The new mathod of continuously iterative casting of hollow cylindrical castings from cast iron without application of core, based on the principle of direction of metal solidification is presented in the work. The thermal condition of crystallizer at iterative temperature influences on its internal surface and solidification of casting in the conditions of intensive one-way heat sink and presence of constant overheat on front of solidification is examined.

E. I. MARUKOVICH, V. F. BEVZA, ITM NAS of Belarus,
A. M. BODYAKO, UCHNPP «TECHNOLIT», U. P. HRUSHA, ITM NAS of Belarus

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THEORETICAL AND TECHNOLOGICAL BASIS OF CASTING OF HOLLOW BILLETS BY THE METHOD OF DIRECTIONAL SOLIDIFICATION

Introduction

Foundry is one of the most universal and economic methods of shaping of metal products. Creation of such technological processes which would provide high operational life of details at the expense of obtaining of high-quality castings with specified structure and properties always was and remains its major task. Thus high efficiency, ecological cleanness, low energy capacity, wastelessness of production are the basic requirements for working out of modern technology.

In machine building and other industries details of solid of revolution type, including considerable quantity of ones from cast iron have wide spread occurrence: cylinder sleeves, piston rings, gear wheels, worm wheels, plugs for different purposes, etc. Billets of details of this type are basically cast in the sandy-argillaceous or core-sand molds, faced chill or by the centrifugal method. However quality of details and their operational life does not meet modern requirements any more.

The process responsible for formation of the majority of castings properties is metal solidification. It is during phase transition when defects which essentially reduce properties of casting are formed in its body: physical and chemical heterogeneity of metal, unsatisfactory structure, shrink holes and blow holes, porosity, cracks, etc. Crystal structure of casting and, hence, the major technological and service properties depend on number, shape, growth rate of crystals and their primary orientation in casting body. Therefore the major task of scientific researches in the field of foundry is research of the methods providing control of structure and properties, heat exchange and mass exchange, thermodeformation interaction of casting and mold, hydrodynamic processes of casting, working out of fundamentally new low-waste and wasteless technologies providing essential increase of physical and mechanical and operational properties of cast metal, first of all of cast iron.

Basic circuit of casting

The organization of directional solidification of metal in the course of casting formation allows to exclude the majority of foundry defects, to obtain dense fine structure and high mechanical properties. Fundamentally new method of obtaining of hollow cylindrical billets without core application by directional solidification (freezing up) from various types of cast irons is developed at Institute of Technology of Metals of National Academy of Sciences of Belarus [1–4].

The essence of the method consists in the following (Fig. 1). Liquid metal is fed through siphon gating system *1* and a connecting sleeve *2* into steel water cooled crystallizer consisting of stationary *3* and mobile *4* parts, before its filling on the height equal to height of obtained casting *5*. Then metal feeding is stopped and holding for freezing up of billet wall of necessary thickness is made. Solidified rim *5* being a

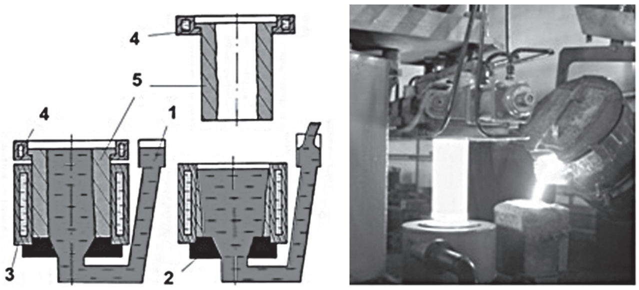

Fig. 1. Basic circuit and process of continuous-iterative casting of hollow billets without core; *1* – metal feeder; *2* – connecting sleeve; *3* – stationary part of crystallizer; *4* – mobile part of crystallizer (pincher); *5* – casting

body of casting, is extracted by pincher *4* upwards from melt and stationary crystallizer 3 on the distance exceeding its height. Simultaneously with the beginning of extraction of billet melt, being in its axial part, contact with released sites of the working bushing of crystallizer 3 and freezing up of the following casting begins. At this time a new portion of melt in the volume equal to volume of extracted casting is fed in crystallizer through siphon gating system providing smooth filling, submit, mobile part of crystallizer is returned in starting position and it is filled again to specified level. The cycle repeats.

Thus, metal solidification in crystallizer occurs continuously during all time of pouring and extraction of billets carry out cyclically in specified periods. In view of this the method is called the *«continuous-iterative casting by freezing up»* (CICF). Only peripheral part of volume of liquid metal participating in formation of given casting solidifies in each cycle. Hence, the thickness of a rim which is obtained by the end of casting solidification is always less than radius of an internal cavity of crystallizer. It is determined by holding time, intensity of heat rejection, temperature and chemistry of filled in melt.

At CICF as well as at any other kind of casting quality of billets first of all is determined by character of heat sink from solidification casting and conditions of its interaction with the mold. This interaction begins with the moment of contact of liquid metal with working surface of crystallizer. Solidification of metal rim in radial direction into the depth of melt begins and consistently proceeds in the place of contact. In this case dendrites grow normally in the structure of castings, i. e. perpendicularly to heat sink surface and to external surface of forming casting. It is this position of structural components that provides maximally high wear resistance of working surface of details of solid of revolution type.

At the moment of extraction from crystallizer and melt a casting has high temperature close to the temperature of solidus of alloy. For example, for cast iron it is 950–1050 °C. It gives the possibility *to control the process of structurization* by means of change of intensity of heat sink from casting in zone of secondary cooling in enough wide limits.

Thus the basic advantages of essentially new method of casting of hollow cylindrical billets from cast iron in comparison with all existing methods are:

- intensive unilateral heat sink from solidification casting which determines obtaining of dense superfine structure and increase of physicomechanical properties;
- abundant superfluous feeding of solidification front by overheated melt during all time of formation of casting in the crystallizer that excludes occurrence of shrinkage and gas porosity, holes, nonmetallic inclusions, etc.;
- possibility of control of structurization process of castings by means of use of their primary heat what provides obtaining of specified structure;
- absence of internal core defines free shrinkage of solidification casting that excludes defect on hot cracks and provides stability of casting process;
- high productivity of casting process by means of great solidification rate of metal (v = 0,4–0,6 mm/s) and obtaining of specific cut length (L = 100–250 mm) without cutting in conditions of continuous pouring.

Due to the fact that the described scheme of casting *has no analogues*, it was necessary to work out the *specialized equipment*, accessory and technologies of obtaining of castings for its realization. A set of theoretic researches and the analysis of influence of thermal, hydrodynamic, physical, chemical and other phenomena on casting formation were carried out for solving this problem and reception of initial data. In this case the leading part belongs to thermal phenomena which determine all changes occurring in a casting and a casting mould. Thermal processes underlie formation of basic indicators of quality.

Temperature field of crystallizer

At CICF the key element which carries out the role of form-builder and of heat exchanger for solidifications casting is the crystallizer. Stability of process of casting and quality of obtained billets are determined by its operating capacity which depends in large measure on temperature working conditions. Determination of temperature field of crystallizer gives the opportunity to calculate the intensity of heat sink from the surface of casting and to carry out the analysis of its solidification.

At CICF the crystallizer works in the conditions of iterative thermal influence simultaneously on all internal surface from melt and intensive cooling of external surface of its working bushing. In the established mode of casting fluctuations in temperature of working (internal) surface of crystallizer occur near some average value T_{2av}. The temperature of water-cooled surface in pouring process changes slightly and is accepted as constant.

The problem solving was carried out on the basis of differential equation of heat conductivity which for a cylindrical wall takes the form:

$$\frac{\partial T}{\partial t} = a_2\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right). \qquad (1)$$

Initial temperature distribution on wall thickness of crystallizer is expressed by logarithmic curve

$$T(r;0)=\frac{T_{R_i}\ \ln\dfrac{R_2}{r}+T_{R_2}\ \ln\dfrac{r}{R_i}}{\ln\dfrac{R_2}{R_i}}. \qquad (2)$$

Boundary conditions take the form

$$T(R_i;\,t)=T_{R_i}+\sum_{n=1}^{\infty}A_n\cos(n\omega t-\varepsilon_n), \qquad (3)$$

$$T(R_2;\,t)=T_{R_2}=\text{const}\,,$$

where a_2 – temperature conductivity coefficient of crystallizer material; n – harmonic number; A_n, ξ_n – fluctuation amplitude and initial phase of a corresponding harmonic; ω – circular frequency of temperature change; t – time; R_i and R_2 – radiuses of surfaces on which boundary conditions are specified; r – current co-ordinate.

Solution of the equation (1) taking into account (2) and (3) is received in the form

$$T(r;\,t)=\frac{T_R\ln\dfrac{R_2}{r}+T_{R_2}\ \ln\dfrac{r}{R_i}}{\ln\dfrac{R_2}{R_i}}+\frac{\ln\dfrac{R_2}{r}}{\ln\dfrac{R_2}{R_i}}\times$$

$$\times\sum_{n=1}^{\infty}A_n\cos(n\omega t-\varepsilon_n)+\pi\sum_{k=1}^{\infty}\frac{I_0^2(\eta\mu_k)V_0(\mu_k\dfrac{r}{R_i})}{I_0^2(\mu_k)-I_0^2(\eta\mu_k)}\times \qquad (4)$$

$$\times\sum_{n=1}^{\infty}\frac{A_n(n\omega)}{\left(\dfrac{\alpha_2\mu_k^2}{R_i^2}\right)^2+(n\omega)^2}\times$$

$$\times\left[n\omega\cos(n\omega t-\varepsilon_n)-\frac{\alpha_2\mu_k^2}{R_i^2}\sin(n\omega t-\varepsilon_n)\right],$$

where V_0 – transformation kernel;

$$R_2/R_i=\eta,\ p_kR_i=\mu_k,$$

where μ_k – roots of equation $I_0(\eta\mu_k)Y_0(\mu_k)-I_0(\mu_k)\times Y_0(\eta\mu_k)=0$; $I_0(x)$ and $Y_0(x)$ – respectively Bessel functions of the first and second genre of zeroth order.

We will deduce change of density of heat current on working surface of crystallizer according to Fourier's law

$$q_2=-\lambda_2\frac{\partial T}{\partial x}\ \Big|_{x=0,}$$

$$q_2=\frac{\lambda_2}{X_2}(T_2-T_3)+\sum_{n=1}^{\infty}A_n\,b_2\sqrt{n\omega}\,\cos\left(n\omega t-\varepsilon_n+\frac{\pi}{4}\right), \qquad (5)$$

where λ_2 – heat-conduction coefficient of crystallizer material; $b_2=\dfrac{\lambda_2}{\sqrt{a_2}}$ – heat accumulation coefficient of crystallizer material; X_2 – thickness of crystallizer wall.

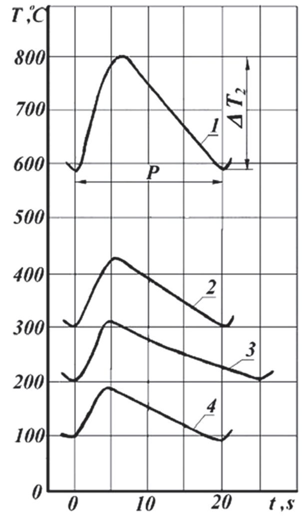

Fig. 2. Change of temperature of crystallizer wall during one cycle on the distance of 0,5 mm from working surface, *1* – X_2 = 28 mm; *2* – 17; *3* – 9; *4* – 7 mm

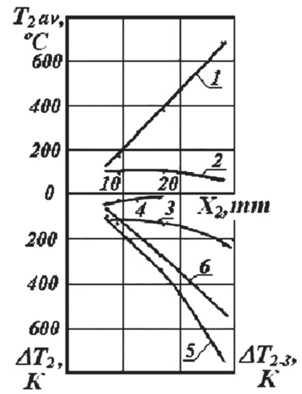

Fig. 3. Change of average temperature (*1*, *2*), value of amplitude of fluctuation (*3*, *4*) and difference of temperatures on section of the working bushing (*5*, *6*) depending on wall thickness; *1*, *3* – the working surface; *2*, *4* – water-cooled surface; *5* – at maximum value of temperature of working surface of crystallizer; *6* – at minimum value of temperature of working surface of crystallizer

The analysis of temperature field of crystallizer was carried out on degree of temperature difference between internal and external surface of wall of the working bushing (ΔT_{2-3}), value of amplitude of fluctuation of temperature of working surface (ΔT_2) and level of average temperature of this surface ($T_{2\text{av.}}$) at change of wall thickness from 7 to 28 mm and diameter from 50 to 200 mm. Dependence of the specified parameters on wall thickness is presented on Fig. 2 and Fig. 3.

Thus, wall thickness of working bushing of crystallizer (X_2) is chosen taking into account strength characteristics and temperature particularities of casting process.

Change of density of heat current during a cycle on working surface of crystallizer has the same character, as well as change of its temperature. The heat

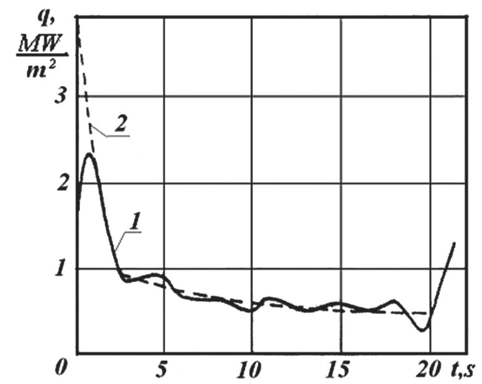

Fig. 4. Change of density of heat current on working surface of crystallizer during a cycle; *1* – calculated curve; *2* – averaged curve

current at the moment of contact of crystallizer with liquid metal almost instantly increases and has peak character in all cases (Fig. 4). Then in the first 3–5 seconds of casting formation heat current falls several times in relation to the maximum value. Then there is its smooth decrease to the minimum value. At following cycle of thermal influence change of density of heat current repeats.

Thermodeformation interaction of casting and crystallizer

During the process of solidification and metal cooling gas backlash is formed between casting and crystallizer what considerably influence on their heat exchange and conditions of casting solidification. Backlash formation in each specific case has its particularities depending on casting method, heating rate of the mould and character of its interaction with solidification metal [5–7].

Formation and modification of backlash is determined by three factors at CICF: shrinkage of solidification casting; deformation of crystallizer during the cycle of formation of casting; plastic expansion of rim under influence of ferrostatic pressure. Due to the fact that at CICF the height of column of melt is not big (≤250 mm), and heat sink from solidification casting is carried out with high intensity, the last factor operates very short time (<1 s) and its influence on backlash formation may be neglected. The main contribution to formation of backlash and kinetics of its modifications is brought by two first factors.

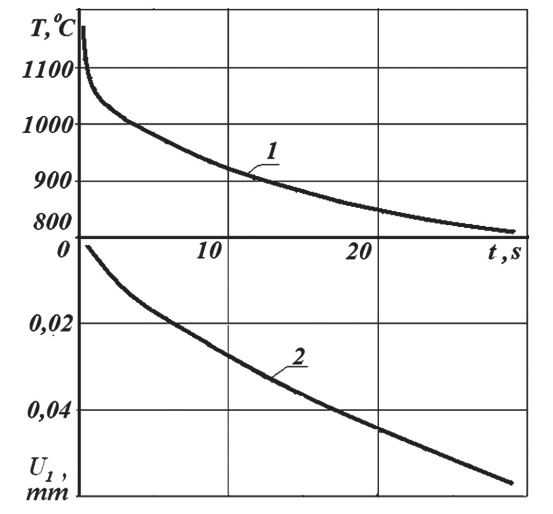

Fig. 5. Changing of temperature of external surface (*1*) and of shrinkage (*2*) of casting during its formation process in crystallizer

Calculations are made with use of the software based on the finite elements method.

The backlash is a value that is variable in time and it is determined by change of temperature field of crystallizer and casting during the cycle of solidification of the latter. Its size (Z) is composed of the sum of absolute values of casting shrinkage (U_1) and crystallizer deformation (U_2). In this case if external diameter of solidification casting decreases monotonously due to shrinkage during all time of formation (Fig. 5), then the modification of internal diameter of the working bushing of crystallizer occurs on a curve with maximum during a cycle (Fig. 6).

The analysis shows that during the time of solidification of casting there is a constant growth of gas backlash and in the end of a cycle it gets the greatest value (Fig. 7). Moreover, maximum intensity of growth of backlash takes place at initial period of the cycle. Average intensity of increase of backlash in the first 5–6 s is 0,0067–0,0073 mm/s. During the subse-

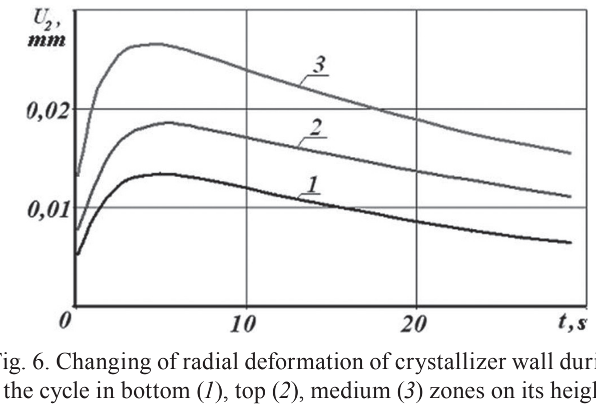

Fig. 6. Changing of radial deformation of crystallizer wall during the cycle in bottom (*1*), top (*2*), medium (*3*) zones on its height

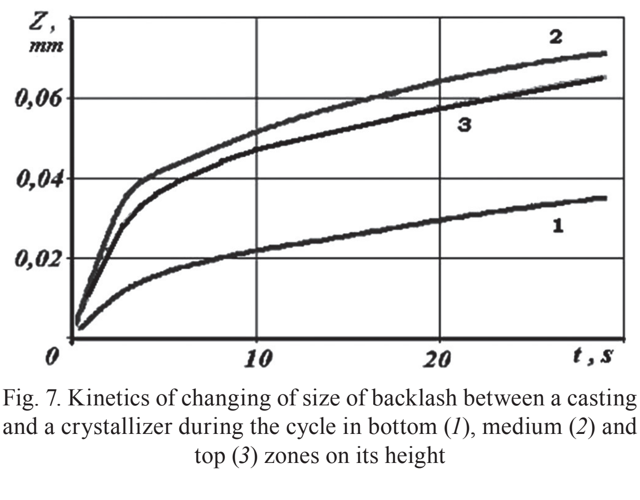

Fig. 7. Kinetics of changing of size of backlash between a casting and a crystallizer during the cycle in bottom (*1*), medium (*2*) and top (*3*) zones on its height

quent period of the cycle this value decreases to 0,00117–0,001087 mm/s, i. e. 5–7 times.

Thus, the main contribution to value of gas backlash between a crystallizer and a solidification casting brings its shrinkage during approximately 80% of duration of the cycle. The crystallizer after achievement of the maximum deformation starts to reduce its radial size and as though «approaches» to the casting which constantly decreases in diameter.

The described mechanism of interaction of crystallizer and solidification cover determinates rather small size of gas backlash during all time of casting formation in crystallizer. As a result conditions for high intensity of heat sink from the surface of casting and high solidification rate of metal are kept during all cycle.

Solidification and cooling of casting

Character of change of density of heat current on working surface of crystallizer determine generally the conditions of solidification of castings. It is possible to present calculating formulas of determination of thickness of rim in the form [8]:

$$\xi_i = R - \sqrt{(R-\xi_{i-1})^2 - \frac{2q_{1i}(t)\Delta t_i R}{\rho_1 L_{ef\,i}}}, \qquad (6)$$

$$T_{1i} = T_{sol} - \frac{q_i(t)\xi_{avi}}{\lambda_1}, \qquad (7)$$

$$L_{ef} = L_1 + C_1'(T_{pour}(t) - T_{sol}) + C_1(T_{sol} - T_{1i}) \times$$

$$\times \frac{1 - \frac{\xi_{i-1}}{3R_1}}{2 - \left[1 - \frac{\xi_{i-1}}{2R_1}\right]}, \qquad (8)$$

$$\xi_{avi} = \xi_{i-1} + \frac{\xi_1 - \xi_{i-1}}{2}, \qquad (9)$$

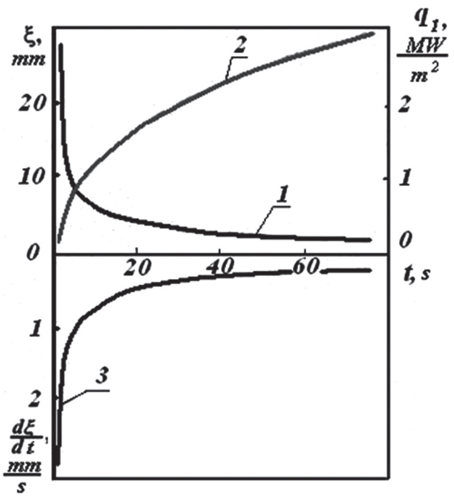

Fig. 8. Change of density of heat current on working surface of crystallizer (*1*), wall thickness of casting (*2*) and solidification rate of grey cast iron (*3*) during the time of formation (∅ of casting is 105 mm)

$$t_{avi} = t_{i-1} + \frac{\Delta t_i}{2}, \qquad (10)$$

$$\xi_{tot.i} = \xi_i + b\Delta\xi_i = \xi_i + b\xi_{1i}\left[\frac{T_l - T_{sol}}{T_{sol} - T_{1i}}\right], \qquad (11)$$

where C_1', C_1 – specific heat of liquid and hard metal; L_{ef}, L_1 – effective and true crystallization heat; ρ_1 – density of casting material; λ_1 – heat-conduction coefficient of solid rim; b – coefficient considering share of transitive hard-liquid zone entrained by casting from crystallizer; T_1, T_{sol} – temperature of surface of casting and temperature of solidus of metal.

Step-by-step calculation of the received system of equations by the successive approximation method allows to determine kinetics of growth of solid rim and on this basis – modifications of solidification rate of casting in time.

The analysis shows that according to the character of change of specific heat current, solidification rate of casting also changes. At initial period when the heat current has maximum value, solidification rate of metal exceeds 3 mm/s (Fig. 8). While increasing of solid rim it sharply falls in the first 10s to 0,5 mm/s, and then smoothly decreases to 0,3 mm/s during subsequent periods of formation.

The obtained interrelation of thermal parameters and kinetics of increase of solid rim in the conditions of constant overheat at solidification front gives the opportunity to carry out the analysis of change of conditions of primary crystallization of cast iron and to forecast the character of structure of castings on wall thickness what provides reasonable choice of mode of secondary cooling for obtaining of specified final structure.

After freezing-up of specified wall thickness the casting is removed from crystallizer and melt and its cooling occurs outside of the mould [9, 10]. Cooling conditions during this period greatly influence on formation of finite structure and properties of casting. Let's divide the period of cooling of casting into steps and find solution for each of them (Fig. 9).

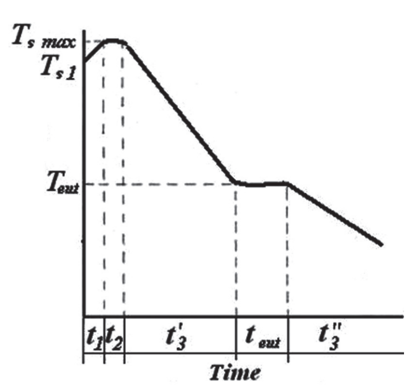

Fig. 9. Change of temperature of external surface of casting after extraction from crystallizer

We accept that there is no heat transport along the forming casting, and all heat from its internal surface is transferred only by heat conductivity through the wall. The duration of the first step t_1 which begins at the moment of extraction of casting from crystallizer will be determined under the formula:

$$t_1 = \frac{\rho_1 L_{ef} \Delta\xi}{\frac{\lambda_1}{\xi_f}(\vartheta_{cr} - \vartheta_s)}, \quad (12)$$

where ρ_1 and λ_1 – density and the heat-conduction coefficient of casting material; L_{ef} – effective heat of crystallization; ξ_f – wall thickness of casting at the moment of extraction from crystallizer; $\vartheta_{cr.} = T_{cr.} - T_{en.}$; $\vartheta_{s.} = T_1 - T_{en.}$; T_1 – average temperature of external surface of casting at the first step of cooling; T_{en} – environment temperature; $\Delta\xi = b\xi_f \frac{\vartheta_{liq.} - \vartheta_{cr.}}{\vartheta_{cr.} - \vartheta_{s1.}}$, – thickness of layer of liquid phase which is entrained by casting from crystallizer; b – coefficient considering the share of transitive hard-liquid zone entrained by casting from crystallizer; ϑ_{liq} – exces sive temperature of liquidus; $\vartheta_{s1} = T_{s1} - T_{en}$; T_{s1} – temperature of external surface of casting at the moment of extraction from crystallizer.

The first step of cooling of casting finishes at the moment of complete solidification of liquid phase being entrained from crystallizer. By this moment the temperature of external surface reaches the maximum value ($T_{n\max}$), and its heating-up stops. During the second step of cooling (t_2) the temperature of external surface remains constant and equal to Tn max, and the temperature of internal surface changes from $T_{\text{кр}}$. to T_1.

$$t_2 = \frac{\xi_f \rho_1 C_1}{2\alpha_1}\left[\frac{\vartheta_{cr}}{\vartheta_{s\max}} - \frac{\alpha_1 \xi_f}{\lambda_1} - 1\right], \quad (13)$$

where α_1 – aggregate heat-transfer coefficient from external surface of casting; C_1 – specific heat capacity of casting material;

Cooling of casting at the third step occurs under the law of regular heating rate. This rate is broken only during the period of eutectoid transformation with which must be pointed out as a separate step. Duration of the third step is determined from the expression:

$$\vartheta_s = \vartheta_{sinit} e^{-\frac{2R\alpha_1 t_3}{C_1\rho_1\xi_f(R+r_1)}}, \quad (14)$$

where ϑ_{sinit} – excessive temperature of external surface of casting in the beginning of the third step of cooling; R and r_1 – external and internal radiuses of casting; α_1 – is accepted for average temperature in calculated interval of time.

Duration of eutectoid transformation $t_{eut.}$:

$$t_{eut} = \frac{L_{eut}\xi_f(R + r_1)}{2R\left[C10^{-8}(T_{eut}^4 - T_{en}^4) + \alpha_A(T_{eut}^4 - T_{en}^4)\right]}, \quad (15)$$

where T_{eut} and L_{eut} – temperature and specific heat of perlite transformation; C – radiation coefficient of surface of casting; α_A – heat-transfer coefficient by contact.

General time of cooling of casting outside of crystallizer will be:

$$t_{tot} = t_1 + t_2 + t_3^{'} + t_{eut} + t_3^{''}. \quad (16)$$

Thus, it is possible to optimize the mode of heat sink from the point of view of obtaining of the specified structure and properties and minimization of residual voltage using corresponding techniques (shielding, heating or forced cooling) at various steps of secondary cooling of casting.

Hydrodynamics of casting process

Due to the fact that at CICF the internal surface of casting is obtained directly from melt without application of core and is determined only by solidification front, the hydrodynamics of liquid metal during the process of pouring greatly influences on the conditions of its formation in crystallizer.

Basic circuit of CICF represents communicating vessels system (crystallizer – casting bowl), connected by means of siphon metal wire and filled with liquid metal (Fig. 1). Solidified rim constituent body of a casting is periodically taken from one of them (crystallizer) and the removed amount of metal is compensated by a new portion of melt through another one (casting bowl) in the same period. At the moment of extraction of casting all system comes out from equilibrium state and the transitive hydrodynamic process caused by occurrence of forced circulating currents of melt in liquid bath of crystallizer. These currents are caused by perturbation action of moving casting, feeding of a new portion of melt in the casting bowl and its flow into the crystallizer.

Thus, solidification of each casting at the initial step occurs in the presence of forced circulating currents in liquid bath of crystallizer. These currents determine intensity of heat-transfer from liquid metal to solidification rim. During subsequent moments of time after attenuation of forced currents solidification front interact with melt which is in the state of natural convection.

Laws of heat-transfer from molten metals close to solidification temperatures are not enough studied. As a rule dependences of type Nu = f(Pe, Pr) are used at

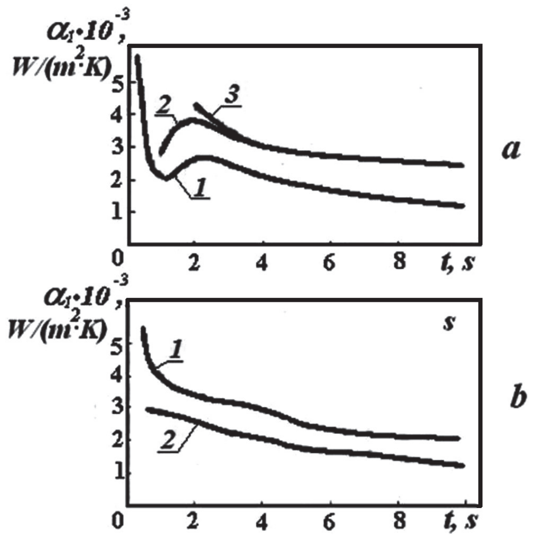

Fig. 10. Change of heat-transfer coefficient at solidification front in time at central (*a*) and peripheral (*b*) feeding of metal in crystallizer: *1* – at distance of 30 mm from the bottom butt-end of crystallizer; *2* – 40–50; *3* – 60–70 mm

forced convection. In the present work determination of the heat-transfer coefficient on phase boundary (α_1) is realized under the formula [11]:

$$\mathrm{Nu} = 1{,}1\ [(1\text{–}\mathrm{Pr})^{0{,}33}\mathrm{Pe}]^{0{,}5}, \quad (17)$$

where Pr and Pe – Prandtl and Pecklet numbers.

Character of local currents arising in melt at the moment of casting extraction and pouring of new portion depends on the way of its feeding and formation of jets of metal fed in crystallizer.

Calculations and experimental research show that change of α_1 corresponds to change of rate of circulating currents. Coefficient α1 has maximum value during that moment of time and in that zone of crystallizer when the rate of forced currents has maximum value (Fig. 10).

This coefficient sharply increases in zone of intensive circulating currents which destroy rather immobile boundary layer of liquid metal what interfere with formation of liquid-solid component of two-phase zone and decelerate growth of solid cover. The more are rate and concentration of currents the more is the size α_1 and the more considerable is non-uniformity of solidification front.

It is established that non-uniformity of wall thickness formed during the initial moment of solidification is almost not smoothed out during the subsequent period and remains during all time of formation in crystallizer. It is necessary to organize metal feeding in crystallizer in such a way in order to exclude bulge of wall at the bottom butt-end and local washout of rim in overlying zones during the initial moment and to provide approximately equal intensity of heat-transfer on all solidification front during the subsequent period to minimize variations in wall thickness of castings.

This problem was solved due to peripheral feeding of metal in crystallizer through slot feeders equally-spaced on perimeter of pouring sleeve.

After attenuation of forced circulating currents there is only natural convection in liquid bath of crystallizer caused by difference of temperatures of liquid cast iron at solidification front and in axial zone of crystallizer. In this case determination of α_1 was made by approximate criterial equation [12]:

$$\mathrm{Nu} = 0{,}12\mathrm{Ra}^{0{,}33}, \quad (18)$$

where $\mathrm{Ra} = \mathrm{GrPr} = g\beta\Delta T\dfrac{d_{eq}^3}{\nu_1 a_1}$ – Rayleigh criterion; β – temperature coefficient of volume expansion, 1/°C; ΔT – difference of temperatures; g – gravitational acceleration, m/s^2.

Research has shown that local washouts of solidification rim are excluded at natural convection and rate of freezing-out of solidification rim remains approximately identical on the whole solidification front.

According to technological requirements it is necessary to fill the crystallizer with melt to the specified level as soon as possible after extraction of solidified casting. At the same time it is essential to provide monotonous movement of level of metal in crystallizer without stops and fluctuations. It was necessary to find out dependence of conditions of flow of melt and filling of crystallizer on technological parameters and design of gating system and to determine optimum values of these parameters.

The problem was solved due to minimization of time of flow of melt (t_f) and quadratic integral test in the form of $I_{\mathrm{sum}} = \int_0^\infty y^2(t)dt$ provided that fluctuations of level are excepted, where y is position of level of metal in crystallizer [13].

Mathematic simulation of transitive hydrodynamic process has shown that cut of running channels is one of the major factors considerably influencing on variability of system and on duration of filling of crystallizer. It is obviously that the more it is the faster is flow of melt. However in this case transitive process has strongly marked fluctuating character (Fig. 11, curve *1*).

A set of mathematical experiments on the basis of application of three-level second-order plan for 7 factors was carried out to receive dependences of influence of constructive and technological parameters of casting process $t_п$ and I_{sum}. Multi-criteria optimization of hydrodynamic process with maximum convolution

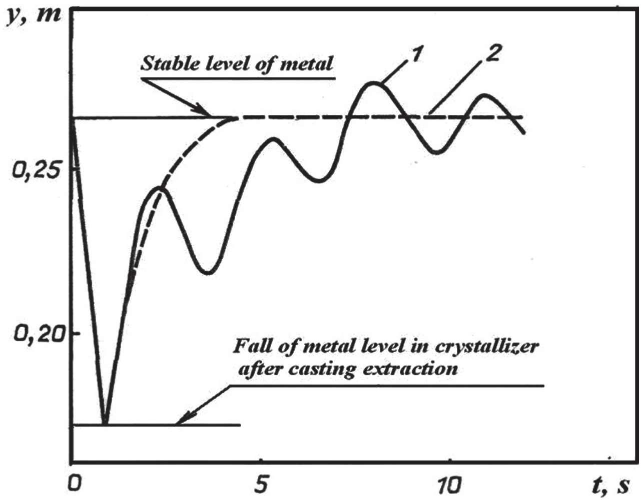

Fig. 11. Character of filling of crystallizer after extraction of casting: *1* – D_4 = 0.04; *2* – 0.024 m respectively

of partial criterion in global one and with determination of functions of desirability and ranking of factors was carried out on the basis of received dependences. In this case the basis of working out for t_n was resolvability of foundry equipment and accessory, and minimum value for I_{sum} ($3 \le t_f \le 6$ c; $0 \le I_{sum} \le 0{,}5$).

For example, it is established that for casting of billets from grey cast iron of 100 mm in diameter with wall thickness of 11–12 mm gating system should have following parameters: diameter of pouring basin – 0.114 m, of running channels – 0.052 m, of calibrated orifice of limiting element determination melt consumption at flow D_{4-}0,024 m. In this case it is necessary to carry out metal pouring simultaneously with the beginning of extraction of casting in each cycle. As a result enough fast and smooth filling of crystallizer with melt is provided (Fig. 11, curve *2*).

Thus the received results allowed to create optimum design of gating system providing obtaining of castings with uniform wall thickness and minimum duration of filling of crystallizer with melt in each cycle when excluding fluctuation of level of metal in it.

Structure and properties of castings

Quality of castings from cast iron is determined by character of inclusions of graphite and structure of metal matrix on which mechanical and operating properties of details depend. Size of graphitic inclusions (LG_l), proportions of structurally-free cementite (C) and ferrite (F) are taken as microstructure indicators. Wall thickness of casting (ξ) and roughness of its internal surface (Δξ/ξ, where Δξ is average height of ledges) are also considered among quality indicators as they directly depend on technological parameters of process. We studied influence on considered indicators of following basic technological factors: time of casting formation (12 s $\le t \le$ 34 s), temperature of metal feeding in crystallizer (1180 ºC $\le T_c \le$ 1380 ºC), rate of cooling of casting outside of crystallizer to temperature of pearlite transformation (0.12 K/s $\le V \le$ 1.75 K/s), conditions of carrying out of pearlite transformation (in the air in natural conditions, at shielding), chemistry of cast iron considered by degree of eutecticity ($0.74 \le S_e \le 1.0$), proportions of Silicon ($1.26 \le Si \le 2.5$) and integral coefficient ($-0.13 \le C_k \le -0.04$) considering influence of alloying elements on chill [14, 15].

In general regressive dependence between indicators of quality of casting and parameters of casting process can be presented as follows:

$$\xi = f_1(t, S_e, T_{en}, X_2),$$

$$\frac{\Delta\xi}{\xi} = f_2(t, S_e, T_{en}),$$

$$LG_l = f_3(t, S_e, C_к),$$

$$C = f_4(t, S_e, C_к, V),$$

$$F = f_3(Si, S_e).$$

Formation of cast structure of cast iron casting is determined by processes of primary crystallization and character eutectoid transformations.

Creation of optimum conditions of castings formation at casting by freezing-up provides essential increase of strength and operational characteristics of material. It is connected with the fact that in quick-cooled cast iron numerous, thin-axis and intertwining dendrites of austenite are formed. Remained liquid phase is reinforced by dense grid of such dendrites. It is one of the reasons of increase of resistance of cast iron at CICF. In this case strongly branched dendrites of primary austenite determine essential growth of contacting surface of austenite phase with melt. During the process of eutectic transformation austenitic-graphite colonies crystallizing close to dendrites strengthen the latter, which is the result of growth of eutectic austenite on dendritic axes. This also promotes increase of strength of cast iron.

Comparative tests of piston rings (PR) ∅150 mm from grey cast iron for diesel engine produced by serial process in dry core moulds and by the method of freezing-up have shown that the rings obtained by freezing-up have higher level of properties on all basic parameters [16]:

relative coefficient of elasticity, % 12
elasticity, % 16,5
bending strength, % 6
residual deformation, % 30,8
endurance limit, % .... to 21

Comparative tests of PR produced from castings obtained by the various methods of casting have shown that PR obtained by CICF have the greatest wear-resistance and resistance to tearing as well as high elastic properties. PR and billets obtained by casting in sand mould (SM) by continuous horizontal casting (CHC) and CICF were analyzed. Results of researches are given in Table 1.

Table 1. **Properties of piston rings produced from castings obtained by various methods of casting**

Method of casting	Hardness [HB]	Strength $\sigma_в/\sigma_{-1}$, [MPa]	Wear*, [mg/100 h]	Resistance to tearing, P_3, [MPa]	Elastisity, [Nn]
CHC	235	229 / 121	51,2 / 70,6	20,8	8,5–10,0
CICF	241	320 / 125	47,5 / 69,8	21,7	9,0–11,0
SM	235	295 / 115	54,3 / 72,7	18,4	6,0–8,0

Note: * numerator is PR; denominator is cylinder sleeve.

Full-scale bench tests of cylinders sleeves have shown that sleeves obtained by CICF meet to the full requirements made to augmented diesel engines – their strength characteristics exceed similar characteristics of sleeves of other manufacturers (Table 2) [17].

Table 2. **Characteristics of cylinder sleeves produced by various manufacturers**

Parameter	ITM of NAS of Belarus	JSC «Motordetal», Ukraine	«Ichin», Czechia
Average fracture pressure, [MPa]	48,8	33,1	42,0
$\sigma_в$, [MPa]	327–360	260–280	280–310
Fuel consumption, [g/(kWh)]	225,2	–	222,9
Pressure of crankcase fumes, [Pa]	250	–	280
Consumption of crankcase fumes, [l/min]	55	–	59
Average wear, [μm]	0–21,3	–	0–31,3

Obtained results have allowed to organize production of high-quality details with high operational characteristics from various types of cast iron by fundamentally new method. A complex of special foundry equipment and technological accessory was created for realization of this casting method of hollow cylindrical billets. Half-automatic casting machine with reciprocative movement of operating element (Fig. 12) has following technical characteristics:

Size of castings, mm:
external diameter 70–220
height 100–250
wall thickness.. 10–30

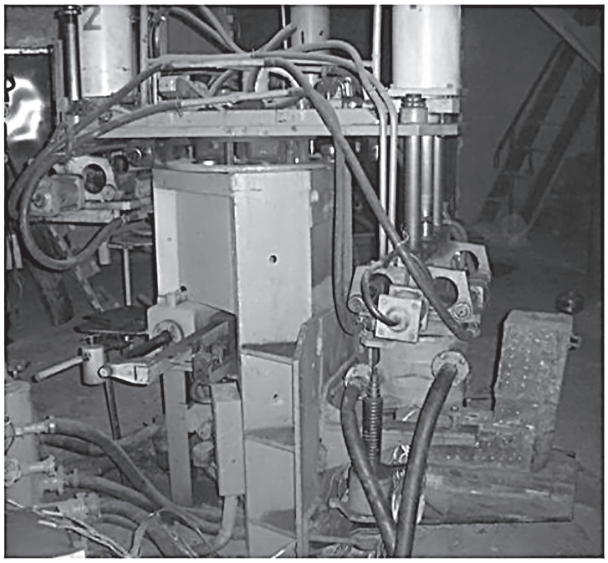

Fig. 12. General view of CICF machine

Productivity, pcs/h 60–180
Consumption of recirculated cooling water, m^3/h ... 20
Drive .... Pneumatic
Operating air pressure, MPa 0,5
Air consumption, nm^3/h.. 100
Control system ....Electric
Weight, kg 1500
Machine overall dimensions, mm....1000×1500×2000

Worked out technological process provides:

- essential increase of set of mechanical properties of castings material and operational life of details;
- obtaining of billets with specified structure without additional heat treatment;
- high productivity of casting process;
- obtaining of billets of specified length without cutting operation in conditions of continuous casting;
- improvement of ecological environment.

Thus fundamentally new effective method of obtaining of hollow cylindrical billets by directional solidification without application of core from various types of cast iron in continuous-cyclic mode of casting is proposed. Process theory is worked out; laws of complex influence of thermal, hydrodynamic and metallurgical parametres on casting formation are established. Manufacture of wide range (more than 700 items) of high-duty products is created by new technology.

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