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CHAPTER 2

MODERN TECHNOLOGICAL PROCESSES OF OBTAINING CAST PRODUCTS AND STRUCTURES OF RESPONSIBLE PURPOSE FROM ALUMINUM, FERROUS CARBON AND HEATRESISTANT ALLOYS

CHAPTER 2

ABSTRACT

The chapter presents the results of scientific research and development of new highly efficient foundry technologies for the production of cast and composite structural materials and products with high operational characteristics from alloyed and reinforced aluminum, iron-carbon and heat-resistant alloys.

The latest technological processes for the production of cast construction materials from aluminum alloys combine the influence of electromagnetic, plasma kinetic, centrifugal actions on metal systems in a vacuum, which makes it possible to obtain large-sized custom products for the space and atomic industries by the casting method.

The results of theoretical and experimental studies using the method of jet gas cooling of molds in a vacuum for obtaining blades of gas turbine engines (GTE) with a regular directional casting structure are given.

Promising technologies for obtaining cast iron and steel reinforced structures based on gasification patterns by liquid-phase combination of system components have been developed. The results of the study of the thermal state of the reinforced casting by the methods of mathematical and computer modeling are presented, the physical model of mass and heat transfer of reinforcing elements and matrix alloy during the formation of the structure and properties of cast reinforced structures is presented.

The works carried out by the authors at the Physical and Technological Institute of Metals and Alloys of the National Academy of Sciences of Ukraine are of high scientific and practical importance for the development of foundry production and will be useful for foundry product manufacturers, scientific and scientific-pedagogical workers in the specialty "Metallurgy" (Foundry production).

KEYWORDS

Aluminum alloys, vacuum magnetohydrodynamic mixer, continuous ingot casting machine, modification, heat-resistant corrosion-resistant nickel alloys, gas turbine engine blades, directional crystallization, composite castings, cast reinforced structures, iron-carbon alloys, lost foam casting.

The development of mechanical engineering is largely related to the production of cast products from aluminum, iron-carbon and heat-resistant alloys with the required level of physical, mechanical and operational characteristics, the improvement of existing ones and the creation of new materials and technologies based on them with enhanced functionality.

A promising direction is the use in industry of composite materials that have high anti-friction properties, thermal and electrical conductivity in a wide temperature range. Currently, various technologies for obtaining composite products are being created and their nomenclature is expanding. At the same time, the requirements for operational characteristics and special properties of structural materials are constantly growing, and modern processes of their production do not provide the necessary technical and economic indicators.

The high quality of structural materials can be ensured by using the latest methods of preparing alloys, based on the intensification of the processes of interaction of gas, liquid and solid phases with the melt. The use of plasma, centrifugal and electromagnetic actions on metal systems in a vacuum provides wide opportunities for the creation of effective technologies for mass and special purpose metal production, based on the processes of treating alloys with dispersed and active reagents in a highly reactive state.

The creation of such breakthrough technologies for obtaining high-quality structural materials with economical consumption of energy resources and materials is relevant and meets the requirements of science and practice at the current stage.

It is at the basis of the further recovery and development of the domestic foundry industry that the above concept will be used to provide the machine-building complex of Ukraine with mono- and reinforced cast structural materials and products from high-strength aluminum and iron-carbon alloys with a reduced mass by 2…3 times and an increase in resource by 3…5 times, and this will provide the needs of highly competitive products for the Ukrainian and foreign consumers, as well as make it possible to reduce the overall metal content of engineering products, primarily vehicles, by 25…30 %, increase its resource by 1.5…2 times and at the same time reduce material costs and energy costs during its production by 30…50 %.

To achieve the goal, the authors used original methods of strengthening alloys with transition and rare earth metals and particles synthesized in the matrix melt under magnetodynamic, centrifugal, vacuum, and plasmakinetic effects on the processes of mass transfer, physicochemical, and interphase interactions in metal systems; the influence of the reinforcement of alloys in the liquid phase state on structure formation and heat and mass exchange processes during the production of castings by lost foam casting was investigated and determined; the technology of obtaining blades of gas turbine engines (GTE) with a regular directional casting structure was researched and improved.

2.1 MODERN PROCESSES OF OBTAINING CAST STRUCTURAL MATERIALS FROM ALUMINUM ALLOYS OF RESPONSIBLE PURPOSE

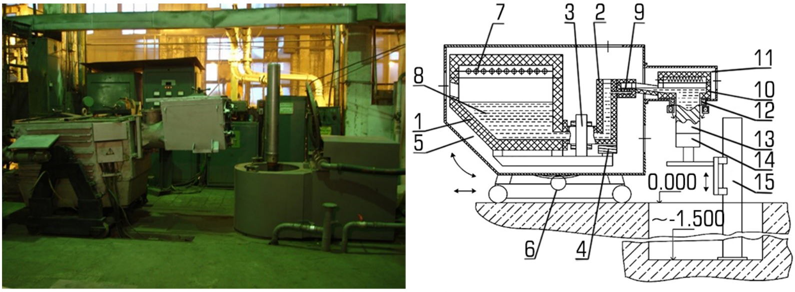
The high quality of structural materials made of aluminum alloys is ensured by new technologies for their preparation, which are based on the intensification of the processes of interaction of gas, liquid and solid phases in the melt. The use of electromagnetic, plasma, centrifugal and vacuum effects on metal melts allows for effective processing of alloys with dispersed and active reagents in a highly reactive (liquid, vaporous and gaseous) state. The creation of such technologies for the production of high-quality construction materials with economical consumption of energy resources meets the requirements of science and practice at the current stage.

The Physical and Technological Institute of Metals and Alloys of the National Academy of Sciences of Ukraine (PTIMA of the National Academy of Sciences of Ukraine) has developed and successfully operates electromagnetic melting and pouring equipment for the preparation of aluminum alloys and the production of continuously cast ingots from them [1]. The equipment includes a vacuum magneto-hydrodynamic mixer (MHD-mixer) and a continuous ingot casting machine (CICM) (**Fig. 2.1**).

The operation of the MHD mixer is based on the process of converting electrical energy into thermal energy, in which the primary winding is an inductor, and the secondary winding is a flow of liquid metal in the channel and mixer crucible. The operation of such equipment is as follows: after filling the U-shaped horizontal channel with liquid metal, voltage is applied to the inductor and electromagnet. As a result, an alternating electric current is induced by the magnetic flux of the inductor in the melt, which fills the horizontal channel. This current heats the alloy at a rate that depends on its magnitude. As a result of the interaction of the current in the melt and the magnetic field of the electromagnet, the alloy circulates in the channel and crucible of the mixer.

When the voltage on the electromagnet of the MHD-mixer increases, the electromagnetic force increases, under the influence of which the melt moves along the metal conduit to the crystallizer. At the same time, the alloy is affected by an electric current, a magnetic field, hydrodynamic and vortex pulsations in the liquid metal. Such actions intensify the processes of assimilation of alloying and modifying elements by the melt and average its chemical composition in the entire volume. At the same time, in the channel of the MHD mixer, in the area of the melt, through which the magnetic flux from the electromagnet passes, an "active zone" is formed, in which the alloying and modifying components introduced into the alloys are maximally influenced by magnetohydrodynamic factors. The presence of such factors makes it possible to intensify the dissolution processes of the introduced components at reduced heating temperatures of aluminum alloys [2]. As a result, the content of gases in the melt and its oxidation, as well as the consumption of electricity for the alloy preparation process, are reduced.

The channel, crucible and electromagnetic system of the MHD mixer are placed in a vacuum chamber, where the liquid metal is refined with its constant stirring. Regardless of the initial content of hydrogen in the melt, vacuum refining in the MHD mixer allows reducing its residual concentration in the alloy to 0.05...0.12 cm^3/100 g of metal, which allows obtaining ingots without gas porosity. For the vacuum refining of aluminum alloys with a high (more than 4 % by mass) zinc content, a technology has been developed that allows to eliminate the loss of alloying elements by evaporation [3]. For products of responsible purpose, a method of refining alloys using successive vacuum pulses has been created, which ensures the residual content of hydrogen in ingots at the level of 0.01...0.03 cm^3/100 g of metal [4]. Methods of operational control of hydrogen content in liquid metal [5] were also developed, which made it possible to automate the processes of preparing alloys with the help of industrial devices.

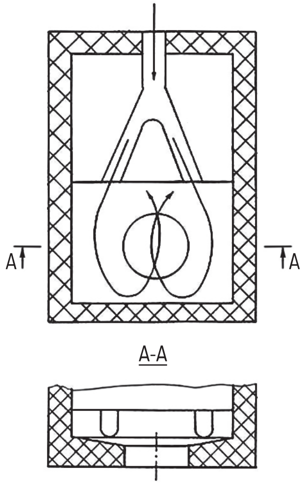


1 – crucible;
2 – metal conduit;
3 – inductor;
4 – electromagnet;
5 – vacuum chamber;
6 – vacuum chamber rotation drive;
7 – heating elements;
8 – liquid metal;
9 – camera with foam ceramic filter;
10 – thermal nozzle;
11 – filling device;
12 – crystallizer;
13 – ingot;
14 – seed;
15 – mechanism of vertical movement of the crystallizer

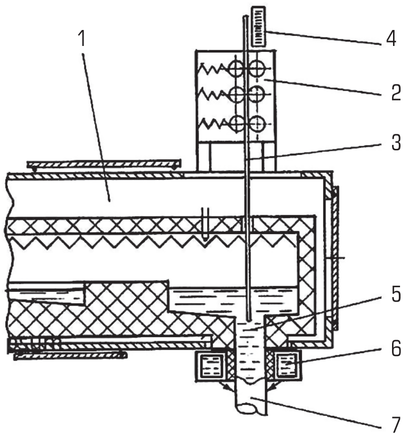
Fig. 2.1 Vacuum MHD equipment for the preparation of aluminum alloys and continuous casting of ingots from them

After vacuuming, the alloy from the MHD mixer is passed through a chamber with a porous ceramic filter under adjustable electromagnetic pressure. As a result of filtration, the alloy is cleaned of oxide inclusions to a residual concentration of ≤0.05 vol. %. The purified alloy enters the pouring unit, which is attached to the front wall of the vacuum chamber of the MHD mixer and is also a vacuum chamber in which the thermal nozzle is placed. The melt fills the thermal nozzle with two laminar flows (**Fig. 2.2**), which contributes to the mixing of the melt, averaging its temperature, and excludes mixing of oxide films into the alloy. The thermal nozzle is equipped with heating elements, which allows to compensate for the heat loss of the melt on the way of its movement from the MHD mixer to the crystallizer, and also reduces the temperature gradient along the height of the overflow part of the ingot, thereby creating favorable conditions for its directional crystallization.

Continuous modification of the alloy during the production of ingots at the CICM can be carried out with a ligature rod, which is fed into the liquid metal during pouring (**Fig. 2.3**). It is expedient to insert the rod into the zone of melt vortices formed by its two tangential flows of melt. As a result, intermetallics and modifiers are evenly distributed throughout the volume of the liquid phase of the ingot during crystallization.



⬡ **Fig. 2.2** Flow diagram of the melt in the heat nozzle

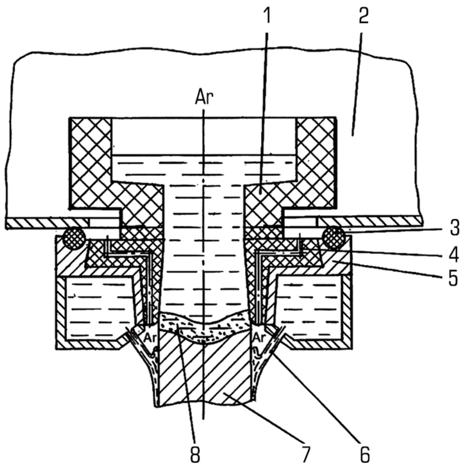


1 – thermal nozzle;
2 – ligature rod feeding device;
3 – ligature rod;
4 – crystallizer;
5 – ingot

⬡ **Fig. 2.3** Device for feeding the ligature rod into the melt

The complex of vacuum MHD equipment includes a vertical type CICM with smooth adjustment of the speed of movement of the casting table. The CICM is equipped with a low (*h* – 33 mm) crystallizer, the feature of which is the use of a heat-insulating lining layer with low thermal conductivity [6], which ensures the absence of radial heat dissipation from the liquid metal along the height of the crystallizer and leads to a significant decrease in the depth of the hole and the height of the transition zone of the ingot during crystallization and positively affects its structure. A gas-forming coating is applied to the inner surface of the crystallizer, during sublimation of which a gaseous layer is formed around the perimeter of the ingot, which also reduces heat removal from the ingot through the wall of the crystallizer. Thus, a thin film of crystallized metal is formed in the crystallizer, and the crystallization of the inner layers of the ingot takes place in the water-cooling zone below the level of the crystallizer. The speed of heat removal from the crystallizing ingot is a key parameter for controlling the structure of the ingots, therefore, the CICM is equipped with a system of adjustable coolant supply to the ingot.

When preparing highly oxidizable alloys in the MHD mixer, such as the Al-Mg system, it becomes necessary to protect the melt using an inert gas. For this purpose, it is possible to seal not only the furnace space of the MHD mixer, but also the entire metal tract, including the crystallizer of the machine for continuous casting of ingots [7] (**Fig. 2.4**).



1 – thermal nozzle;
2 – distribution unit;
3 – seal;
4 – channel for the passage of protective gas;
5 – crystallizer;
6 – cooling liquid;
7 – ingot;
8 – solid-liquid phase of the ingot

Fig. 2.4 Scheme of a crystallizer for creating a protective atmosphere around the solid-liquid phase of the ingot

Electromagnetic stirring of the liquid phase of the crystallizing ingot affects heat and mass transfer processes, the intensity of convective flows in the melt, and also creates shear stresses along the crystallization front of the alloy. As a result, the dendritic structure in the alloy is destroyed with transformation into a globular form [8]. An electromagnetic stirrer of the liquid phase of the ingot can be placed on the CICM crystallizer, which increases the efficiency of the processes of dispersing structural components in ingots during continuous casting.

The created MHD equipment makes it possible to obtain high-quality ingots from aluminum deformable alloys with high chemical uniformity, without internal defects, having a homogeneous fine crystal structure and a smooth shiny surface that does not require mechanical processing before pressing. Technical characteristics of the complex of vacuum MHD equipment: the maximum capacity of the crucible is 200 kg, diameters of ingots are from 50 to 250 mm; the length of ingots is up to 1500 mm.

The vacuum MHD mixer can also be used for casting under combined (electromagnetic and pneumatic) pressure, for dosing and controlled programmable electromagnetic pouring of liquid aluminum alloys into casting molds, including in the hopper of centrifugal casting machines for obtaining custom blanks.

The space and atomic industries require large-sized custom products made of aluminum alloys (rings, bushings, bandages, pipes), which are most often obtained by welding rolled sheets or rolling continuously cast ingots after piercing them. These technologies have a low rate of metal use, high labor intensity and cost. It is more expedient to obtain custom-made products by the centrifugal casting method, which allows to intensify the process of crystallization of the alloy and disperse its structure. During crystallization of alloys under the action of centrifugal forces, the density and homogeneity of cast products increase. Crystallization of alloys under high pressure leads to a shift in the boundaries of phase transformations. At the same time, phases absent in the equilibrium diagrams can be obtained. In addition, it is possible to achieve wetting between phases, if it was absent under normal conditions. For the implementation of centrifugal casting technologies, the PTIMA of the National Academy of Sciences of Ukraine produced a machine for the production of custom castings, bushings and pipes up to 800 mm in length and up to 450 mm in diameter at an adjustable casting speed of up to 3000 rpm (**Fig. 2.5**).

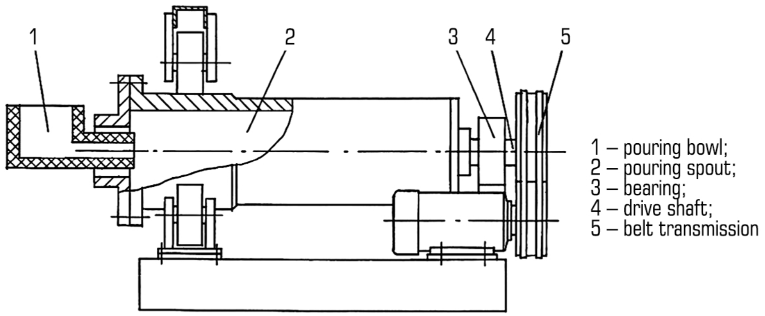
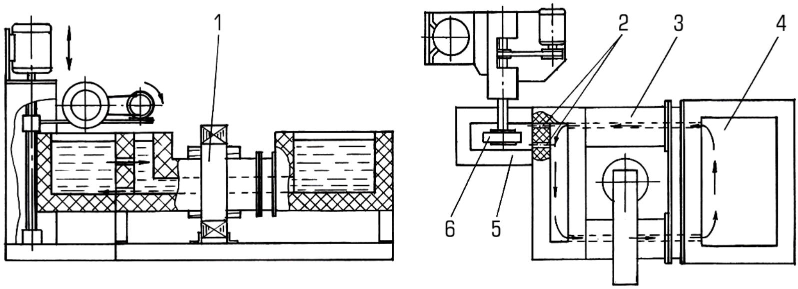


Fig. 2.5 Diagram of a centrifugal casting machine

For the production of cast and composite products from aluminum alloys, dispersed particles, fibers and powders are widely used. In foundry production, it is also advisable to use quickly crystallized ligatures. Such dispersed materials with a homogeneous structure can be produced by the method of extracting the melt in an electromagnetic field [9]. For the implementation of such technologies, electromagnetic equipment [10] has been created at the PTIMA of the National Academy of Sciences of Ukraine, which includes an MHD installation and a water-cooled disk-crystallizer with adjustable rotation speed (**Fig. 2.6**). When the crystallizer disk comes into contact with the surface of the melt, the alloy freezes on its ribbed surface, from which it is thrown into a separate hopper. The shape of the crystallized particles varies depending on the geometry of the disc's ribbed surface and the speed of its rotation.

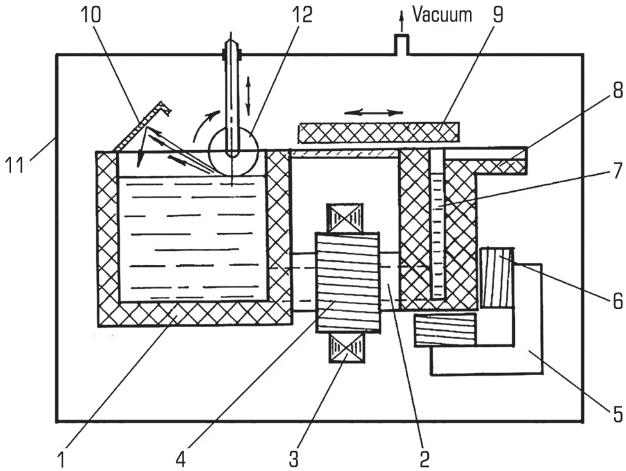
For the modification (alloying) of aluminum alloys with fine-crystalline particles and fibers, a method was proposed and equipment for melt processing was created [11]. According to this method, the liquid metal modification operation is carried out in a vacuum with dispersed particles, which are extracted from the matrix melt during the preparation of the alloy in the MHD installation (**Fig. 2.7**).

The alloy solidifying on the crystallizer disk is thrown onto the screen by centrifugal forces in the form of particles and fibers. Dispersed particles of the alloy are reflected from the screen and fall into the liquid metal bath. Fine-crystalline fibers and particles that fall into the metal, related to the matrix alloy, are well wetted and assimilated by it. As a result, the processes of nucleation in the alloy during crystallization are intensified, which contributes to the grinding of structural components in the cast metal.\The technology of obtaining powder from aluminum melt, which is in an electromagnetic field, has been introduced into industrial production. MHD mixer (**Fig. 2.8, *a***) is installed on the melting furnace with a capacity of 1.5 tons, which is made in the form of a U-shaped horizontal channel with an open vertical section for installing a nozzle. The channel is connected to the melting crucible of the furnace and covers the inductor with a W-shaped magnetic conductor, on the central rod of which there are coils.



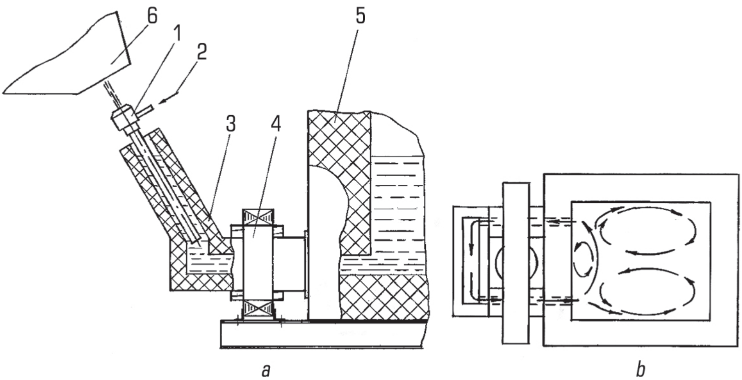
1 – inductor;
2 – overflow holes;
3 – channel;
4 – crucible;
5 – distribution department;
6 – disk-crystallizer

Fig. 2.6 Schematic of MHD equipment for obtaining rapidly crystallized aluminum fibers and powder



1 – crucible;
2 – channel;
3 – inductor;
4 – coil;
5 – electromagnet;
6 – electromagnet coil;
7 – central metal wire;
8 – gutter;
9 – crucible cover;
10 – screen;
11 – vacuum chamber;
12 – rotating disk-crystallizer

Fig. 2.7 Scheme of the MHD unit for processing aluminum alloys with fine crystalline particles



1 – nozzle;
2 – compressed air;
3 – channel;
4 – inductor;
5 – resistance furnace;
6 – powder hopper

Fig. 2.8 Diagram: *a* – of the equipment for obtaining aluminum powder; *b* – the movement of the melt in the crucible of the resistance furnace during electromagnetic stirring

The use of continuous electromagnetic stirring made it possible to eliminate the formation of stagnant zones in the melt (**Fig. 2.8, *b***), reduce overheating and stabilize its temperature at the level of 790 °C±10 °C. Lowering the alloy preparation temperature by 50...60 °C made it possible to reduce the oxidation of crystallized particles and improve the quality of the powder. Due to the heating of the melt in the active zone of the annular horizontal channel, the temperature of the metal at the exit from the nozzle is 840...850 °C. At such injection temperature regimes, crystallization of the melt near the nozzle of the nozzle is excluded and its service life is increased. At the same time, the productivity of aluminum powder production increases from 300 to 500 kg/h.

The use of plasma technology opens up wide possibilities for the creation of combined processes that will allow treating alloys with a high-temperature gas jet with simultaneous heating, melting or evaporating fluxes and special additives. The plasma thermo-kinetic influence brings the reagents into a highly reactive physico-chemical state, which intensifies the processes of their interphase interaction with the melt.

The Physical and Technological Institute of Metals and Alloys of the National Academy of Sciences of Ukraine has created processes for vacuum-plasma processing of non-ferrous alloys that have no analogues abroad [12–16]. Such technologies make it possible to process alloys with plasma in a vacuum during portioned and continuous pouring of metal with the help of simple equipment (**Fig. 2.9**). The plasmatron together with the camera is immersed in the melt and a vacuum is created. The metal in the chamber rises to a certain height, which depends on the amount of vacuum above the surface of the liquid bath. Vacuum sealing of the chamber during alloy processing provides the melt in which it is immersed.

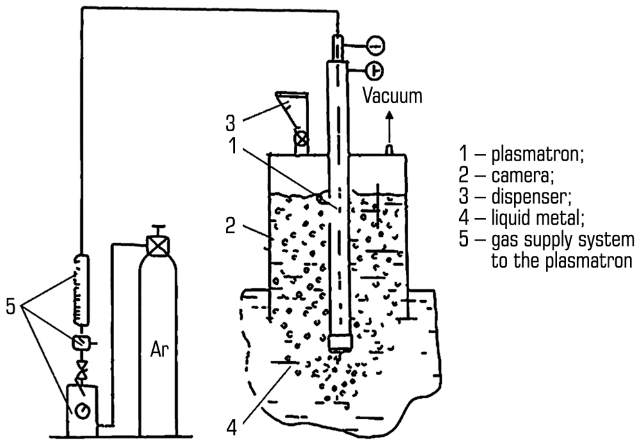


Fig. 2.9 Scheme of melt processing with a vacuum-plasma unit

The diameter of the chamber and the location of the plasmatron nozzle are chosen so that all gas bubbles enter the chamber during metal blowing. In this case, the surface of the melt outside the chamber is in a calm state, the oxide film or the flux applied to its surface prevent the inflow of hydrogen from the atmosphere into the melt during processing.

The necessary reagents are preloaded into the dispenser, and then fed into the chamber in the process of metal processing. The reagents are mixed in the upper layers of the melt, where the highest intensity of mass transfer is achieved during blowing with a gas jet, and are evenly distributed in the metal.

The industrial development of such technologies has shown that vacuum-plasma processing of aluminum alloys allows: to heat the melt in the process of refining or modification; reduce the amount of non-metallic inclusions in the alloy by 1.5...2 times, the hydrogen content – up to 80 %; reduce by 3–4 times (or eliminate the use of) the consumption of reagents for the processing of alloys. Along with this, after vacuum-plasma treatment in the melt, the average size of microclusters decreases by 2–2.5 times (from 26.8 to 11.2 nm), the tensile strength of the cast metal increases by 14–25 %, the relative elongation by 1.5...1.8 times.

Employees of the PTIMA of the National Academy of Sciences of Ukraine have also developed complex environmentally friendly processes for processing and pouring aluminum melts using the created MHD equipment, in which vacuum-plasma systems are installed [17–21]. Such technologies, due to thermoforce effects on liquid metal, allow:

– intensify structural and phase transformations in alloys;

– disperse intermetallics and microgroups in alloys;

– evenly distribute alloying and strengthening particles in the liquid metal bath;

– control the rate of crystallization of the alloy;

– effectively doping alloys with active metals, in particular, using consumable electrodes in plasmatrons;

– treat alloys with carbon and silicon nanoparticles synthesized by reactions of carbon with silicon-containing media on crystalline metal centers and compounds that are introduced into the melt;

– increase the efficiency of plasma heating of liquid metal to ≥90 %;

– change the structure and properties of cast products by effective plasma effects on alloys (dissociation of gases, ionization of atoms, controlled energy and density of charged particles, etc.).

According to the results of research of hydrodynamic, heat-mass transfer and physico-chemical processes in metal melts during their deep processing with plasma reagent media, the following were determined:

1. The temperature of the plasma jet immersed in the liquid metal increases to 5000 °C when approaching the plasmatron nozzle. In the zone of introduction of a deep plasma jet into the melt, the temperature of the alloy is 400–600 °C higher (with cold blowing – ~100 degrees lower) than its average mass temperature. As a result, during plasma treatment, the processes of gas-reactive interaction in alloys, as well as mass transfer of hydrogen in the superheated melt, are intensified.

2. The rate of heating of solid particles with a dispersion of 50...100 μm in the plasma jet is 350...490 degrees/ms. Reagents used for processing aluminum and copper alloys, when introduced through a plasmatron, are heated and enter the melt in a highly reactive (liquid and vapor) state. As a result, the processes of interaction of reagents with the melt intensify and the degree of their assimilation increases.

3. It was established that during the cooling of plasma-heated argon bubbles to the average mass temperature of the aluminum melt (0.1...0.4 ms), their radii decrease by 15...40 %, and the boundary layer renewal time on them decreases by 1.5...2.5 times.

4. When blowing with a plasma jet, the intensity of mass transfer processes in the melt is 25–70 % higher than with cold argon. Treatment of the melt with reagents in the liquid state makes it possible to increase the rate of mass exchange in the bath by 20...30 % compared to the solid one. At the same time, regardless of the depth of outflow of the cold or plasma jet, the maximum mixing and turbulization of the melt occurs in the surface layers of the bath.

5. In the reaction zone of the plasma jet, along with the thermo-time treatment of the alloy, evaporation of its components with rapid cooling ("condensation") of vapors in the melt being processed is possible. Dispersed particles of such "condensate" intensify the process of nucleation of components in alloys and contribute to the emergence of synthesized strengthening phases in the melt. At the same time, intermetallic and oxide inclusions are destroyed under the high-temperature influence ("thermal shock") of the plasma jet.

2.2 EFFECTIVE PROCESSES FOR OBTAINING CAST TURBINE BLADES FOR MARINE AND POWER GAS TURBINE ENGINES

2.2.1 MODERN TECHNOLOGIES FOR OBTAINING WORKING BLADES OF GAS TURBINE ENGINES

Increasing the service life of gas turbine engine (GTE) blades is associated not only with the development of new composite heat-resistant alloys, but also with methods of controlling the process of crystallization of castings from these alloys. In this regard, research is being carried out on such processes that ensure the formation of given structures in the parts, which guarantee the preservation of the necessary characteristics of the part during the given resource of its operation [22–25]. It is known that GTE blades are obtained by two methods, namely, equiaxial casting and casting with directional crystallization (DC).

Nickel alloys have high strength at high temperatures, because the formation of fatigue cracks occurs between grains. Therefore, it is better to have a blade with fewer grains and the ability to control their orientation. These questions are studied in many scientific centers of domestic and foreign scientists. The main reasons for the destruction of turbine blades are the grain boundaries, which are perpendicular to the direction of the external load. In order to improve the long-term strength of nickel heat-resistant alloys, it is necessary to have a directional structure in which the grain boundaries are parallel to the direction of action of the principal stresses. One of the ways to further develop DC technologies is to obtain blades with a monocrystalline structure. Studies show that the destruction of the blades occurs mainly through the grain boundaries, which are perpendicular to the vector of the external load on the turbine blades.

In order to improve the long-term strength of nickel heat-resistant alloys, it is necessary to provide a directional structure in which the grain boundaries will be parallel to the direction of the main stresses. The use of monocrystalline blades can significantly increase the resource and capacity of gas turbines by 20...30 % and 10...15 %, respectively, which makes them more efficient [26, 27].

Although the casting of blades with a polycrystalline structure is more common than casting with a directional or monocrystalline structure, many researchers are engaged in the development of new methods of manufacturing blades with a more directional structure to increase their strength and durability.

One of the main factors determining the prevalence of casting blades with a polycrystalline structure is the lower complexity of the technological process compared to casting with directional and monocrystalline structures. To achieve better quality when casting GTE blades with a polycrystalline structure, vacuum melting units with heated molds (VMUHM) are used. One of the main parameters that are controlled during such a process is the depth of the vacuum, the temperature of the melt during the melting process, and the temperature of the mold heating furnace.

As a rule, at enterprises, turbine cooling blades are melted to obtain a polycrystalline structure, since it is impossible to obtain such blades by the method of directional crystallization with the required crystallographic orientation. At gas turbine manufacturers, cast turbine blades without internal cooling are produced with a directional structure or a monostructure, depending on the responsibility of the purpose.

Numerous methods of obtaining oriented dendritic and single crystal structures are presented and analyzed in the scientific and patent literature, such as the Bridgman, Shubnikov, Kiropoulos, Stockberger, Chochralsky method [28]. These methods can differ both in the method of heating and maintaining high temperatures in a ceramic mold with a crystallized melt, and in cooling the finished product, that is, in the method of heat removal.

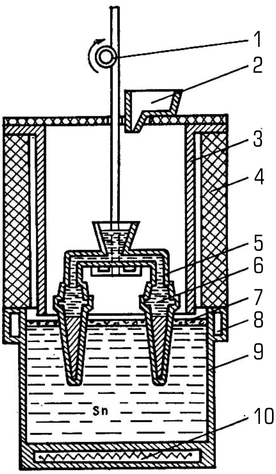
The main methods of heating during the production of parts with a directional structure include, first of all, the following: direct induction heating, use of a resistance heater. The world's leading manufacturers of gas turbine installations use the Bridgman-Stockbarger (High Rate Solidification – HRS) method for manufacturing gas turbine blades [29]. The essence of the method is that in the heating zone, the alloy is poured into a ceramic mold that stands on a copper cooling crystallizer. Then the crystallizer is vertically moved into the cooling zone at a given speed, as a result of which a temperature difference is created at the crystallization front. Intensive heat removal is carried out in the lower part of the mold through a copper crystallizer, the upper part of the mold with melt is cooled by heat radiation from the side surface of the mold to the walls of the chamber. Such heat removal leads to slow cooling rates of castings, as a result of which a directional structure is formed.

The main tasks of thermal calculation in the development of the directional crystallization process are the determination of the following technological parameters: cooling rate of castings; temperature gradient at the crystallization front; crystallization speed of parts; the length of the transitional solid-liquid zone of the alloy and its location relative to the level of the cooler or heater.

A mandatory condition for obtaining a directional structure is the support during melting of the directional solidification of the liquid metal of the flat crystallization front. During the heat flow, the speed of advancement of the crystallization front practically becomes constant, which depends on the method of removal of the heat of crystallization.

In the practice of manufacturing-oriented parts, the so-called high-speed directional crystallization using a liquid metal cooler – the Liquid Metal Cooling (LMC) method [30] has received wide industrial application. This method makes it possible to obtain an oriented structure with crushed dendrites, small inter-dendritic distances and more dispersed and homogeneous secondary phases (carbides, intermetallics) in conditions of high-gradient cooling of the mold, for example, in liquid aluminum or tin, which leads to a significant increase in the mechanical level of alloys, including its long-term strength and plasticity.

Furnaces with liquid metal cooling (**Fig. 2.10**) can be used both for casting blades from eutectic heat-resistant alloys and from nickel-based alloys with intermetallic strengthening. The rate of crystallization in the first case is 0.1...0.2 mm/min, in the second 10...15 mm/min. Accelerated cooling of the alloy leads to the formation of a current dendritic structure, while endurance can be increased by 15–20 % compared to an alloy cast at a lower speed.



1 – mechanism for lowering the mold into the cooler (tin);
2 – bowl for draining metal into a mold;
3 – mold heating furnace;
4 – thermal insulation;
5 – shell form made of electrocorundum;
6 – working alloy;
7 – heat shield consisting of ceramic granules;
8 – refrigerator;
9 – cooler capacity;
10 – heater

Fig. 2.10 Scheme of a high-gradient installation for obtaining castings with directional crystallization

Domestic gas turbine manufacturers use UVNK-8B industrial units with a tin crystallizer and UVNK-8P with an aluminum crystallizer. The alloys obtained by this technology have a small (8–10 times smaller) microporosity (up to 0.1 %) and a finely dispersed homogeneous structure (inter-dendritic distance 100–150 μm), which provides an increase in strength by 10–15 % and fatigue properties by 20...25 % compared to alloys obtained at normal temperature gradients (20...30 degrees/cm) [31]. The best results are obtained if the melt is preliminarily subjected to high-temperature treatment, and the obtained blanks are subjected to thermovacuum treatment. This ensures minimum values of dispersion of service properties and maximum reliability of blades. The liquid metal used for mold cooling must meet a number of requirements: high thermal conductivity and heat capacity, relatively low melting point, small value of partial pressure at the contact temperature, low adhesion to the surface of the molds, low cost and non-scarcity. In addition, the accidental ingress of liquid metal coolant into the alloy should not lead to deterioration of the latter's properties.

Since the production of GTE blades from heat-resistant alloys is carried out in a vacuum, only metal melts with low vapor elasticity in a vacuum at temperatures of contact with the mold (1100 °C) can be used as liquid cooling media.

When casting large-sized blades, there are difficulties associated with the use of a bulky beam containing a large volume of molten aluminum. During the immersion of the mold in aluminum, there is a significant change in the level of the melt in the bath, which slows down the speed of drawing the mold and, accordingly, reduces the productivity of the casting process to achieve the necessary longitudinal gradient during crystallization. Also, during casting, the installation is contaminated with aluminum (Al) and silicon (Si) oxide sublimates, which creates a risk of foaming of the aluminum melt. In the event of a mold break with heat-resistant alloy melt, it is necessary to replace the bath with aluminum. In addition, in molten aluminum, the solidified areas of the vane are cooled at an excessively high rate, which can lead to warping and cracking of the vanes, especially in the area of oversized banded vanes.

The company Houmet takes the first place in castings of monocrystalline large-sized blades of powerful energy turbines up to 600 mm long. Since 2005, they have been successfully using the GCC (Gas Cooling Casting) method of jet gas cooling of molds in a vacuum [32]. The GCC technological process involves convective jet cooling with argon in a vacuum of ceramic molds during directional crystallization while preserving the effect of cooling the molds by radiation. This process allows for optimal temperature control during casting, ensuring high quality and perfect crystal structure of the blades. From **Fig. 2.11**, it can be seen that the process of jet gas cooling of forms provides an increase in the productivity of single-crystal casting in comparison with liquid metal cooling by 2...3 times and 1.5 times, respectively. The use of such a process does not require special design and manufacture of new equipment. For this purpose, available in the industry installations with liquid metal cooling can be used, with the dismantling of the aluminum bath and the modification of the installation for the supply and distribution of inert gas.

One of the most effective ways to ensure the necessary characteristics of cyclic strength and durability of blades is to choose the optimal crystallographic orientation relative to the geometry of the blade, taking into account the large anisotropy of mechanical properties. The complete crystallographic orientation of the blade is determined by the axial and azimuthal orientations. Based on the results of numerous studies and practical experience, it has been confirmed that for turbine blades with optimal axial orientation, a set of strength properties is achieved in the [001] direction with an accuracy of $\alpha[001]=10...15°$. Directionally crystallized and single-crystal turbine blades of modern gas turbines are manufactured with this axial orientation [32].

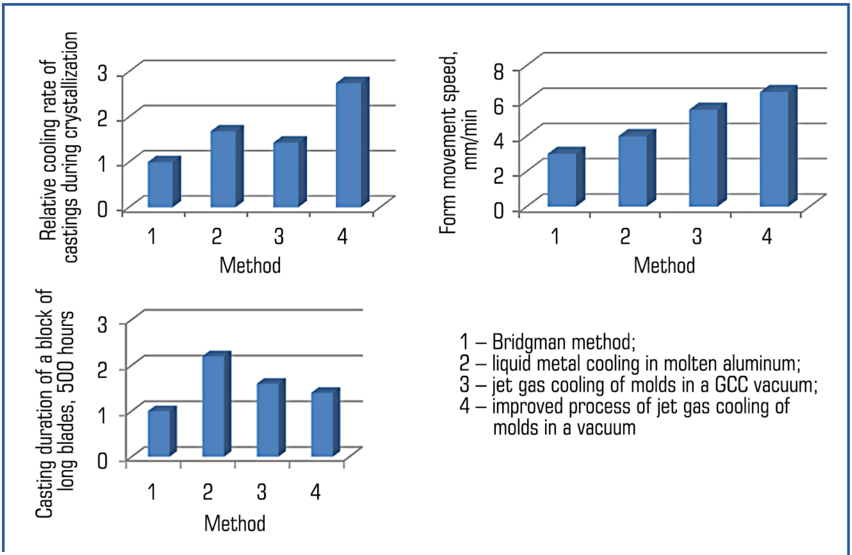


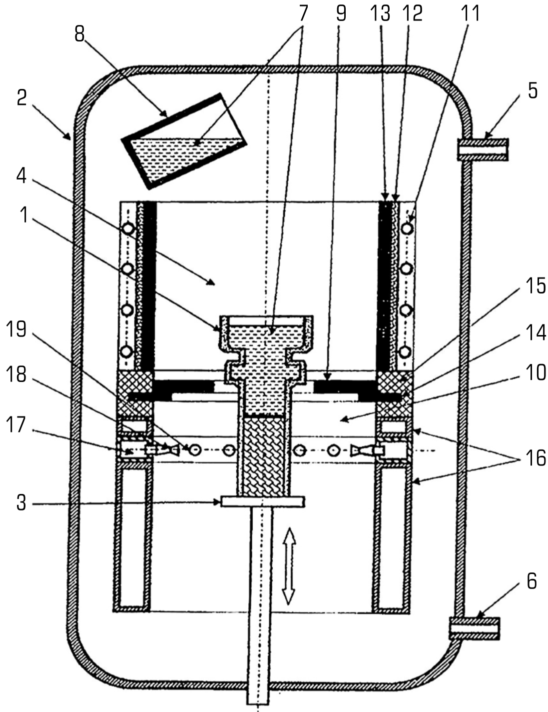
Fig. 2.11 Comparative parameters of DC methods

To achieve a given orientation in cast castings, the seeding method is used [32]. When melting gas turbine blades from heat-resistant nickel alloys, Ni-W alloy is used as a primer (Ni is the base, W 32...36 % by weight).

2.2.2 EXPERIMENTAL STUDIES USING THE GCC TECHNOLOGICAL PROCESS

The analysis of the data presented in subsection 2.2.1 indicates the need to develop new technologies for the production of special purpose products. Among the various options, one of the most promising is the method of jet gas cooling of molds in a vacuum. Within the framework of this method, theoretical and experimental studies were conducted to obtain a regular directional structure of the casting with [001] orientation depending on the conditions of product formation.

For research, a modernized foundry plant was used, which is implemented in the VIM-25-175C unit of the vertical type, which can be used, including for obtaining an oriented dendritic structure in castings. The improvement included the installation of an additional cooling unit using an inert gas, namely argon. In **Fig. 2.12** it is possible to see the installation where the compatible casting crystallization process is implemented. The initial crystallization front is provided using the Bridgman-Stockbarger method (see section 2.2.1), and then, through a special crystallizer and a starting cone, the directed growth of grains in the blades is formed by directed argon blowing through a special system of nozzles. Up to 15 kg of material can be placed in the DC crucible, and the maximum pouring speed is 15 kg/sec per second. The dimensions of the ceramic mold are as follows: diameter – 200 mm, height – 400 mm. To control the temperature of the liquid metal, a thermocouple and an optical two-color pyrometer were used, in particular, a device of the Mikron type, model M-780. The time required to reach a working vacuum of 7×10^{-2} Pa after loading the charge was 2 minutes.



1 – mold;
2 – vacuum casing (vacuum container);
3 – crystallizer;
4 – heating zone of the technological chamber;
5 – pipe for connecting the system;
6 – pipe for connection to the system of additional unloading of the cooling zone of the working chamber;
7 – melt;
8 – crucible of the loading device with melt;
9 – heat-insulating screen with a central hole;
10 – cooling zone of the technological chamber;
11 – heating zone inductors;
12 – thermal insulation of the inductor;
13 – graphite muffle furnace;
14 – locking ring of the heat-insulating screen;
15 – cylindrical wall of the heat-insulating screen;
16 – casing of the process chamber in the cooling zone;
17 – annular gas collector;
18 – gas ejectors;
19 – openings for gas ejectors

Fig. 2.12 Scheme of a foundry installation with an additional cooling unit

For cooling, the inert gas supply device is implemented in the form of a ring gas collector, which is equipped with gas ejectors. Ejectors are located in a row at a distance of 45...75 mm from the lower surface of the heat-insulating screen. These ejectors allow to change the direction of the gas flow for cooling. They are also designed in such a way that it is possible to change the direction of the gas flow for cooling and are located in a row at a distance of 45...75 mm from the lower surface of the heat-insulating screen.

In the inner wall of the annular collector, holes for ejectors are provided, which can be closed with plugs, for the possibility of positioning the ejectors in different variants. For this process, the critical diameter of the nozzles is 0.7...0.9 mm, the opening angle of the bell is 10...15°, and the gas pressure in the critical section of the nozzle is $(7...10)\times10^5$ Pa. The use of this cooling method contributes to the intensification of the melt crystallization process and changes the temperature gradient at the crystallization front in comparison with convective cooling in a vacuum. As a result, the kinetics of structure formation changes significantly (**Fig. 2.12**).

The temperature-speed conditions of the crystallization process, which depend on the speed of movement of the ceramic mold (V_f, mm/min) and the temperature gradient at the crystal growth front (G, K/mm), have a significant effect on the intragranular structure, dispersion, and phase composition of the alloy [33]. Thermal analysis data were used to determine the optimal temperature intervals that affect the structural and phase characteristics of the DC process. With the help of the experiment, the optimal technological parameters for the DC process in the production of working non-cooling blades of the II stage of the power turbine were established. These parameters include the following: top heater temperature is (1560±10) °C, cooler temperature is (1560±10) °C, pouring temperature is (1570±10) °C, crystallization front speed is 10–12 mm/min.

For conducting experimental fusions, a serial heat-resistant corrosion-resistant nickel-based alloy SM88 was used, the chemical composition of which is shown in **Table 2.1** [34]. In order to determine the local values of the parameters of the directional crystallization process during melting, the temperature distribution in the volume of the casting was measured experimentally at five points along the axis of the casting using tungsten-rhenium thermocouples (BP 5/20) with an electrode diameter of 0.30 mm. To obtain turbine blades with a directional structure, a technology was used, in which for each casting, a seed composition of Ni – base, W 32...36 % by weight was added to the bottom of the mold and [001] orientation. By analyzing thermo-kinetic curves built on the basis of the results of experimental measurements (**Fig. 2.13**), it is possible to determine the distribution of temperatures in the metal at any moment in time. The speed of immersion of the mold in the cooling zone directly affects the speed of crystallization of the melt.

Table 2.1 Chemical composition of heat-resistant alloy based on nickel

Element content, wt. %													
C	Cr	Co	Mo	Ti	Al	W	Nb	Fe	B	Zr	Si	Hf	Zr
0.09	15.6	10.7	1.9	4.6	3.0	5.3	0.11	0.5	0.05	0.05	0.04	0.5	0.05

Analysis of the microstructure of the alloy samples was carried out using a scanning electron microscope JSM-35CF of the company "JEOL" (Japan). The resolution of the microscope is up to 1.2 nm, and the accelerating voltage is from 0.5 to 30 kV. Grits for metallographic studies were subjected to chemical etching using the Marble reagent ($CuSO_4$ – 4 g, HCl – 20 ml, water – 20 ml). Phase analysis of alloys and parameters of crystal lattices of phases were determined on the "DRON-3M" installation in CuK_α radiation ($\lambda_{CuK\alpha}$=0.154187 nm).

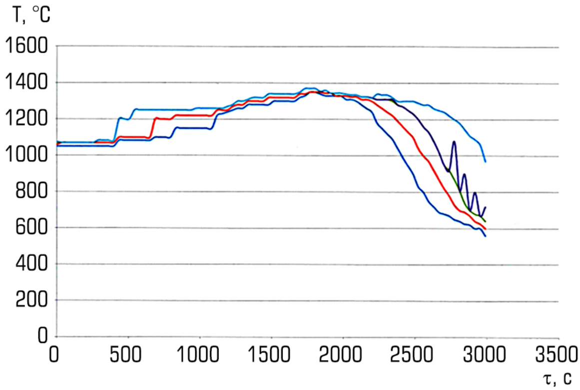


Fig. 2.13 Thermo-kinetic curves of five experimental melting thermocouples with DC

The study of the structure after melting according to the above regimes in the modernized unit showed that the crystallographic orientation (CGO) of the obtained blades, which was determined by the X-ray diffraction method on each block sample, was [001]. The deviation from the orientation does not exceed the permissible angle of deviation from the main axis up to 20 degrees. according to the data presented in [35]. In all cross-sections (**Fig. 2.14**), the macrostructure shows a regular structure that meets the requirements concerning the structure of the second-degree blade samples, according to the technical standards of the enterprise [35].

The microstructure of the as-cast samples is mainly characterized by dendritic heterogeneity, as shown in **Fig. 2.15**. The strengthening γ'-phase has a size variation both in the axes of the dendrites and in the intermediate spaces between them. In the latter, the formation of a carbide phase in the rail morphology is observed, which indicates its eutectic nature. Eutectic structures γ-γ' can also be observed in the intermediate spaces in a limited amount, so the next necessary component of obtaining high-quality products is their heat treatment according to the enterprise standard.

The introduction of additional cooling in the improved design of the casting unit VIM-25-175C led to the improvement of the cooling process of the crystallizer during directional crystallization and ensured obtaining a regular structure of castings.

The analysis of the technical literature, the current state of the issue and experimental studies showed that the works devoted to improving the quality of structure formation of blade castings with directional crystallization are promising and require further improvement.

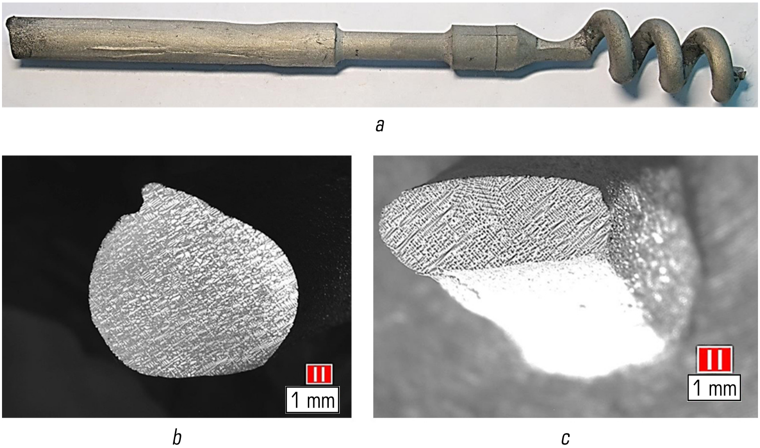


Fig. 2.14 Macrostructure of the sample in the cast state: *a* – appearance of the sample; *b* – macrostructure of the middle part of the sample; *c* – section from the seed (near the cone)

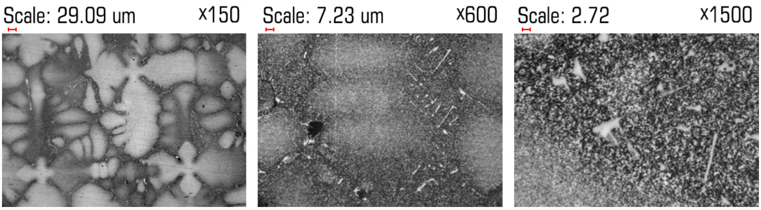


Fig. 2.15 Microstructure of test samples in the cast state at different magnifications

2.3 PROMISING TECHNOLOGIES FOR OBTAINING CAST IRON AND STEEL REINFORCED STRUCTURES BY LOST FOAM CASTING

2.3.1 METHODS OF OBTAINING PRODUCTS WITH HIGH SPECIAL PROPERTIES

Special properties in products are obtained by various methods: mechanical or chemical-thermal treatment of materials, casting, forging, welding, riveting and combined methods, but some methods do not allow to ensure the strength characteristics of the joint zone at the level of the main material, which reduces the duration of product operation [36].

When obtaining products with special properties, the most acceptable methods are types of casting, in which the joining of casting layers occurs due to diffusion penetration or sub-melting, which makes it possible to use products under dynamic, shock and static loads. Usually, such castings are obtained by centrifugal and continuous casting methods, and sometimes by other methods.

In the manufacture of composite products, Al_2O_3, SiO_2, SiC, titanium carbides, vanadium, tungsten and others are used as reinforcing fillers.

One of the necessary conditions for obtaining a high-quality casting with special properties is the presence of a strong connection of its various layers. When used for the separation of two liquid metals, the interphase diffusion processes at the interface between the liquid metal and the partition have a great influence, thanks to which mass transfer, structural and phase transformations occur.

As research has shown, taking into account the fact that the diffusion coefficient in a liquid iron-carbon alloy is 4–6 orders of magnitude higher than in a solid one, the formation of the transition zone occurs mainly during solidification in the liquid phase. The longer the period when the alloy is in a liquid state, the wider the transition zone [37].

To obtain cast composite materials, various methods of liquid-phase connection of a metal matrix with high-strength reinforcing material of the required configuration are used.

The main technological schemes for obtaining composite castings are presented in the chapter [38]. The authors considered the general theoretical provisions of the processes occurring in the mold and which make it possible to obtain composite (reinforced) castings, recommended matrix alloys and grades of reinforcing phase (RP). It should be noted that castings with volumetric reinforcement, for example: metal rods, should be made by lost foam casting, because this method is "flexible" from the point of view of controlling the properties of the casting, and the mold and polystyrene pattern can be used as an active-functional system and tool for introducing reinforcing elements [39].

The liquid-phase method has significant advantages over other methods of obtaining reinforced structures and makes it possible to manufacture high-precision products with minimal force impact on reinforcing elements with the possibility of mechanization, automation and implementation of continuous technological processes. The RP mixing with the matrix melt is carried out under the influence of convection and circulation flows that arise in the liquid metal during the RP filling [38].

2.3.2 PRODUCTION TECHNOLOGIES OF CAST REINFORCED STRUCTURES, WHICH ARE OBTAINED BY LIQUID-PHASE COMBINATION OF SYSTEM COMPONENTS

The most effective method of obtaining materials with special functional properties from iron-carbon alloys is reinforcement during the liquid-phase combination of system components [38].

There are known options for manufacturing composite cast iron, which is locally reinforced with ceramics to increase abrasive wear resistance. At the same time, to ensure a uniform distribution of particles in the casting, it is necessary to fix the ceramic insert in the cavity of the mold, which leads to an increase in labor intensity during the production of castings [40].

The technology of casting according to gasified models is the most suitable for obtaining reinforced castings. There are options for local strengthening of cast materials by introducing wear-resistant inserts to create locally strengthened areas based on refractory carbides in the polystyrene foam pattern [41].

It is also possible to modify gray cast iron with ferrosilicon FeSi45 using a dispersion-filled polystyrene pattern [42], that is, the polystyrene pattern is used as a tool for introduction into the mold cavity.

In order to obtain cast reinforced structures of guaranteed quality, the structure of the materials must be heterogeneous and consist of solid grains evenly distributed in the elastic-plastic matrix, and the adhesive bond must be maintained between the components. The maximum strength of the matrix alloy can be ensured using the pressure casting method, in which the pressure on the matrix alloy is maintained during the crystallization of the cast reinforced structure (CRS) using the direct impact of a pressing punch [43].

The liquid-phase method of combining the components of the reinforced system is divided into two groups: involuntary (gravitational) and forced impregnation.

When implementing the process of involuntary (gravitational) impregnation, reinforcing frames can be tied, simply placed in a casting mold or pre-aggregated (pre-tied). With this method, it is impossible to obtain reinforced castings of a complex shape, gas-shrinkage defects and the formation of an imperfect structure may occur during the CRS production.

During the process of forced impregnation with the help of additional mechanical influence on the matrix melt, there is an intensification of the flow of the melt on the surface of the reinforcing filler and the achievement of a better connection of the CRS components [44]. In order to obtain optimal reinforced systems and achieve maximum operational characteristics, it is necessary to establish technological parameters that determine the choice of composition and quantity of RP and matrix alloy (MA).

In order to achieve perfect results regarding the combination of the components of reinforced systems, a clear understanding of the technological bases of such combination is necessary, primarily from the point of view of the formation of macro-heterogeneous structures, the emergence of a simple connection between various elements of the system and, as a result, the emergence of the process of physical and chemical interaction at their boundaries contact [45].

When obtaining reinforced castings with macro-implants, which are placed in the cavity of a casting mold or in a polystyrene pattern, new multi-component systems for the theory of casting processes arise: "metal – model – implant – mold" and "metal – reinforcing phase – mold".

The technological process of manufacturing reinforced castings by casting according to gasified models is carried out according to the following scheme:

– preparation of components (calibration, cleaning and plating of the surface, provision of the reinforcing structure of the required shape and configuration);

– production of expanded polystyrene patterns with reinforcing elements;

– form assembly;

– matrix alloy filling, impregnation;

– holding time for solidification of the liquid phase;

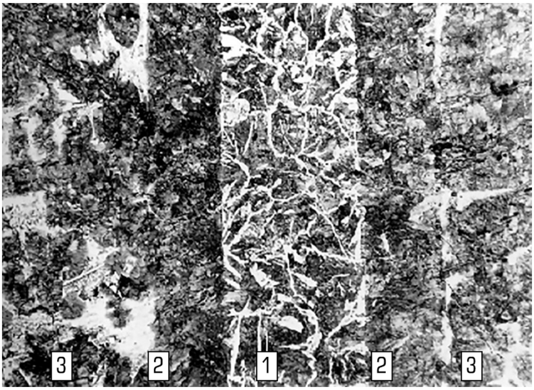
– knocking out of the mold;

– thermal or mechanical treatment of reinforced products.

The AF influence on the formation of the structure and properties of cast reinforced structures was tested on cast reinforced materials from iron-carbon alloys (MA – gray and high-strength cast iron with spherical graphite, RP – metal rods (diameter 2 and 5 mm) made of Steel 20 and steel plate Steel 3 with a thickness of 0.3 and 0.7 mm).

When steel elements are used to reinforce cast iron castings, the intensification of heat and mass exchange processes in the transition zone and the increase in the values of the effective diffusion coefficients of chemical elements occurs due to the significant advantage of the mass of cast iron over steel. At the same time, the higher the degree of doping of the alloys that are joined, the smaller the value of the effective diffusion coefficients due to the lower mobility of the atoms of the alloying elements in the transition zone [45].

During the research, it was established that the steel partition with a thickness of 0.3 mm was deformed under the influence of gas-dynamic flows in the form and in the place where the metal was fed, it melted through in several places. The use of a steel plate made of Steel 3 with a thickness of 0.7 mm ensured complete preservation of the diaphragm (**Fig. 2.16**). The quality of the diffusion connection and the strength properties of the transition layer are determined by temperature conditions and physical and chemical processes at the interphase boundaries. The intense flow of heat and mass exchange processes during the interaction of cast iron with a partition made of St3 steel causes a significant melting of the partition. This is confirmed by the presence of a sufficiently large width of the transition zone – (0.15–0.18) mm (**Fig. 2.16**). In the process of interaction, the steel was intensively saturated with cast iron carbon and a zone with a lamellar pearlite structure (Pt1; PD0.5), characteristic of St5 steel, was formed along the junction boundary. The microstructure of cast iron is a pearlite base with carbide and graphite inclusions.



1 – diaphragm; 2 – transitional layer; 3 – cast iron

Fig. 2.16 Microstructure of a two-layer casting made of cast iron with a diaphragm made of a steel plate St3 with a thickness of 0.7 mm

Numerous oxidation-reduction reactions take place at the interface between the liquid metal and the solid partition. The process of interaction of liquid cast iron with a steel plate is characterized by high speeds and fairly deep penetration of elements deep into the steel plate due to the large difference in chemical potentials and mass of cast iron compared to the diaphragm.

The active flow of high-temperature oxidation-reduction processes is also facilitated by the long stay of cast iron in a liquid state at the place of metal supply.

Carburization of the surface layer of the steel diaphragm also occurs due to the local accumulation of the liquid carbon phase of the destruction of the model, which depends on hydrodynamic and convective flows in the melt in the process of filling the mold with metal.

A physical model of the mass and heat exchange of reinforcing materials was developed according to the established laws about the conditions of solidification, the movement of matrix alloys (MA) in molds with a macroreinforcing phase (MRP), the interaction of MA, MRP with a polystyrene foam pattern and its thermal destruction products in the form of liquid, gaseous, and solid phases elements and matrix alloy when forming the structure and properties of cast reinforced structures in multicomponent systems new for the theory of foundry processes: "metal – model – MRP – form".

The interaction of the macroreinforcing phase (MRP) with the matrix alloy (MA) in the cavity of the casting mold is shown in (**Fig. 2.17**). The MA enters the mold under the influence of hydrostatic or elevated pressure P_m and comes into contact with the reinforcing phase (MRP), which can be located directly in the cavity of the mold or at the boundary of the "liquid metal – mold" system (**Fig. 2.17**).

When filling the casting mold, microexchange zones are formed around the MRP in the "MA – RP" system with the formation of a transition zone g_m, heat exchange in this system takes place along the contact surface S_f, S_{mp} with a characteristic parameter for RP – R_{RP}. The boundary temperature conditions at the heat exchange boundary of the MA – RP system T_0=450 °C, and the final temperature at the heat exchange boundary of this system:

$$T_F = \frac{T_L - T_S}{2}, \qquad (2.1)$$

where T_L, T_S – the liquidus and solidus temperatures for the matrix alloy, °C.

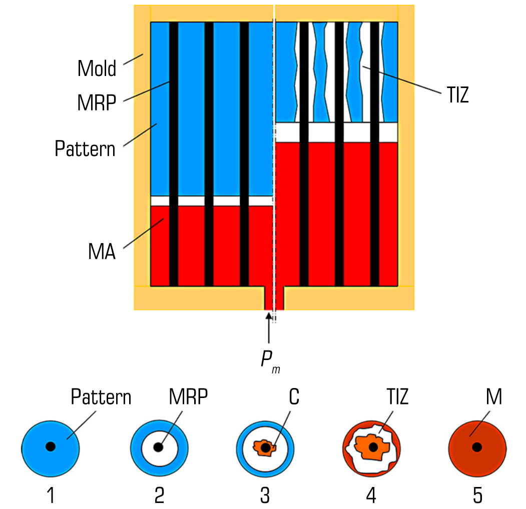
For the integrated MA – RP system, the heat exchange contact area will be $n \cdot S_F$, $n \cdot S_{PR}$, respectively, where n is the number of MRP elements located in the cavity of the casting mold, pcs., and their mass will be:

$$m = 0.785 \times n \times g_{MRP} \times R_{MRP}^2 \times L_{MRP}, \text{ kg} \qquad (2.2)$$

where g_{MRP} – density, kg/m^3; L_{MRP} – the characteristic length of the MRP element, m.

The interaction of the matrix alloy, the macro-aluminous phase, the polystyrene pattern and its thermal destruction products with the liquid and solidifying metal occurs as follows [46]: at the moment when the MA melt (**Fig. 2.17, item 2**) enters the mold under the action of hydrostatic or increased PM pressure, which leads to rapid heating of the metal rod (MAF) placed in the polystyrene pattern (**Fig. 2.17, item 1**), which is confirmed by the calculated data of the heating time of the rod along the entire height of the model to its gasification temperature (450 °C), which does not exceed 0.4...0.5 s.

In this and subsequent stages, filling the mold with vertical macroreinforcing elements (MRE) installed in it (in our case in the form of rods) complicates the area of liquid metal flow (the mold) and exerts a certain influence on the thermophysical and hydrodynamic processes occurring in it.



1 – initial stage;
2 – stage of GM thermal destruction;
3 – initial stage of crystallization;
4 – hardening stage;
5 – cooling

Fig. 2.17 Physical model of production of cast reinforced structures

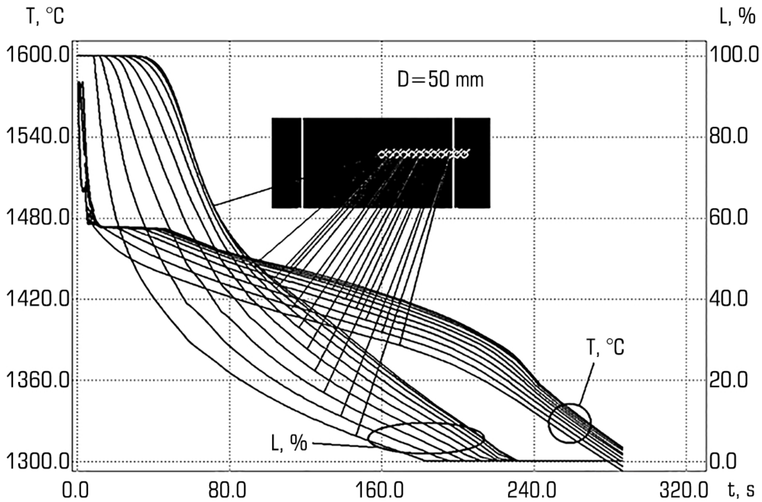
In the next period of MA movement in the mold with the foam model, the initial stage of gasification of the pattern (**Fig. 2.17, item 2**) occurs in two directions: at the front of the liquid metal flow with the formation of a "metal – model" gap and around the rod with the formation of a "macroreinforcing element (MRE) – model" gap. During this period, the products of thermal destruction of the model (vapor-gas phase (VGP), liquid phase (LF)) migrate into the mold through the gaps formed, and the gap "MRE – model" constantly increases and reaches the mold limit.

During the movement of thermal destruction products (VGP, LP and GP), partial condensation occurs on the rod (**Fig. 2.17, item 3**) with the formation of a border around the rod in the pyrocarbon form (PF), which leads to carbonization in the contact zone of the rod, the carbon content of which is clearly lower than in MA (cast iron, medium and high carbon steel). During this period, the rod melts in the form of a decrease in its melting temperature, which contributes to the formation of a strong transition zone (**Fig. 2.17, item 4**) on the "MRP – MA" contact surface.

2.3.3 RESEARCH OF HEAT AND MASS EXCHANGE PROCESSES IN REINFORCED CASTINGS FROM IRON-CARBON ALLOYS

To evaluate the conditions of heat and mass transfer and solidification in reinforced castings made of iron-carbon alloys, cast samples of carbon steel (Steel 45L) with a size of ∅50×200 mm in a hollow sand mold made of loose refractory (LAC process) and a reinforcing phase in the form of rods (Steel 45), occupying 50 % of its cross-sectional area [47].

During computer modeling of the hardening of a casting ∅50 mm made of 45L steel in a hollow form, it was established that on the contact surface "metal – form" this alloy reaches the temperature T_l after 8.9 s (**Fig. 2.18**), and the temperature T_s – after 165.0 s. During the same period, at a point located at a distance of 1/4 diameter from the surface of the casting, the alloy reaches the temperature T_l after 14.2 s, and the temperature T_s after 181.5 s. In the center of the casting, during the same period, the alloy reaches the temperature T_l after 8.5 s (**Fig. 2.18**), and the temperature T_s – after 211.5 s, then the liquid phase disappears in all sections of the casting.



L – amount of the liquid phase in the metal that hardens, %
T – temperature of the metal that hardens, °C

Fig. 2.18 Kinetics of solidification and cooling of a casting (F 50×200 mm) made of 45L steel in a hollow form

During the hardening of a ∅50 mm casting made of 45L steel in a mold with MAF, which is 1/2 of its diameter, it was established that on the contact surface "metal – mold" this alloy reaches the temperature T_l after 5.3 s (**Fig. 2.19**), and temperature T_s – after 42.0 s. During the same period, at a point located at a distance of 1/4 of the diameter from the surface of the casting, the alloy reaches the temperature T_l after 8.8 s (**Fig. 2.19**), and the temperature T_s – after 124.0 s, and at the "metal – MRP" boundary, the alloy reaches the temperature T_l after 1.8 s (**Fig. 2.19**), and the temperature T_s – after 80.0 s, then the liquid phase disappears in all sections of the casting.

It should be noted that under these conditions, the surface and center of the MRP warms up to a maximum temperature of 1410 °C after 5.0 s, and then cools at a rate of 1.5 2.0°C/s (**Fig. 2.20**).

It is also important to note that the rate of removal of overheating of the melt to the temperature T_l in all experiments differs from each other. Thus, when the sample solidifies in an empty form, this rate is 8.5...14.0 °C/s, and the lower value refers to the central part of the casting, and the cooling rate of the latter is already 4.0...5.0 °C/s, where the greater value refers to the surface of the rod.

During solidification of the casting in the form where the MRP is located, which is 1/2 of its diameter, the speed at which the melt reaches the temperature T_l is 15.0...70.0 °C/s, and the higher value refers to the part of the casting adjacent to the boundary of the MRP, and the cooling rate of the casting is 2.0...3.0 °C/s, where the greater value refers to the "metal – MRP" contact surface.

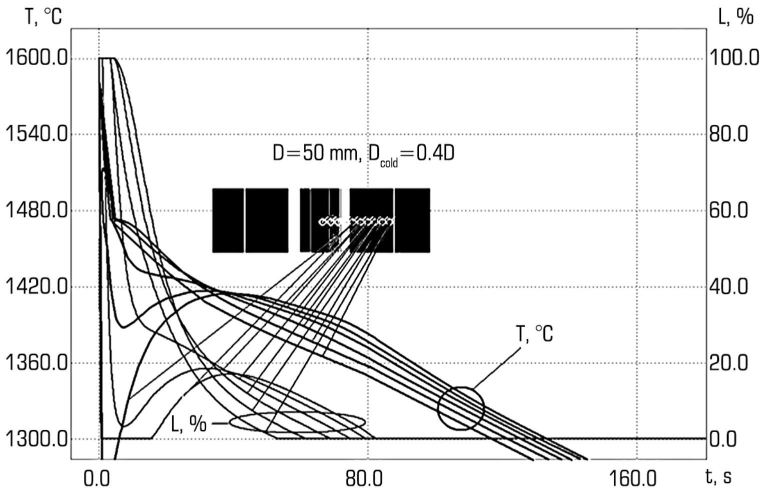
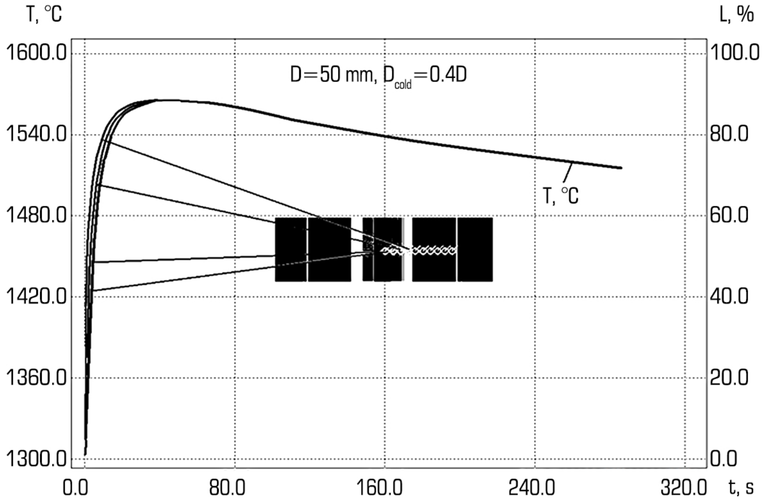


Fig. 2.19 Kinetics of solidification and cooling of a casting (F 50×200 mm) made of 45L steel in a mold with MRP (0.5D_{cast})



T – temperature of MRP heating and cooling, °C

Fig. 2.20 Kinetics of MRP heating and cooling (0.5 D_{cast})

Based on the analysis of the received data, it was established:

– MRP presence creates conditions for increasing the rate of solidification of the alloy in direct proportion to its mass and with its increase in relation to the volume of metal in the mold, while the MPR presence in the mold significantly affects the removal of overheating of the alloy to a temperature T_l, which exceeds the similar one during solidification of the casting in a hollow mold in 1.4...2.0 times;

– MRP presence in the mold affects the cooling of the casting in the same way, but to a lesser extent, the ratio between the cooling rate of the casting in the hollow mold and in the MRP presence is only 1/(1.15...8.0);

– it is important to note that on the "MAF – metal" contact surface the hardening process proceeds initially with the rapid formation of a solid phase (freezing), then up to 15...20 % of the solid phase is formed in this layer. The final formation of solid metal around the MRP occurs when the previous layers have already crystallized.

2.3.4 SELECTION OF FUNCTIONAL SCHEMES FOR OBTAINING CAST REINFORCED STRUCTURES AND OPTIMIZATION OF THEIR TECHNOLOGICAL PARAMETERS

The analysis and generalization of methods for optimizing technological parameters, the mutual influence of MS and AF on the characteristics of cast reinforced structures (CRS) and schemes for their production made it possible to create a system for selecting materials and technologies based on their functional characteristics. This system of choosing the optimal technological process and materials for obtaining high-quality cast products based on iron-carbon and non-ferrous alloys is based on the following functional links and blocks (**Fig. 2.21**):

1. The choice of cast reinforced materials L_0 is made in accordance with the requirements for the cast product, the properties of which are determined by a complex of mechanical, elastic-dynamic, corrosion-resistant and tribotechnical characteristics I_0. Therefore, the choice of the necessary characteristics, such as mechanical A_{01}, elastic-dynamic A_{03}, corrosion-resistant A_{04} and tribotechnical A_{02}, is determined by the set of data I_0 and they functionally depend on the similar characteristics of the matrix alloy M_{01}–M_{02} and the reinforcing phase A_{01}–A_{02}. So, first, the characteristics of L_{01}–L_{02} are determined using adapted or created databases DB1–DB2, and then on this basis MS and AF are established, the properties of which are determined according to DB1 and DB2. Moreover, it is advisable to initially search for new CRSs from no less than two versions of the "$MA_1 - RP_1$" and "$MA_2 - RP_2$" systems, which are implemented as CRM_1 and CRM_2 with similar required characteristics to I_0. Next, based on the selected characteristics of M_{01}–M_{02} and A_{01}–A_{02}, the chemical composition of M_{03} for M_{10}/M_{20}, as well as the type of A_{03}–A_{04} and the geometrical characteristics of A_0 for A_{10}/A_{20} are established. In order to choose the optimal CRM from n given ones, it is advisable to determine the complex quality indicator of each of them according to the equation of the form:

$$K_c = \sqrt{A^m B^L C^K D^S E^T .... W^Z Z^d Y^{\varphi} X^l}, \qquad (2.3)$$

where K_c – CRS comprehensive quality indicator; A, B, C, ... X – factors that determine the CRS properties; m, L, e, s, ... t are degrees of significance of the CRS qualities.

Moreover, the complex indicator K_c takes into account tribotechnical K_1, mechanical K_2, technological K_3, thermo-mechanical K_4, foundry K_5, electrotechnical K_6 and elastic-plastic K_8 properties and economic indicators K_7 (**Fig. 2.21**). The values of the indicated indicators A...X and their indices m...i are determined by the method of expert evaluation by interviewing at least 25 specialists working in this field. The material for which the value of the K_c coefficient exceeds the analogues by at least 10 % is considered optimal.

2. After the CRS final selection, using the DB3 database, the MA and RP characteristics are set, including thermophysical M_{04}, foundry M_{05}, mechanical M_{01}, elastic-dynamic A_{01}, tribotechnical A_{02}, and finally the same parameters for the CRS (L_{01}–L_{02}). Based on the obtained data, the technological parameters of the process T_1, t_c, t_p, T_{RP}, T_{MA}, T_f, V, H, P, t_{hard} and t_{cool} are determined according to the block diagram "$T - t$" (**Fig. 2.21**).

3. The choice of material and geometry of the F_0 mold is determined by the geometry of the casting, the thermophysical properties of the mold, the series of castings, and the preparation of a particular casting manufacturer.

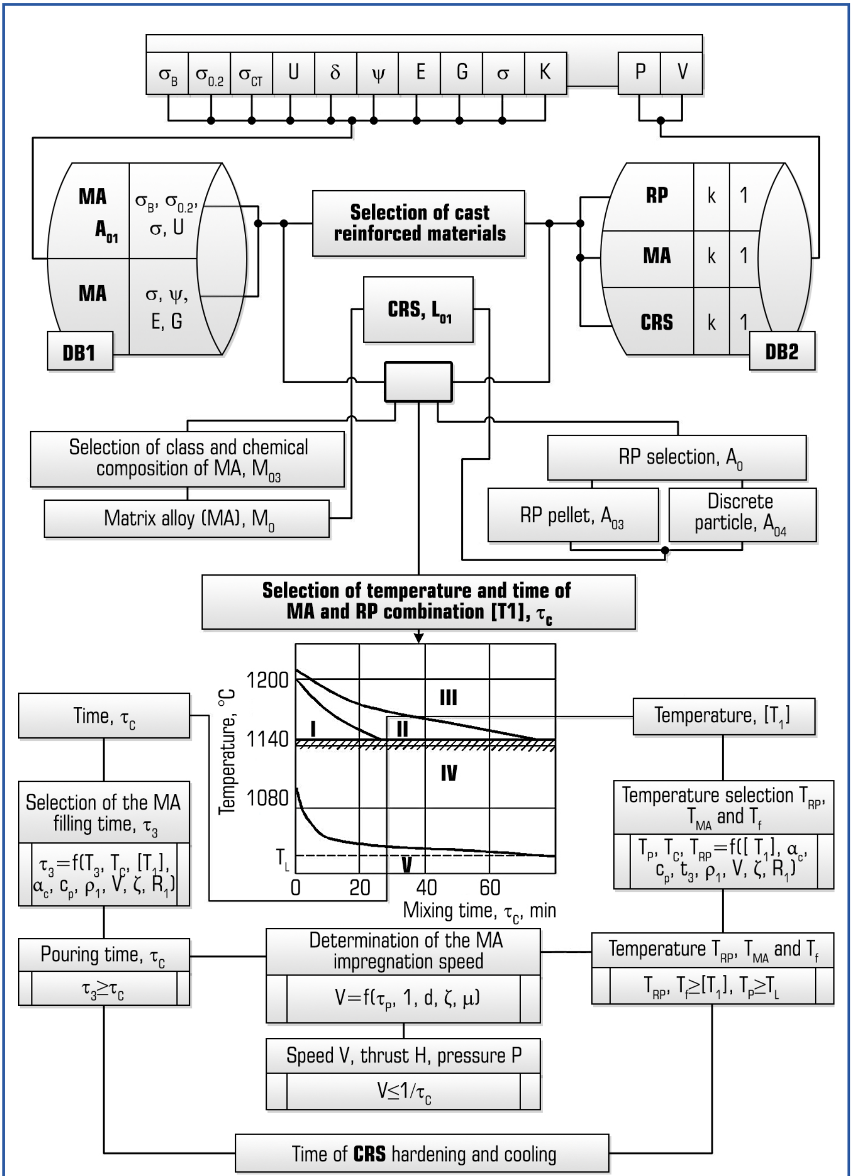


Fig. 2.21 Selection and optimization of materials and basic technological parameters for obtaining reinforced cast structures and castings with differential properties using macroreinforcing phase (MRP)

The method of pouring Z_0 is determined by the RP geometrical parameters, the MA casting properties (M_{05}), the geometry of the form F_0, the specified speed [V] and its filling time [t_3], as well as the RP temperature [T_1].

4. After choosing all the necessary casting parameters, materials, shape geometry and pouring method, it is advisable to determine the optimal implementation scheme of the technological process of obtaining varnish. The selection is carried out in accordance with the requirements of specific manufacturing processes of casting on gasified models.

CONCLUSIONS

The work presents scientific and practical results regarding the development of modern technological processes for the production of cast products and constructions of responsible purpose from aluminum, iron-carbon and heat-resistant alloys, namely:

– a complex of original equipment developed and used at the Physical and Technological Institute of Metals and Alloys of the National Academy of Sciences of Ukraine for the production of cast structural materials from aluminum alloys under the influence of electromagnetic, plasma kinetic, centrifugal effects on metal systems in a vacuum, which allows intensifying structural and phase transformations in alloys; disperse intermetallics and microgroups in alloys; evenly distribute alloying and strengthening particles in the liquid metal bath; control the rate of crystallization of the alloy; effectively doping alloys with active metals, in particular, using consumable electrodes in plasmatrons; process alloys with carbon and silicon nanoparticles synthesized by reactions of carbon with silicon-containing media on crystalline metal centers and compounds that are introduced into the melt; increase the efficiency of plasma heating of liquid metal to ≥90 %; to change the structure and properties of cast products by effective plasma effects on alloys;

– the improved design of the casting unit VIM-25-175C with the introduction of additional cooling, which led to the improvement of the cooling process of the crystallizer during directional crystallization and ensured obtaining a regular structure of castings of GTE blades made of heat-resistant alloys;

– a physical model of the heat and mass transfer of reinforcing elements and matrix alloy during the formation of the structure and properties of cast reinforced structures when lost foam casting, and the results of studies of heat and mass transfer processes in reinforced castings from iron-carbon alloys, which made it possible to establish that the MRP presence creates conditions for increasing the speed solidification of the alloy is directly proportional to its mass and with its increase in relation to the volume of metal in the mold, while the MRP presence in the mold significantly affects the removal of overheating of the alloy to the temperature T_l, which is 1.4...2.0 times higher than the similar casting in a hollow mold during solidification, while on the contact surface "MRP – metal" the solidification process proceeds initially with the rapid formation of a solid phase (freezing), then up to 15...20 % of the solid phase is formed in this layer. The final formation of solid metal around the MRP occurs when the previous layers have already crystallized.

The latest technologies have been developed:

– complex ecologically clean processes of processing and pouring of aluminum melts with the help of the created MHD equipment, in which vacuum-plasma systems are installed;

– production of castings of working blades of gas turbine engines with a regular structure by the method of directional crystallization;

– production of cast reinforced structures from iron-carbon alloys by the method of casting according to gasified models, with the possibility of optimizing their technological parameters depending on the initial casting data.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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