclusions. Ratio between amount of these two kinds of inclusions is to a great degree

**Figure 3.** MnO-SiO₂ constitutional diagram [12]

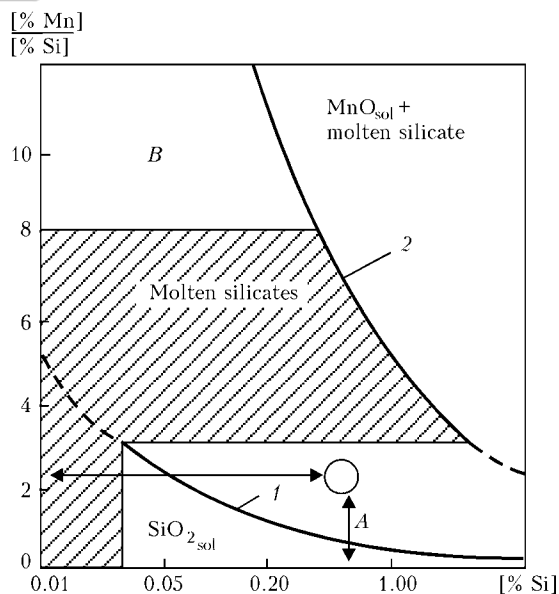


Figure 4. Areas of solid and molten products of deoxidation by manganese and silicon at 1600 °C [13]: 1 — manganese silicates, saturated with silica, separated from solid silica; 2 — molten manganese silicates, separated from solid solutions on basis of manganese oxide; A — products of deoxidation reaction are in solid-molten state; B — formation of particles of solid manganese oxide; O — composition of products of oxidation reaction for ratio [% Mn]/[% Si] in ShKh15SG-V steel

determined both by residual content of dissolved calcium and aluminium and ratio of their concentrations, i.e. [% Al]:[% Ca]. It follows from the diagram (Figure 5, a), which illustrates phase equilibriums in the Fe–C–O–Al–Ca system on surface of solubility of the components in molten metal that change of calcium

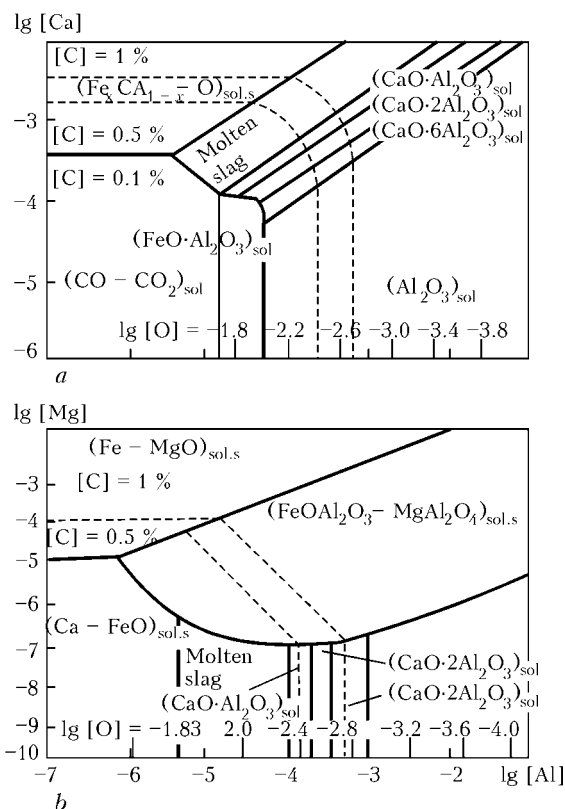


Figure 5. Solubility surfaces of components in molten metal of Fe–C–O–Al–Ca [15, 16] (a) and Fe–C–O–Al–Ca–Mg systems at 1550 °C, 5 ppm [Ca] [17] (b)

and aluminium amount in molten metal causes formation of different primary inclusions of morphological type: homogeneous liquid-phase solutions of the CaO–Al₂O₃ system, the *m*CaO·*n*Al₂O₃ calcium aluminates, and Al₂O₃ corundum.

Participation of magnesium in formation of spinel and heterophase alumocalcium inclusions. In [5–7] influence of dissolved in the bearing steel magnesium on formation of globular heterophase inclusions, presented by the MgO·Al₂O₃ spinel both as independent phase and spinelides (Mg, Fe²⁺)O·(Al³⁺, Cr³⁺, Fe³⁺)₂O₃, is investigated. Source of influx of magnesium into the melt in melting of both steel in reduction electric furnaces [18] and ferroalloys (for example, production of metal manganese by silicothermal method [12]) are the processes of reduction of magnesium by carbon [19], silicon and aluminium from the MgO-containing linings of the furnace and slag-line area of the ladle in the course of ladle treatment.

According to data of [20], the MgO·Al₂O₃ spinel in austenite steels is formed at contents of [Mg] and [Al] equal respectively to 1 and 10 ppm (*T* = 1873 K). In order to exclude formation of the spinel it is suggested to control content of [Mg] and [Al] in the following way:

- replacement of the Al₂O₃–MgO lining of the ladle walls and bottom for dolomite one;
- reduction of aluminium content in the used ferrosilicon from 1 to 0.01 wt.%;
- reduction of the Al₂O₃ content in the slag at tapping from electric arc furnace from 17–23 to 5 wt.%, renewal of the slag before treatment on the ladle-furnace installation and achievement of 2 wt.% Al₂O₃ after the treatment instead of 7 wt.% according to the valid technology.

Precision investigations [21] confirmed participation of magnesium in transformation of primarily formed corundum inclusions into heterophase structure, the nucleus of which is corundum with the MgO·Al₂O₃ spinel trimming. Crystal-chemical structure of multiphase oxide inclusions is determined by physical-chemical state of the pool, sequence of introduction of the deoxidizers, and interaction of dissolved in the metal elements.

Validity of the provisions of regularities of formation of heterophase inclusions, determined by the ratio of activities of the dissolved elements-deoxidizers, is confirmed by results of investigation of the metal deoxidation by magnesium [22] and treatment of the ShKh15SG-V steel by magnesium in composition of iron-silicon-magnesium (8 % Mg) hardener [6].

At introduction up to 0.3 kg/t of magnesium in the ShKh15SG-V steel of experimental melts changed crystal-chemical structure of oxide inclusions, which was stipulated by redistribution of elements-deoxidizers in process of formation of alumocalcium and spinel phases. Identification of composition of inclusions by methods of X-ray microspectral analysis detected the following intensity of X-ray radiation of the *K_α* elements:

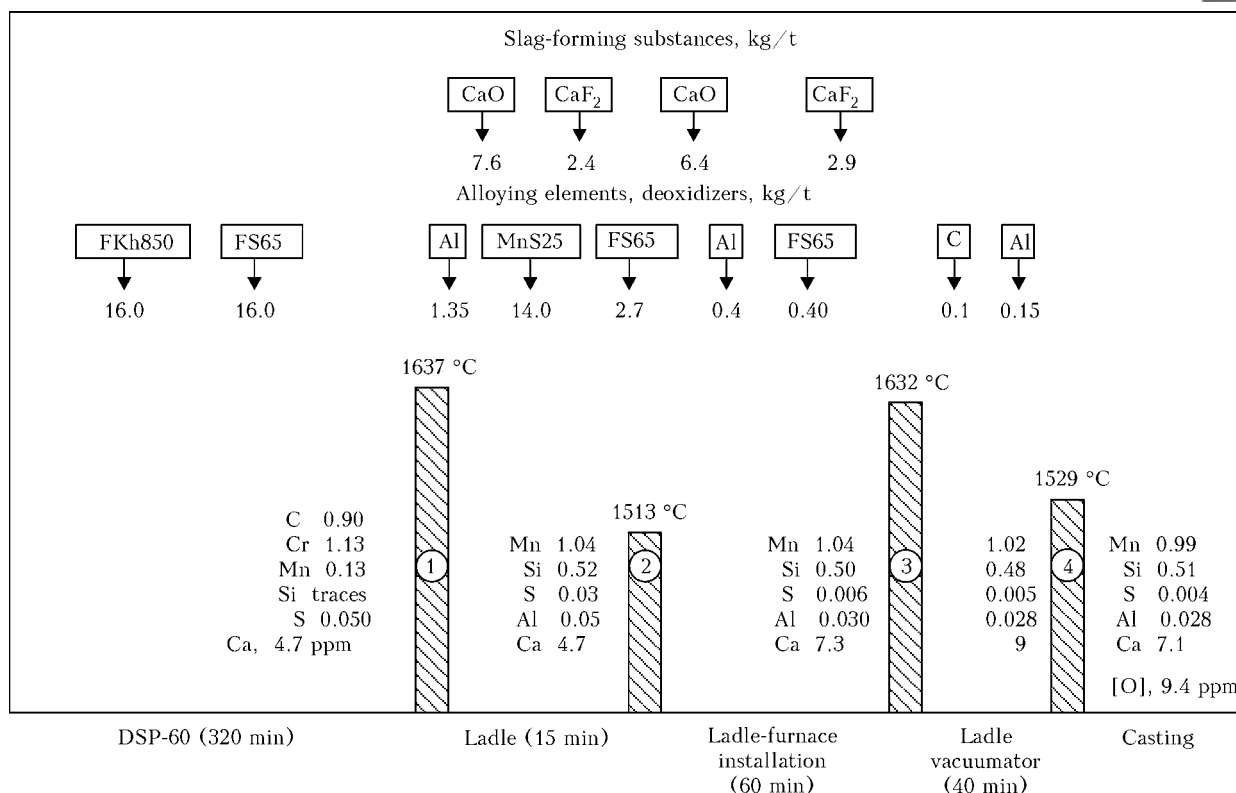


Figure 6. Characteristics of process of ShKh15SG-V steel alloying and deoxidation using FMnS25 ferromanganese silicon: 1 — at tapping from DSP-60; 2 — before treatment in ladle-furnace; 3 — at end of treatment in ladle-furnace; 4 — after degassing

	$(J_{Ca}/J_{Al}) \cdot 10^3$	$(J_{Mg}/J_{Al}) \cdot 10^3$
Valid technology with treatment of metal using synthetic lime-alumina slag	441	458
Treatment of metal by magnesium-containing hardener in combination with synthetic slag	136	1259

Methods of optical microscopy and X-ray microspectral analysis showed that increase of magnesium content in the melt (48 and 25 ppm, respectively, in the metal of experimental melts and the metal, produced according to valid technology) limited formation of the $MgO \cdot Al_2O_3$ spinel as independent structure and created prerequisites for formation in the composition of heterophase oxide inclusions of solid solutions (Fe, Al, Mg)O.

Results of carried out investigations are confirmed by thermodynamic model of interaction reactions of dissolved in the metal calcium, aluminium and carbon with oxygen (Figure 5, b), which establishes ratios of mentioned elements for formation of solid solutions of the spinel series and liquid-phase products of deoxidation in the form of calcium aluminates.

Main provisions and options of developed technology of alloying and deoxidation of steel using the MnS25 ferromanganese silicon. Analysis of results of systemic investigations of the oxide phase formation processes in structure of non-metal inclusions and influence of technological parameters of melting and ladle treatment of steels of the bearing assortment on quality of the metal products became the basis for development of technology for alloying

and deoxidation of the ShKh15SG-V steel, which ensures regulated composition of heterophase globular inclusions and reduction of general level of the metal contamination with inclusions.

In the course of industrial mastering of the ShKh15SG-V steel alloying and deoxidation the MnS25 ferromanganese silicon (DSTU 3548–97) was used, produced at OJSC ZFZ. Chemical composition of the MnS25, FMn78 and FS65 ferroalloys is presented in Table 4.

As follows from data of Table 4, content of calcium and aluminium in MnS25, which participate in the process of deoxidation and formation of globular alumocalcium inclusions, is 10–20 times smaller than in the FS65 composition. That's why during deoxidation and alloying of the metal with the MnS25 ferromanganese silicon (0.01 % Ca) amount of calcium, introduced into the metal, is one order lower than in case of using FS65 (0.42 % Ca) according to the valid technology.

Within the framework of this work 15 experimental-commercial melts were carried out in the DSP-60 arc reduction furnace according to five technological versions with application of the MnS25 ferromanganese silicon, which differed both by sequence of its additions into the furnace and into the ladle at tapping of the melt or at the stage of treatment of the steel in the ladle-furnace and by introduction of correction additions (ferromanganese and ferrosilicon) and aluminium at different stages (in the ladle-furnace and ladle vacuumator) of ladle treatment of the steel (Table 5).

Option 1. The metal-intermediate product was alloyed in the furnace using carbonaceous ferro-

**Table 4.** Chemical composition of ferroalloys used in performance of experimental melts of ShKh15SG-V steel

Material	Weight share of elements, %																	
	C	Mn	Si	P	S	Ca	Ni	Mo	Ti	Al	Cu	As	Pb	Sn	Zn	[O]	[N]	[H], ppm
MnS25	0.32	71.3	25.0	0.075	0.018	0.010	0.020	0.023	0.19	0.083	0.016	0.016	0.012	0.0013	0.033	0.023	0.001	15
FMn78	6.30	79.1	1.8	0.230	0.020	0.022	0.062	0.025	0.08	0.086	0.027	0.030	0.014	0.0015	0.035	0.130	0.040	46
FS65	0.08	0.27	64.0	0.023	0.003	0.420	0.100	0.036	0.20	2.00	0.083	0.020	0.015	0.0009	0.037	0.047	0.004	14

chromium, having preliminarily deoxidized pool with approximately 1 kg/t of aluminium, then it was tapped into the ladle with separation of the furnace slag and creation in the ladle of oxide-fluoride slag of the CaO–CaF₂ system with ratio of components 4:1. In the course of tapping of the intermediate product into the ladle the MnS25 ferromanganese silicon was added. Correction of manganese and silicon content was performed in the ladle-furnace. Because of discordance of carbon content in the steel at the stage of the metal treatment in the ladle vacuumator, caused by low share of carbon influx with the MnS25 addition (% C < 0.35), steel in the ladle was carbonized by the coke powder, which is not envisaged by the valid technological instructions. This enabled increased contamination of the steel with inclusions, which was taken into account in analysis of results of the delivery and investigation control of the billets and sectioned rolled stock.

Option 2. It is similar to option 1, but together with solid slag-forming materials (SFM) and MnS25 (amount of MnS25 was increased up to 850 kg per a melt) 250 kg of standard FS65 per a melt were added for correction into the ladle.

Option 3. Peculiar feature of this option is addition of MnS25 into the DSP-60 furnace before tapping. Correction of chemical composition of the metal was performed in the furnace-ladle.

Option 4. Difference of this option from the previous ones consists in addition of MnS25 in the ladle-furnace.

Option 5. The metal-intermediate product, partially deoxidized in the furnace by the FS65 ferrosilicon, was tapped into the ladle with simultaneous addition of MnS25 and deoxidation with aluminium on

bars. In the furnace-ladle the steel was deoxidized by aluminium, and final deoxidation was performed in the vacuumator (Figure 6).

In the course of ladle treatment of the steel chemical composition of the slag was analyzed (Table 6).

Casting of the metal and further processing were performed according to the valid technological instructions. Change of content of the elements in process of melting of the steel is shown in Table 7.

Results of quality control of billets and sectioned rolled stock of experimental melts of ShKh15SG-V steel. Analysis of data, presented in Table 7, proves that developed technology of deoxidation and alloying of the ShKh15SG-V steel by the MnS25 ferromanganese silicon ensured reduction of calcium content in the steel down to 8.4 instead of 9.6 ppm in the serial metal, i.e. on average by 1.2 ppm. Best results were achieved in melts of options 2 and 5 of the experimental technology — respectively 6.7 and 7.1 ppm, which was stipulated by smaller amount of the correction FS65 addition in the ladle-furnace (respectively 30 and 25 kg per a melt). Content of aluminium, sulfur, nitrogen and hydrogen in steel of experimental melts was the same as in the serial metal.

According to technical norms, sampling of the metal for control in regard to non-metal inclusions was performed from rolled bars of one ingot of first bottom plate and one ingot of the last bottom plate. Horizons of the sampling corresponded to head (A), middle (B) and bottom (N) parts of each ingot. Quality control of the metal was performed using method of maximum number according to scales of GOST 801–78, and for metal of export designation using in addition the ASTM E45 scales (method A).

Table 5. Technological conditions of deoxidation and alloying of ShKh15SG-V steel of experimental melts with application of MnS25

Option	Quantity of melts	DSP-50	[Ca], ppm	Ladle	Ladle-furnace	[Ca], ppm	IA	[Ca], ppm	[Ca], ppm, in finished metal	% of drop-outs O + S + Gl	Yield of efficient metal
1	1	Al	4.0	SiMn; Al	FS; Al	12.0	Al	13.0	10.0	40.9	0
2	4	Al	3.5	SiMn; FS	Al	6.8	Al	6.8	6.7	31.3	57
3	1	SiMn	3.0	Al	FS; Al	25.0	Al	20.0	10.0	0	100
4	2	–	4.0	Al	SiMn; FS; Al	10.0	Al	–	8.5	6.7	100
5	7	FS	4.7	SiMn; FS; Al	FS; Al	7.3	Al	9.0	7.1	9.2	89
Valid technology	–	FS	4.0	Al	FS; FMn; Al	13.8	Al	10.6	9.6	15.9	64

**Table 6.** Change of chemical composition of slag at stages of ladle treatment of ShKh15SG-V steel according to option 5

Melt number	Sample number	Weight share of components, %							
		CaO	MgO	Al ₂ O ₃	SiO ₂	MnO	FeO	S	CaF ₂
V15656	1	46.83	18.20	16.4	15.70	0.37	<0.15	0.47	8.72
	2	59.95	6.36	10.0	17.44	0.30	0.92	0.12	13.55
	3	53.75	7.00	12.8	17.22	<0.30	0.54	0.09	9.68
	4	50.83	13.40	10.2	17.20	<0.30	<0.15	0.20	6.00
V15710	1	48.20	7.60	9.8	15.40	<0.30	0.84	0.51	12.20
	2	53.00	8.00	7.6	15.30	<0.30	0.78	0.24	15.67
	3	53.00	9.40	8.9	16.30	<0.30	0.15	--	--
	4	50.40	10.40	13.2	15.40	<0.30	<0.15	0.71	7.74
V15775	1	57.50	10.70	16.4	14.77	0.54	0.15	0.82	8.13
	2	>61.80	6.82	14.2	15.30	0.50	1.15	0.24	7.94
	3	55.43	11.91	15.9	15.82	0.48	<0.15	0.14	8.72
	4	53.09	11.24	16.5	15.10	0.46	<0.15	0.49	8.72

Note. Sample 1 — after treatment of metal with SFM in ladle; sample 2 — in ladle-furnace after renovation of slag; sample 3 — at end of treatment in ladle-furnace; sample 4 — after degassing.

Table 7. Content of elements in course of experimental melts of ShKh15SG-V steel

Melt number	Mn, %						Si, %				
	Furnace at tapping	Ladle-furnace			Vacuumator	Ladle	Ladle-furnace			Vacuumator	Ladle
		1*	2*	3*			1*	2*	3*		
Option 1											
V14608	0.09	0.84	1.06	1.07	1.06	1.04	0.20	0.19	0.35	0.46	0.45
Option 2											
V14618	0.12	1.04	1.09	–	1.04	1.05	0.51	0.45	–	0.48	0.49
V14680	0.13	1.07	1.05	–	1.05	1.00	0.56	0.50	–	0.50	0.50
V14690	0.12	1.04	1.03	–	1.00	1.01	0.51	0.43	–	0.50	0.51
V14859	0.11	1.04	1.13	–	1.10	1.08	0.51	0.56	–	0.57	0.57
Average	0.12	1.05	1.07	–	1.05	1.04	0.52	0.49	–	0.51	0.52
Option 3											
V15114	0.13	0.88	1.13	–	1.07	1.07	0.15	0.60	–	0.58	0.57
Option 4											
V15294	0.14	0.17	1.04	–	1.01	0.99	0.09	0.42	–	0.46	0.44
V15678	0.09	0.99	1.06	–	–	1.00	0.32	0.44	–	–	0.44
Average	0.12	0.58	1.05	–	1.01	0.99	0.21	0.43	–	0.46	0.44
Option 5											
V15155	0.16	1.07	1.07	1.04	1.03	1.01	0.46	0.44	0.46	0.47	0.48
V15656	0.17	1.08	1.07	1.06	1.05	1.06	0.49	0.47	0.46	0.50	0.51
V15710	0.13	1.03	1.01	–	1.04	1.03	0.49	0.46	–	0.48	0.48
V15743	0.09	1.02	1.02	–	–	0.96	0.67	0.56	–	–	0.56
V15744	0.13	1.03	1.02	–	–	0.98	0.43	0.50	–	–	0.51
V15775	0.09	1.02	1.01	1.02	–	0.97	0.63	0.61	0.59	–	0.60
V15788	0.14	1.01	1.00	–	0.94	0.93	0.44	0.47	–	0.48	0.45
Average	0.13	1.04	1.03	1.04	1.02	0.99	0.52	0.50	0.50	0.48	0.51



Table 7 (cont.)

Melt number	Ca, ppm						Al, %, ladle	S, %, ladle	O ₂ /N ₂ , ppm, rolled stock
	Furnace at tapping	Ladle-furnace			Vacuumator	Ladle			
		1*	2*	3*					
Option 1									
V14608	4	6	6	12	13	10	0.024	0.002	8/80
Option 2									
V14618	4	11	5	—	5	7	0.025	0.003	8/70
V14680	3	7	7	—	5	4	0.025	0.003	8/70
V14690	4	5	4	—	7	7	0.029	0.006	10/70
V14859	3	7	11	—	10	9	0.034	0.005	8/70
Average	3.5	7.5	6.8	—	6.8	6.7	0.028	0.004	8.5/70
Option 3									
V15114	3	6	25	—	20	10	0.033	0.003	10/90
Option 4									
V15294	—	—	—	—	—	9	0.028	0.003	9/70
V15678	4	4	10	—	—	8	0.022	0.007	9/80
Average	4	4	10	—	—	8.5	0.025	0.006	9/75
Option 5									
V15155	3	9	5	10	8	7	0.041	0.004	10/80
V15656	8	5	6	6	8	10	0.030	0.003	9/70
V15710	4.9	5	6	—	6	6	0.028	0.004	10/80
V15743	6	5	5	—	—	5	0.029	0.003	10/80
V15744	4	6	8	—	—	9	0.022	0.003	9/80
V15775	4	5	6	6	—	6	0,024	0,004	9/80
V15788	4	5	12	—	14	7	0,024	0,005	9/90
Average	4.7	5.7	6.9	7.3	9	7.1	0.028	0.004	9.4/80

* Sample numbers.

Methodology of the metal estimation using ASTM E45 (method A) is characterized by priority of parameters relating to oxide inclusions, while scales of GOST 801–78 contain more rigid requirements to heterophase globular inclusions. That's why comparative analysis of the metal quality according to two normative documents is subject to further investigations.

Integrated parameters of the delivery and investigation control of the metal of experimental melts and the metal, produced according to the valid technology (with application of the FS65 ferrosilicon and the VMn78 ferromanganese) in relation to content of non-metal inclusions, are presented in Table 8. Carried out within the framework of the investigation control X-ray spectral microanalysis of inclusions of the ultimate number according to GOST 801–78 (I group — number > 2, V group — number > 3) showed that composition of globular inclusions is presented by heterophase formations, containing calcium, aluminium, magnesium, and silicon; oxide row inclusions are formed with participation of elements of aluminium, calcium, magnesium manganese and sulfur.

Criteria of efficiency of the developed technology of deoxidation and alloying of steel using the MnS25

ferromanganese silicon are assumed parameters of yield of efficient metal from the first control, which excludes fulfillment of a repeated control on doubled number of specimens and redirecting of the metal for rolling for another profile and number of specimens with drop-outs in regard to inclusions (globules, oxides, and sulfides).

Analysis of data, presented in Tables 7 and 8, proves that melting of steel with application of MnS25 according to the technological option 5 ensures reduction of calcium in the experimental metal from 9.6 down to 7.1 ppm (by 26 %) in comparison with valid technology, and reduction 1.9 times contamination with globular inclusions (from 11.2 to 5.7 % of drop-outs), oxide inclusions (from 4.5 down to 3.4 % of drop-outs) and increase of the efficient metal yield from the first control from 64 to 89 % [23]. Presented indices were used as a basis for determining rational scheme of application of MnS25 for alloying and deoxidation of the ShKh15SG-V steel according to technological option 5 — production of an intermediate products partially deoxidized by silicon in the furnace with cutoff of the furnace slag, alloying and deoxidation of MnS25 in process of pouring of the metal into the ladle, deoxidation in the ladle by aluminium

**Table 8.** Results of metal quality assessment of experimental melts of ShKh15SG-V steel according to scales of GOST 801–78

Technology option	Group	Type of control	Number, pcs		Yield of efficient metal, %	Kind of non-metal inclusions										
			Lot	Speci- mens		O			S			G			O + S + G	
						Avera- ge num- ber	Specimens with drop-out		Average num- ber	Specimens with drop-out		Average num- ber	Specimens with drop-out		pcs	%
							pcs	%		pcs	%		pcs	%		
1	I	Delivery	1	11	0	2.0	0	0	2.0	0	0	3.3	5	45.5	5	45.5
		Investigation	1	11	0	1.8	1	9.1	1.9	0	0	2.5	3	27.3	4	36.4
		Σ	1	22	0	1.9	1	4.5	1.95	0	0	2.9	8	36.4	9	40.9
2	I	Delivery	3	25	33	2.2	9	36.0	1.8	0	0	1.9	6	24.0	15	60.0
		Investigation	1	8	0	2.4	3	37.5	2.0	0	0	1.7	0	0	3	37.5
		Σ	4	33	25	2.3	12	36.4	1.9	0	0	1.8	6	18.2	18	54.5
	V	Delivery	1	12	100	2.6	0	0	2.3	0	0	2.3	1	8.3	1	8.3
		Investigation	2	22	100	2.7	1	4.5	2.2	0	0	1.8	1	4.5	2	9.0
		Σ	3	34	3	2.65	1	2.9	2.25	0	0	2.05	2	5.9	3	8.8
	I+V	Σ	7	67	57	--	13	19.4	--	0	0	--	8	11.9	21	31.3
3	V	Investigation	1	8	100	1.9	0	0	2.1	0	0	2.4	0	0	0	0
4	I	Delivery	1	6	100	1.8	0	0	1.5	0	0	1.5	0	0	0	0
	V	Same	1	9	100	2.7	1	11.1	2.5	0	0	2.3	0	0	1	11.5
	I+V	Σ	2	15	100	--	1	6.7	--	0	0	--	0	0	1	6.7
5	I	Investigation	1	12	0	2.0	1	8.3	2.0	0	0	1.9	2	16.7	3	25.0
	II	Delivery	2	24	100	1.95	0	0	1.55	0	0	2.0	1	4.2	1	4.2
	III	Same	1	6	100	2.1	0	0	2.0	0	0	1.7	0	0	0	0
	V	»	5	45	100	2.45	2	4.4	2.3	0	0	2.35	2	4.4	4	8.9
	I+II+III+V	--	9	87	89	--	3	3.4	--	0	0	--	5	5.7	8	9.2
Valid technology	I+II+III+V	Delivery	309	3538	64	--	160	4.5	--	5	0.1	--	398	11.2	563	15.9

Note. 1. Here O — oxides; S — sulfides; G — globules. 2. Normative requirements of GOST 801–78, number, not more than:

	O	S	G
I, II groups (profile up to 40 mm)	2.0	2.0	2.0
III, IV groups (profile up to 80 mm)	2.5	2.5	2.5
V group (profile more than 80 mm)	3.0	3.0	3.0

on bars and subsequent ladle treatment on the ladle-furnace installations in the vacuumator under oxide-fluoride slag (Figure 6).

Economic efficiency of the developed technology of the ShKh15SG-V steel production with deoxidation and alloying using the MnS25 ferromanganese silicon is achieved, without taking into account increase of the metal quality, due to reduction by 5.3 kg/t of total amount of ferroalloys (MnS25, correction additions FMn78 and FS65) with simultaneous reduction of specific consumption of ferromanganese by 90 and ferrosilicon by 56 % in comparison with the valid technology.

Positive results of industrial campaign of the ShKh15SG-V steel production with application of MnS25 are prerequisites for further improvement of the through technology of melting of steel of men-

tioned grade with application of the MnS25 ferromanganese silicon with ratio of manganese to silicon 3.2:4.3, which is one of decisive factors in formation of liquid-phase primary inclusions and ensures improvement of economic indices of production.

CONCLUSIONS

1. The developed innovation technology of the ShKh15SG-V steel alloying and deoxidation with application of the MnS25 ferromanganese silicon (DSTU 3548–97) instead of the FMn78 ferromanganese and the FS65 ferrosilicon was mastered, which ensured preliminary deoxidation of metal with formation of liquid-phase inclusions of the MnO–SiO₂ system that allowed reducing level of dissolved oxygen under conditions of formation of oxide phases of



non-metal inclusions and simultaneous reduction of the ratio $[Ca]/[Al]$.

2. It was established on basis of results of experimental melts with application of the MnS25 ferromanganese silicon that a rational option of technological scheme for production of the ShKh15SG-V steel is introduction of MnS25 into the ladle at pouring of the metal from the furnace (option 5), which causes reduction of calcium content in the metal by 26 %, reduction of contamination of the steel with oxide inclusions 1.3 times and globular inclusions — 1.9 times in comparison with parameters of the metal, produced according to the valid technology.

3. It was shown that application of the MnS25 ferromanganese silicon for deoxidation and alloying of the ShKh15SG-V steel increased yield of efficient metal from first control for I group according to GOST 801–78 up to 89 % in comparison with 64 % according to the valid technology.

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IDENTIFICATION OF TECHNOLOGICAL EVENTS IN MELTING OF STEEL IN ARC STEEL FURNACE USING WAVELET-ANALYSIS

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The scheme has been developed for obtaining real-time information about arc voltage and state of the technological process. Using the wavelet-analysis the algorithm for digital processing of a signal was developed, using which it is possible to perform its noise suppression and compression. The algorithm for identification of technological events has been developed that allows determining them at early stage of occurrence. Complex of programs has been developed, which makes it possible to record a signal about arc voltage, register events that correspond to certain moments of the signal readout, carry out digital processing (noise suppression and compression) and form image of the technological event.

Keywords: arc steel furnace, arc, voltage, signal, wavelet-analysis, image, identification

Control of any technological process is based on primary information that allows controlling this process. Difficulties in obtaining such information consist in absence of reliably operating primary sensors or huge expenses, connected with uninterrupted organization of their work.

In connection with this different methods of control, based on indirect parameters of technological processes, were suggested [1–9]: use of information about harmonic composition of current or arc voltage [1–5], values of operation inductive resistance [7], change of constant component of the phase voltage [8, 9], etc.

Developed on this basis methods of identification of states of the technological process of melting are

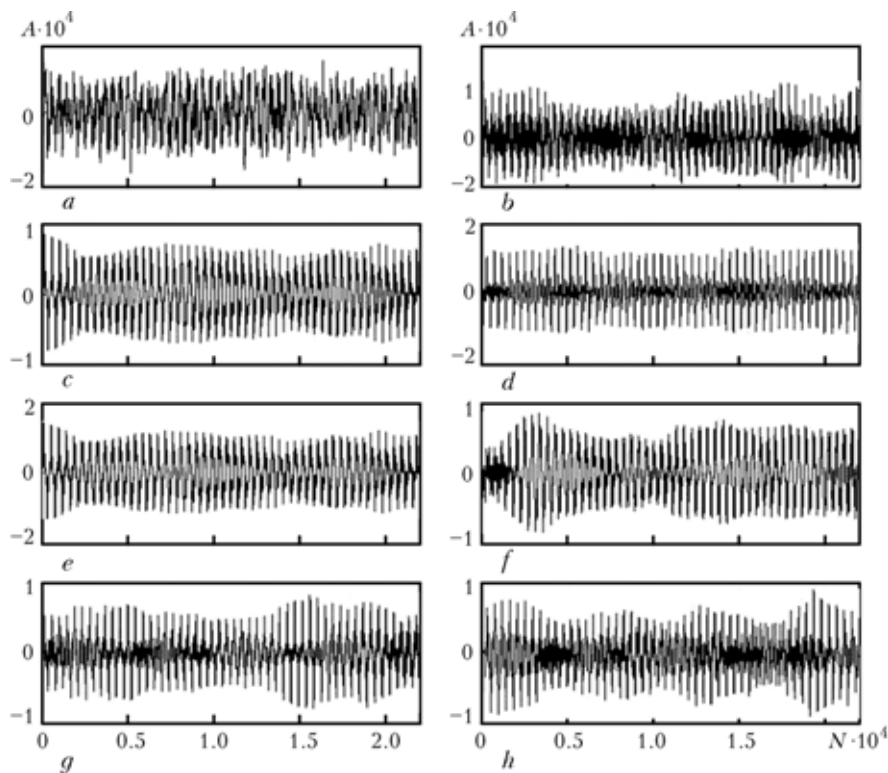


Figure 1. View of signal at different states of technological process (22050 counts within one second): *a* — penetration of wells; *b* — termination of melting of charge from first basket; *c* — uniform progress of process; *d* — termination of melting of charge from second basket; *e* — arc is «open»; *f* — slow vanishing of slag; *g* — slag is at level of threshold; *h* — strong vanishing of slag; *A* — amplitude of signal; *N* — number of signal counts

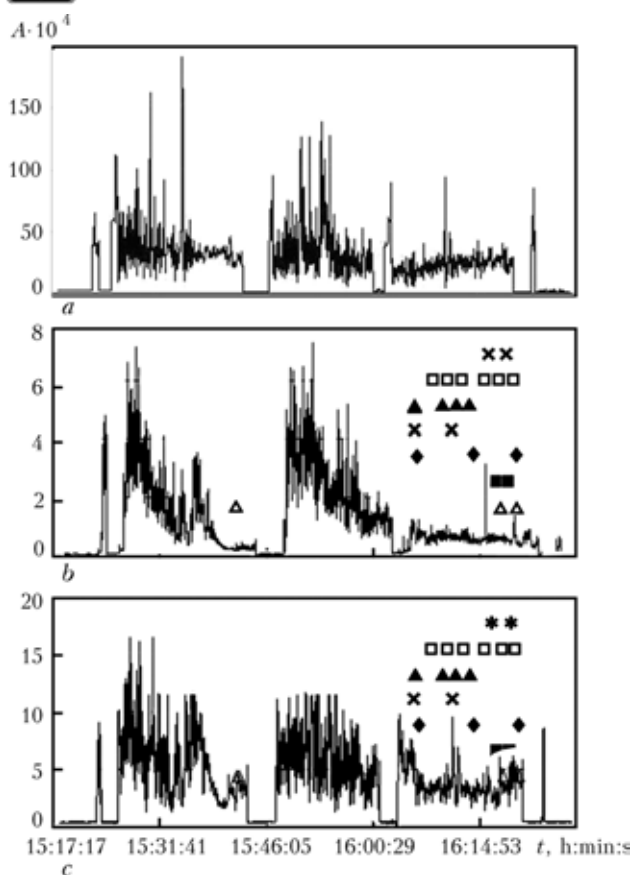


Figure 2. View of three first harmonics of signal about arc voltage in process of melting in ASF: *I* — charging; *II* — melting; *III* — additional charging; *IV* — melting of charge from second basket; *V* — oxidation period; *VI* — tapping; Δ — furnace operates smoothly; $\blacksquare$ — furnace cracks; $\blacklozenge$ — slag goes poorly; $\times$ — slag goes so-so; $\blacktriangle$ — slag goes strongly; $\square$ — slag is at threshold level; $+$ — slag is below threshold

based on invariance of stages of the process within a certain time and clear sequence of their occurrence [3].

For efficient control of state-of-the-art arc steel furnace (ASF) with a boosted technological process it is necessary to identify not just global stages that determine structure of the technological process, but also the events (poppling of the pool, removal of slag, smooth progress of technological process, «open» arc, etc.), existence of which lasts for seconds and which change each other in arbitrary sequence. That's why task of development of the algorithm for presentation of the events on basis of information about the arc voltage signal in reliable and sufficient form for further identification gets special importance.

Direct receiving of a signal about instant arc voltage in ASF is rather problematic because of a number of technical reasons, first of all high voltage, which varies within the range 0–1000 V. That's why a voltmeter, which measures instant arc voltage, was used as source of the signal, while a sound card of a personal computer with sampling frequency 22 kHz was used as an analogue-digital converter. The processed arc voltage signal was recorded on the hard disk and transmitted for visualization. In parallel with this an operator (a process engineer) registered on basis of

visual and audio information state of the technological process, which was also recorded on the hard disk.

Analysis of the received signal showed connection between shape of the signal and the events that occurred in the furnace (Figure 1). Taking this fact into account, the next task consisted in development of a formalized algorithm for singling out an image of a respective technological event.

Traditional mathematical apparatus, used in analysis of arc voltage or current signal, is Fourier transform. It is shown in [2–5] that using so called informative signs (ratio of amplitudes of harmonics, mean value of amplitudes of harmonics, current dispersion and amplitudes of harmonics) it is possible to control period of penetration of the wells and determine termination of the charge melting period of the oxidation stage. Carried out by the authors analysis of the received signal with application of Fourier analysis (Figure 2) confirmed presented above conclusions about possibility of identification of global stages (events) of a technological process. At the same time apparent dependence of the presented above signs of the events, connected, for example, with slag behavior, is absent. These events occur in free sequence and are short-lived. Moreover, it is necessary to identify events of this type as early as at the stage of their origination, i.e. evaluate dynamics of each event, whereby the image should bear information about the signal within the time interval.

It was established [10] that Fourier transform is insufficiently effective for analysis of signals of quickly passing non-stationary processes. Fourier-analysis makes it possible to determine fact of presence in the signal of any frequency and the interval within which lasts this frequency, but does not allow establishing the fact of presence of a certain frequency in the signal at a specific instant of time [11], which is frequently a decisive factor for identification of occurrence, development and disappearance of a certain event of the technological process. Because of this reason the approach, in which for different ranges of frequency temporary windows of different duration are applied in analysis of non-stationary signals, is used on ever growing scale. Window functions are obtained as a result of extension compression and shift in time of basic functions, called wavelets [12].

Taking into account information presented above, wavelet-analysis was suggested as main tool for processing of the data.

For each registered event the signal, which preceded it one second before it happened, was singled out. Then for more detailed analysis and creation of the effect of development of the event the initial signal was separated into equal periods, duration of which was multiple of degree 2 or equaled 2048 counts. As a result for each image 10 sub-images were obtained. But even in such form it is difficult to use information about shape of the signal as image of the event. It is necessary to clean signal from noise and reduce its dimensionality.



Standard method of noise suppression has been used — removal of high-frequency components from the signal spectrum. In relation to wavelet expansions this may be directly implemented by removal of detailing coefficients of high-frequency levels. Among existing at present paradigms of noise suppression the most distributed is Donoho–Johnstone paradigm [13]. It is rather simple for implementation and economical in computation respect, because it implies application of just fast algorithms of wavelet-transformation and contains three steps, which in case of sequential use in relation to the initial signal create effect of noise suppression. So, the analyzed signal is subjected to discrete wavelet-transformation up to the seventh level (Figure 3).

Dobeshi wavelet of tenth order [12], characterized by properties necessary for discrete wavelet-transformation, was used as an analyzing one. Then threshold value of noise component as maximum amplitude of the curve that reflects detailing coefficients of first level of expansion was determined. After this the detailing coefficients of all levels, absolute value of which was less than the assigned threshold, were converted to zero and reverse wavelet-conversion was made (Figure 4).

Scheme of the signal compression is similar to the presented noise-suppression process. The key issue is threshold processing of the wavelet-coefficients. During compression appearance of systematic errors is unavoidable. Occurring errors are proportional to the value of discarded coefficients.

There are several criteria for selection of the threshold. It is recommended to use «rigid» threshold filtration, whereby coefficients, absolute values of which do not exceed the threshold ones, are zeroed, while all other remain without changes. Such method of filtration allows more accurate restoring sharp changes of the signal (jumps, narrow peaks, etc.) and preserving bigger amount of energy in reconstruction of the signal. For example, it is possible to use criterion of balance between the number of zero coefficients and residual energy of the signal. Essence of this method consists in the fact that detailing coefficients with an absolute value, close to zero, contain just a small part of the signal energy. Zeroing of these coefficients causes insignificant loss of energy. Optimum is such value of the threshold, at which percentage of zeroed detailing coefficients will approximately equal percentage of residual energy of the signal after threshold filtration.

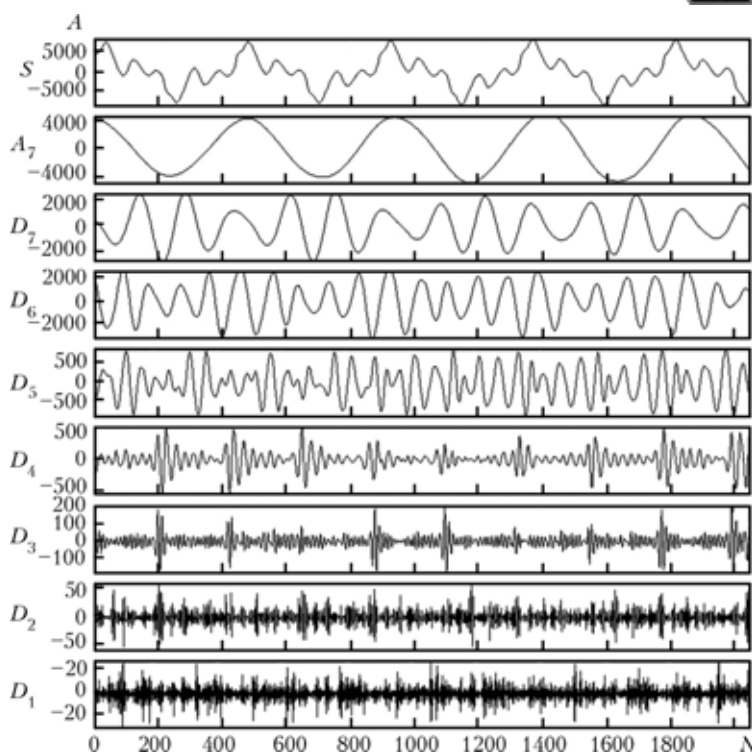


Figure 3. Multilevel discrete wavelet-expansion of signal: S — initial signal; A_i , D_i — coefficients of approximation and detailing, respectively

For the purpose of testing of this method discrete wavelet-expansion of signal up to seventh level was carried out, for which purpose Dobeshi wavelet function of second order was used [12]. Optimum compression was achieved at 97 % of general energy of the coefficients (Figure 5), whereby general number of the coefficients remained sufficiently big for application as an image of the event.

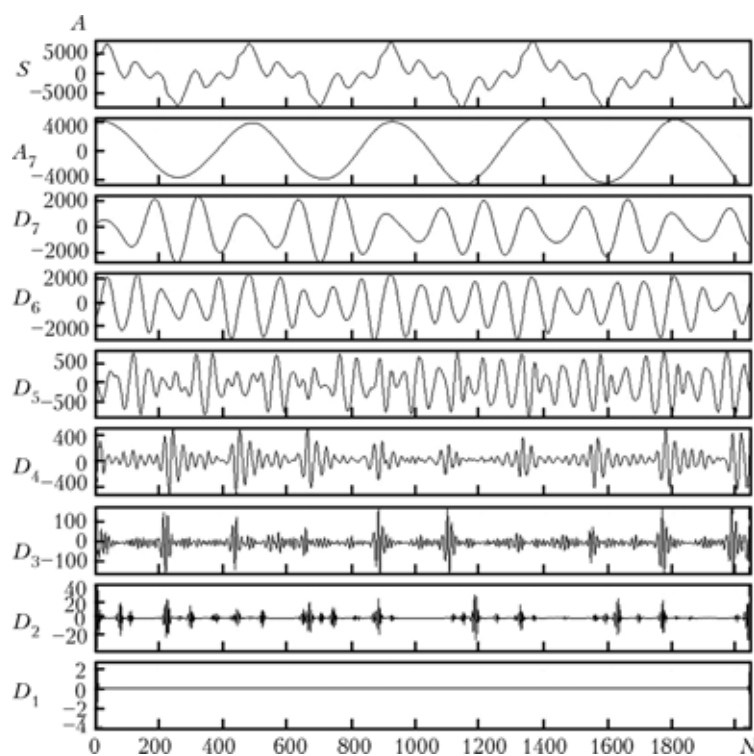


Figure 4. Restored signal

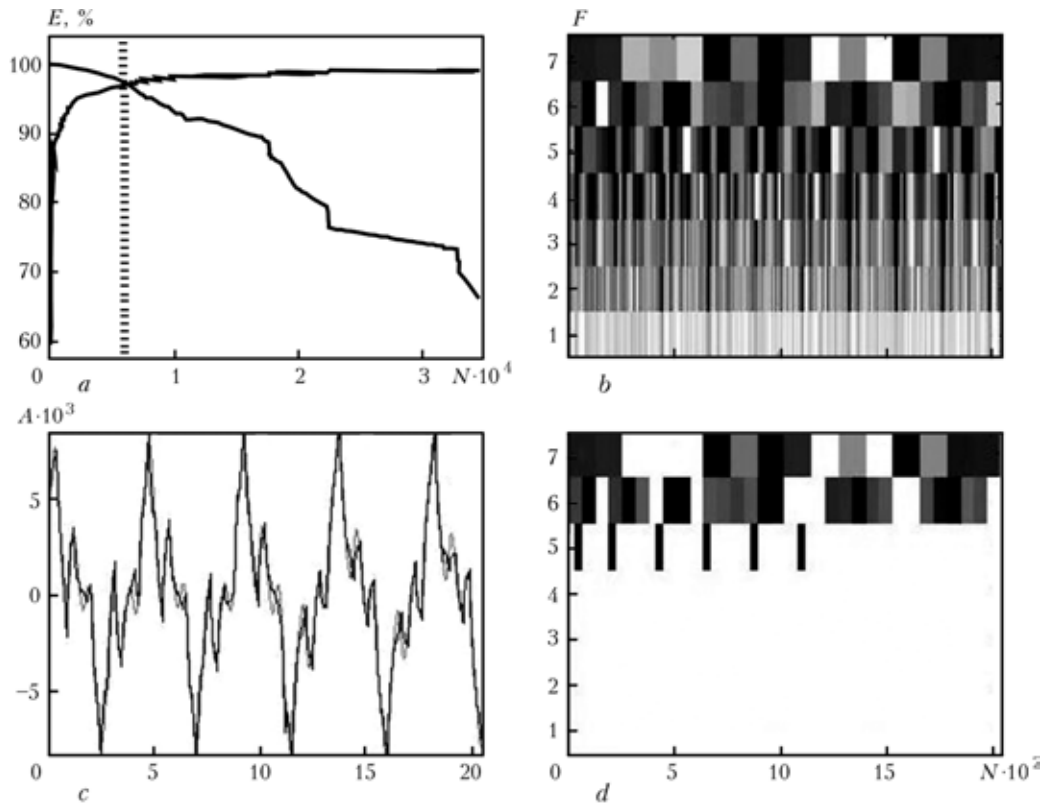


Figure 5. Compression of signal with application of general energy: *a* — criterion of compression is balance E between number of zero coefficients (gray line) and residual energy of signal (dark line); *b* — comparison of initial signal and restored one; *c*, *d* — coefficients of levels of detailing F respectively before and after compression

Because of this reason method of selective choice of meaningful coefficients of wavelet expansion was used. Main information load bear detailing coefficients of second and seventh levels (Figure 5, *d*). At

visual estimation of degree of the signal restoration (Figure 6) 18 values of the approximation coefficients of seventh level and 10 coefficients of sixths and sevenths levels each, which had absolute maximum value,

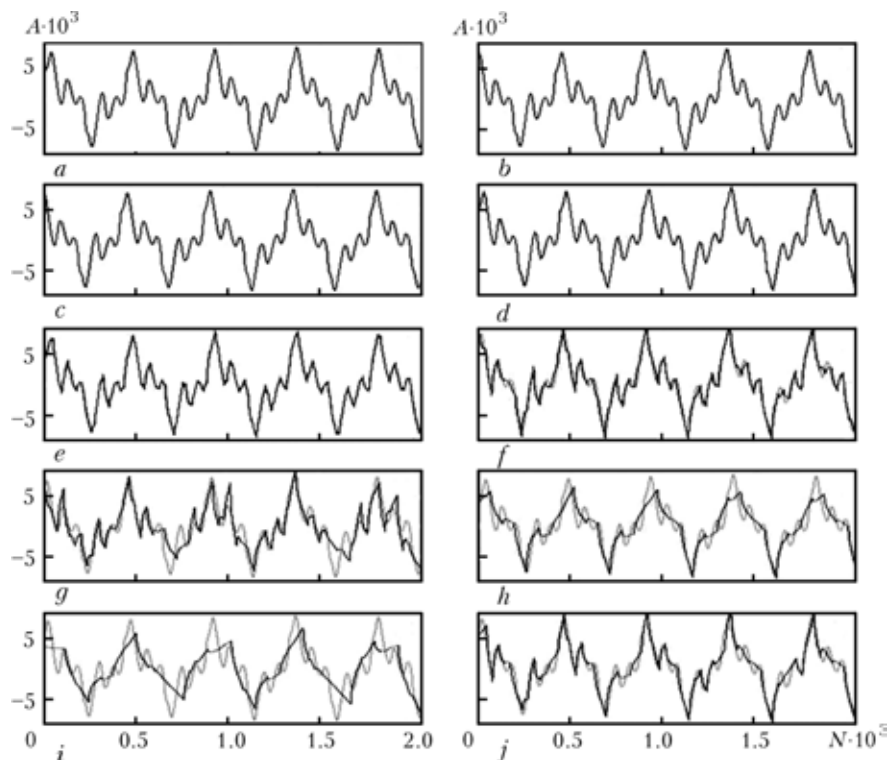


Figure 6. Comparison of results of restoration of signal at different degrees of compression (gray line — initial signal, dark line — restored one): *a* — restoration on basis of 2048 coefficients; *b* — 1038; *c* — 524; *d* — 266; *e* — 136; *f* — 70; *g* — 52; *h* — 36; *i* — 18; *j* — 38 (selective choice)



Figure 7. Signal image

were left, that ensured necessary compression of the signal and sufficient information about initial signal (Figure 6, *j*).

Then obtained coefficients of wavelet-expansion were organized into the vector of properties (image) having 38 coefficients and presenting array of sequentially connected approximation coefficients of seventh level (18 values), detailing coefficients of seventh level (10 values) and detailing coefficients of sixths level (10 values). For each event its image of the signal in the form of a set of coefficients (bar code in Figure 7) was obtained.

As far as signal of 1 s duration was used and image of the event equaled 0.1 s, 10 images were obtained that characterized a specific event. This allowed increasing degree of probability of the event identification.

On basis of presented algorithm of creation of the technological event images the signals were recorded and data of 20 melts in DSP-1 of Belarusian metallurgical plant were processed. Obtained data about each event in different melts were visually and statistically assessed. With 67 % probability images of similar events in different melts coincided, and approximately 15 % of the images were within the area of fiduciary range of coincidence. The rest 18 % of images had deviations from average statistical parameters for each event. That's why for further development of presented identification algorithm of the technological process events it is necessary to use more powerful and flexible methods of classification of presented images (see Figure 7), for example neural networks.

So, developed methodology and algorithm of formation of images of the technological process events in ASF on basis of information about shape of the arc voltage signal, processed with application of wavelet-

analysis, allowed obtaining images that characterized dynamics of development of the events.

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