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ALUMINUM ALLOYS

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CASTING OF ALUMINUM ALLOYS WITH PRESSURE CRYSTALLIZATION. PART 1

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The stages of creation and development of a method of casting with crystallization under pressure for aluminum alloys are described. Special features of formation of castings of aluminum alloys pressed by the main pressing techniques (piston, plunger, and piston-plunger ones) are considered. The force conditions of formation of such castings are studied.

Key words: aluminum alloys, castings, casting with pressure crystallization, cooling curves.

INTRODUCTION

The recent stage of development of mechanical engineering is characterized by growth in the production of castings from aluminum alloys. Elevation of the quality of the castings at simultaneous reduction of material and power expenses may be provided by development and introduction of various methods of action on the melt and on the solidifying casting. Among these actions the application of pressure takes a special place due to the variety of the forms of the application and its efficiency.

The method of casting with pressure crystallization (CPC) developed in the USSR in the middle of the 1970s (V. M. Plyatskii et al) is a quite promising special kind of casting. A great contribution into the development of CPC has been made by V. M. Plyatskii, N. N. Belousov, P. N. Bidulya, A. I. Batyshev, V. V. Markov, G. I. Timofeev, T. N. Lipchin, A. F. Astapov and other researchers. The results of the works devoted to CPC are described in several monographs [1 – 6].

At different stages of its development the method of CPC was known as die casting from liquid metal, liquid metal die casting, liquid die casting, pressing at crystallization, pressing from melt, injection casting, etc. The GOST 19169–86 Standard classifies the method as casting with crystallization under pressure. This name reflects the essence of the process more exactly, because, firstly, the initial material is melt and, secondly, the preforms obtained commonly have a cast structure and are castings rather then forgings.

The development of casting with crystallization under pressure can be divided conventionally into four stages, namely,

(*I*) until the middle of the 1960s; various schemes and modes of the process were tested and worked out; special hydraulic presses and casting machines were created; first studies of the processes of solidification and shrinkage of the castings were performed and their structure and properties determined; the results are generalized in [1 – 9].

(*II*) from the middle of the 1960s to the middle of the 1970s; this period is characterized by development of processes for obtaining specific preforms, systematic investigation of the kinetics of compaction of castings solidified under pressure, of the processes of solidification, of the structure and properties of the castings; the results are generalized in [10, 11].

(*III*) from the middle of the 1970s to the early 1990s; studies of solidification and compaction of castings under the action of mechanical pressure including individual experiments (with the use of one thermocouple) and analytical computations; the cast materials are aluminum, magnesium, copper, iron, and zinc as well as composite materials with metallic matrix. The process of CPC is worked out for specific kinds of castings and their structure and properties are determined; the results are generalized in [12 – 15].

(*IV*) from the beginning of the 1990s until present; studies of CPC of special alloys (wear-resistant, high-strength,

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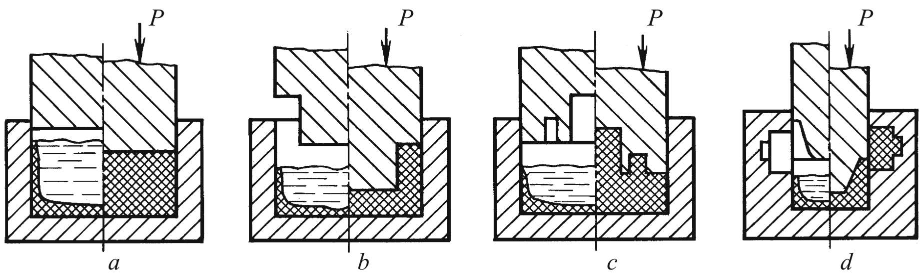

Fig. 1. Schemes of pressing of forming castings by the method of casting with pressure crystallization used in Russia: *a*) piston; *b*) plunger; *c*) piston-plunger; *d*) through gate runners.

etc.), composite materials and alloys in a liquid-solid state; the equipment includes not only hydraulic presses but also special casting machines with metal reservoir located under the press mold or alongside of it; note that in Russia the research of CPC in this period is limited, which finds reflection in a little number of publications on the topic [16, 17].

Despite its obvious advantages (high yield and coefficient of metal utilization, good physical, mechanical and operating properties of the castings) the method of CPC has not found wide application due to the insufficiently developed theoretical and technological substantiation including the role of pressure at individual stages of formation of the castings. The value, the kind of the action, and the rate of growth of the pressure affect considerably the quality of the castings. The following aspects of the process have been studied not exhaustively: (*1*) the thermal and force conditions of formation of castings from aluminum alloys of various systems and composite materials due to the main pressing techniques; (*2*) the efficiency of the action of pressure on the solidifying casting; (*3*) the kinetics of densification of castings from alloys with various degrees of alloying; (*4*) changes in the structure and properties of castings in the cast condition and after heat treatment.

Formation of castings from aluminum alloys has been studied for the main pressing schemes, i.e., piston, plunger, and piston-plunger ones (Fig. 1) [16, 17].

The study has been performed with the help of experimental and analytical methods and using the methods of design of experiment. The objects of the study were castings in the shape of a solid cylinder 50 mm in diameter and 100 – 105 mm high (piston pressing), in the shape of a nozzle with an external diameter of 60 mm, a height of 60 mm and a wall thickness of 5 – 20 mm (plunger pressing), and in the shape of a cylinder with bulging components on the upper end (piston-plunger pressing), which were produced from binary and some commercial aluminum alloys.

The experimental study of the thermal conditions of formation of the castings was performed using thermocouples of type KMTS-KhA (GOST 23847 – 79) with electrodes 0.2 mm in diameter in a steel shell having an external diameter of 1.5 mm). The path of the plunger was determined using rheochord gages. The pressing pressure was determined using strain metering pressure cells. The readings of the thermocouples and gages were recorded simultaneously on one tape of an NO30A (or H43.1) light-beam oscillograph. The tests were performed in a D2430B hydraulic press with rated force of 1 MN.

PISTON PRESSING

Analysis of the cooling curves of castings obtained by piston pressing has shown that their solidification under mechanical pressure occurs at a higher temperature drop over cross section than at atmospheric pressure. The time of solidification of the castings decreases in any zone. The closer the zone to the axis of the casting, the more substantial is the shortening of the time of its solidification under the action of pressure. The effect is explainable by the fact that the surface layers of the casting at a depth of up to 3 mm solidify prior to the moment of application of pressure, whereas the deeper-lying layers solidify either at a growing pressure or first at a growing pressure and then at the rated pressure.

At a pressure above 50 – 80 MPa the temperature of crystallization of the metal increases by 5 – 12°C (depending on the composition of the alloy, the pressing pressure, and the rate of its application). This is explainable by (*1*) a change in the thermodynamic state of the system in accordance with the Clausius – Clapeyron law, (*2*) mismatch between the rates of emission of crystallization heat and of removal of heat by the press mold bottom, (*3*) emission of heat upon deformation of the vertical crust under the action of the pressure.

Generalized dependences of some studied parameters on the rated pressure are presented in Fig. 2. These data show that growth in the rated pressure p_r is accompanied by decrease in the time of solidification of the casting $\tau_s = \tau_r - K\sqrt{p_r}$, in the relative temperature of the surface $t_n/t_s = 0.85 - 0.018\sqrt{p_r}$, and in the temperature drop δt_c on the casting/mold interface. The temperature drop δt_c over the cross section of the casting increases. All the dependences are given in the form of domains that comprise the experimental data for alloys of the Al – Si system (with up to 25% Si). The dependences are also valid for alloys of the Al – Cu and Al – Mg systems and commercial alloys.

The studied parameters vary the most in the pressure domain ranging from atmospheric one to 100 – 120 MPa. Upon further growth in the rated pressure they change too, but to a less degree. This may be explained by a dense contact between the growing side crust and the walls of the mold, decrease (and even disappearance) of the clearance at the casting/mold interface, and the resulting growth of the cooled surface, which increases the rates of heat removal by the walls and of crystallization. At a pressure exceeding 120 MPa the clearance decreases still more due to the pressing of the metal into the microscopic relief of the functional surface of the mold. However, the growth of the cooled (contact) surface is much lower than in the first pressure domain, and this lowers the effect of the rated pressure on the studied parameters.

Mechanical pressure promotes removal of the clearance between the forming casting and the mold, as a result of which the heat exchange at the casting/mold interface intensifies by a factor of 4 – 5. This results in a 3 – 4-times decrease in the time of the solidification of the casting and in a temperature drop on the interface, and increases the temperature drop over the cross section and over the height of the casting.

The time of solidification of the casting increases upon growth in the content of the second component in binary alloys.

We have studied the effect of the scale factor (reduced size) on the time of solidification of cylindrical castings at a pressure of 50 – 200 MPa. Growth in the reduced radius R_{re} (at a constant diameter) is accompanied by a linear increase in the time, i.e.,

$$\tau_s = K_{re} R_{re}, \tag{1}$$

where K_{re} is a coefficient, sec/mm. The time of the existence of the two-phase zone increases with growth in R_{re}.

The displacement of the solidification front from the side surface to the central zone (Fig. 3) can be expressed mathematically as

$$x/R_c = K_c \tau^n, \tag{2}$$

where x is the thickness of the crust growing from the side surface of the mold (mm), R_c is the radius of the casting (mm), K_c is a coefficient ($1/\text{sec}^n$), and τ is the time that has passed from the final moment of pouring of the melt into the mold, sec.

For castings from alloys of the Al – Si system dependence (2) has the following form (at $p_r = 200$ MPa):

$x/R = 0.0261\tau^{1.78}$ at correlation coefficient $k = 0.994$ (alloy AK12);

$x/R = 0.0253\tau^{1.88}$ at $k = 0.998$ (alloy Al – 7% Si);

$x/R = 0.0264\tau^{1.76}$ at $k = 0.993$ (alloy Al – 25% Si);

$x/R = 0.0257\tau^{1.93}$ at $k = 0.997$ (aluminum A7).

It can be seen that factor K_c increases upon decrease in the degree of alloying of the alloy and growth in the pressing pressure. It should be noted that the pressing pressure levels the values of K_c for castings of different composition.

For aluminum A7 and all the studied alloys dependence (2) is representable reliably enough as

$$x/R = K\tau^2. \tag{3}$$

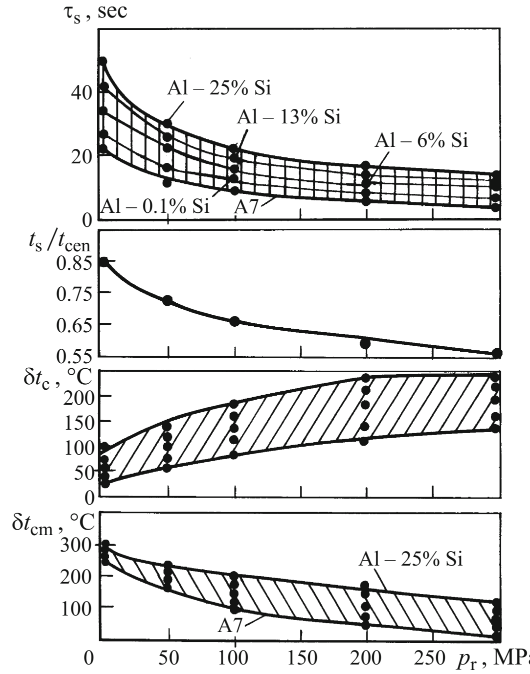

Fig. 2. Dependence of the time of solidification of a casting (τ_s), of the relative surface temperature (t_s/t_{cen}) and of the temperature drop over cross section (δt_c) and on the "casting/mold" interface (δt_{cm}) on the rated pressure (p_r) for Al – Si alloys.

Formula (3) can be used for computation after the following transformation:

$$x = K\tau^2. \tag{4}$$

Growth in the pressing pressure shortens the time of existence of the two-phase zone (Fig. 3). This leads to sequential solidification of castings from alloys with a narrow range of crystallization and sequential-volumetric solidification of castings from alloys with a wide crystallization range. For example, in the case of solidification of castings from alloy Al – 6% Si (narrow crystallization range) at atmospheric pressure the central zone of the casting stops to reside at the liquidus temperature 14 sec after the end of the pouring; for the solidus (eutectic) temperature the time is 35 sec, i.e., a two-phase zone is preserved in the casting for 21 sec. At a pressure of 300 MPa these time intervals decrease to 6 and 12 sec, respectively (a two-phase zone exists in the casting for 6 sec). For castings from alloy Al – 25% Si (the crystallization range is ~ 30°C) solidifying at atmospheric pressure the time of cooling of the thermal center to the liquidus temperature is 10 sec and that of cooling to the solidus (eutectic) temperature is 40 sec. The time of existence of a two-phase zone is 30 sec. Under a mechanical pressure of 300 MPa the respective times are 5 and 10 sec (the time of existence of a two-phase zone is 5 sec).

Inoculation of silumins containing 11 – 17% Si with an AlTi5B1 addition (in order to act on the α-phase) causes in-

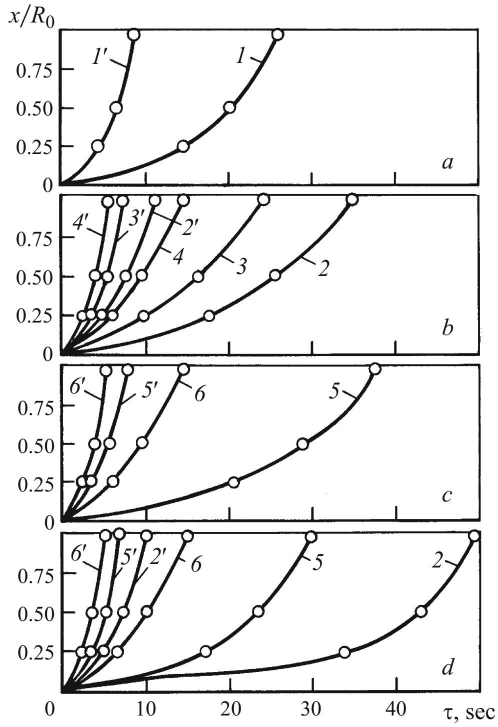

Fig. 3. Curves x/R_0 of displacement of the solidification front in cylindrical castings of alloys of the Al – Si system of different composition subjected to piston pressing: *a*) Al – 0.1% Si; *b*) Al – 6% Si; *c*) Al – 13% Si; *d*) Al – 25% Si; *1* – *6*) solidification at atmospheric pressure; *1'* – *6'*) solidification at a pressure of 200 MPa.

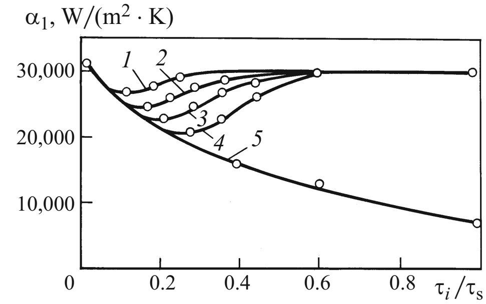

Fig. 4. Variation of the coefficient of heat transfer α_1 during solidification of castings (τ_i/τ_s is the relative time of solidification): *1*, *2*, *3*, *4*) alloys Ak18N, AK12, AK7ch and aluminum A7, respectively (the rated pressure in solidification p_r = 200 MPa); *5*) all the other alloys (solidification at atmospheric pressure).

crease in factor K and decrease in the time of solidification of the casting. For example, for castings from alloy Al – 17% Si solidifying at atmospheric pressure K = 0.011, 0.2 and 0.277 mm/sec^2, whereas the solidifying at a pressure of 160 MPa occurs at K = 0.152, 0.211 and 0.277 mm/sec^2 without inoculation and with 0.2% Ti and 0.5% Ti, respectively. A similar picture is observed when we compare the solidification of castings from alloys AK7ch and A356.2 differing from each other primarily in the content of the inoculating element (strontium).

We used the theory of contact heat exchange and the method of graphical integration to compute the value of the coefficient of heat transfer α_1 between the forming casting and the press mold. By the moment when the pouring of the melt is finished α_1 = 30,000 – 32,000 W/(m^2 · K). If the further formation of the casting occurs at atmospheric pressure, factor α_1 decreases continuously, which is promoted by formation of a clearance between the casting and the mold. As a result, when the solidification of the casting finishes, the value of α_1 attains 7500 – 7700 W/(m^2 · K). At the moment of application of pressure the decrease in α_1 stops and then (in proportion to the growth in the pressure) increases to a specific value typical for the rated pressure p_r. Then α_1 remains virtually unchanged at the level attained until the casting stops to solidify. The variation of coefficient α_1 for castings from aluminum A7 and alloys AK7ch, AK12 and AK18N in the process of solidification (at p_r = 200 MPa) is presented in Fig. 4. It can be seen that the time of the solidification under conditions of enhanced intensity of cooling of the castings from alloys AK18N and AK12 is longer than that of the castings from aluminum A7 and AK7ch, because they have different thermophysical characteristics. The value of the Biot criterion for castings of the alloys mentioned ranges within Bi = 1.7 – 9 for the case of casting with 80 – 100°C superheating above the crystallization (liquidus) temperature and pressure growth from atmospheric one to 300 MPa.

In order to study the process of solidification of a casting on the side of the piston we used a method developed at the MGOU and based on detachment of the growing crust formed on the side of the end of the piston from the not solidified melt remaining in the mold die. The melt was poured into the die of the mold heat-insulated on the side of the functional cavity by a coating (asbestos sheet 3 – 5 mm thick) that decelerated the growth of the crust on the side of the bottom and walls of the die. The end of the pressing piston was not protected by a heat-insulating coating. After a hold at a pressure for a specified time, the piston was lifted to the initial position. The solid "crust" formed on the side of the piston end and detached from the not solidified melt remaining in the cavity of the die was removed together with the piston. After cooling to room temperature the thickness of the "crust" was measured by a caliper at several places over the perimeter.

Mathematical processing of the obtained curves of growth of the "crust" (Fig. 5*a*) allowed us to determine the following dependence of the thickness of the crust x_{cr} on the pressing time τ_p, which is often called a "square root law":

$$x_{cr} = K_{cr}\sqrt{\tau_n}, \quad (5)$$

where K_{cr} is the coefficient of solidification ranging within 5 – 8 mm/sec$^{0.5}$ (aluminum A7 possesses the highest K_{cr}; alloy AK12 exhibits the lowest values of K_{cr} due to the difference in the thermophysical characteristics). The value of K_{cr} for one and the same alloy is the higher, the higher the pressing pressure.

Analysis of the cooling curves of the "crusts" (according to the readings of the thermocouples mounted at a distance of 1, 5, and 10 mm from the end of the piston) shows that growth in the pressing pressure improves the contact between the piston and the "crust." As a result, the temperature of the surface layer of the crust (at a depth of 1 mm) for alloy AK12 decreases markedly and stabilizes at a level of 540 – 530°C (at 10 MPa) and 475 – 450°C (at 200 MPa). The temperature gradient over the thickness of the crust at the pressures mentioned is 7 and 15°C/mm, respectively. The solidification time of the layers at the depths of 1, 5 and 10 mm decreases from 1.3 – 1.5, 5 – 6, and 10 – 12 sec (for 10 MPa) to 0.5 – 0.6, 2.2 – 3, and 5.5 – 6 sec (for 200 MPa), respectively. The dependence of the time of solidification of the crust on the pressing pressure is virtually linear. The change in the thickness of the "crust" of alloy AK12 with time is presented in Fig. 5*b*. The values of the solidification coefficient of the alloy range within $K = 3.5 – 4.5$ mm/sec$^{0.5}$.

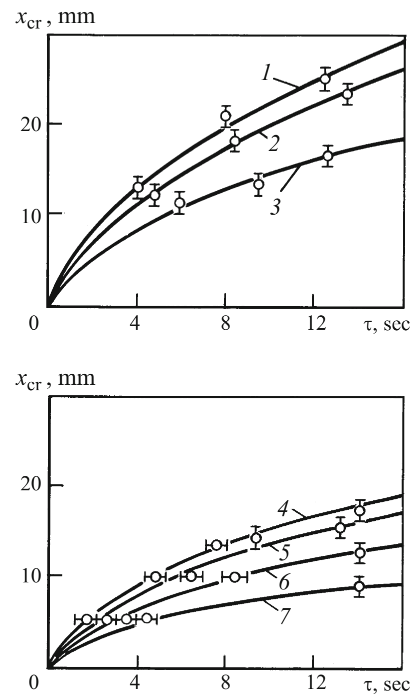

Fig. 5. Variation of the thickness of the crust x_{cr} during solidification of castings: *a*) aluminum A7 (*1*), alloys AK7ch (*2*) and AK12 (*3*) at rated pressure $p_r = 150$ MPa; *b*) alloy AK12 [*4*) at $p_r = 200$ MPa, *5*) at $p_r = 150$ MPa; *6*) at $p_r = 100$ MPa; *7*) at $p_r = 10$ MPa].

PLUNGER PRESSING

In the case of plunger pressing (Fig. 1*b*) a doze of melt is poured into the die of a press mold and then squeezed upward by the protruding part of the plunger until the functional part of the press mold is filled completely. The characteristic feature of this variant of CPC is the fact that the plunger first touches the melt removed from the vertical walls of the die and squeezes it above the poured level filling the functional cavity shaped by the die and the protruding part of the plunger. The shaping factor $K_{sh} = V_{sh}/V_c$ (here V_{sh} is the volume of the melt squeezed by the plunger during shaping of the casting and V_c is the whole of the volume of the casting) can vary from 0.1 to 0.9.

When the shaping finishes, the pressure is transferred by the plunger to only the internal surface of the casting or to the internal surface and the upper end of the casting, or to the internal surface and a part of the upper end of the casting. The latter scheme (Fig. 1*b*) was chosen for testing.

We analyzed the hydrodynamic regimes of CPC with allowance for the discontinuity of the stream. It turned out that the speed of motion of the melt in the functional part of the press mold obeys the following law:

$$v_{sh} = v_{pl}/[(D - d)^2 - 1], \qquad (6)$$

where v_{pl} is the speed of introduction of the plunger into the melt.

Analyzing formula (6) we established that the growth in the wall thickness (at a constant load diameter) from 5 to 20 mm (by a factor of 4) decreases the rate v_{sh} by a factor of 10. This affects the quality of the casting. A low speed of immersion of the plunger in the cavity of the press mold prolongs the time of shaping of the casting and sometimes results in misrun (especially when the temperature of the die is below 50°C and the thickness of the wall of the casting is less than 5 mm). In addition, a low temperature of the press mold may result in formation of a folding that propagates into the depth of the wall at the level of pouring of the melt into the die, which is the most probable in thin-wall castings.

We studied the thermal conditions of shaping of nozzle-type castings (loading diameter 60 mm, height 60 mm, wall thickness 5, 10, 15 and 20 mm) using thermocouples mounted at various points over the height and thickness of the vertical wall. Analyzing the results obtained we established that solidification occurred in the presence of a specific temperature difference over the height depending on the thermal and force conditions of shaping of the casting. The time of the solidification of zones of the casting decreased upon transfer from the top end to the bottom end. The thermal center displaced to the zone of joint of the vertical wall to the bottom part of the casting. This should be allowed for in designing the structure of a casting and of parts of the press mold for obtaining quality preforms (without pipes and pores).

We also studied the variation of the temperature in a cross section of the vertical wall, which was equally distant from the ends. We detected a temperature drop over the cross section, the value of which in the case of little heated press mold was 25 – 85°C at the moment when the shaping of the casting was finished and 60 – 150°C at the moment of final

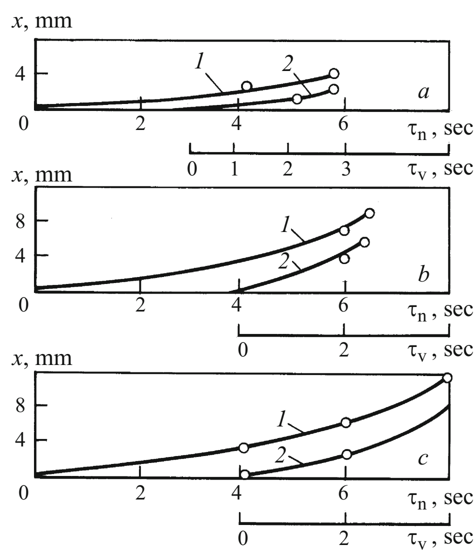

Fig. 6. Curves describing the motion of solidification front on the side of the die (*1*) and on the side of the plunger (*2*): *a*, *b*, *c*) wall thickness of 10, 15, and 20 mm respectively; τ_n) time from the final moment of pouring of the melt into the die (for curve *1*); τ_v) time from the final moment of shaping of the casting (for curve *2*).

solidification of the thermal center. This implies successive (sometimes successive-volumetric) solidification of the vertical wall. The thermal center of the casting displaced to the pressing plunger (other conditions being equal).

The displacement of the solidification front in the vertical wall of a nozzle-type casting can be described by a parabolic dependence (Fig. 6)

$$x_i = K_i \tau_i^2, \tag{7}$$

where $\tau_i = \tau_n$ is the time from the final moment of casting of the melt into the die, sec (for computing the growth of the crust on the side of the die); $\tau_i = \tau_v$ is the time from the final moment of shaping of the casting, sec (for computing the growth of the crust on the side of the plunger). The values of the solidification factor K_i differ for curves *1* and *2* (Fig. 6), which is explainable by the difference in the intensities of cooling at the casting/die and casting/plunger interfaces. Other conditions being equal, the value of factor K_i depends on the thermophysical properties of the alloy and on the regimes of the CPC (primarily on the pressing pressure and on the temperature parameters).

For castings from alloy AK12 at $p_r = 150$ MPa, $K_i = 0.14 - 0.16$ mm/sec^2 (for computing the displacement of the solidification front on the side of the loaded surface, i.e., on the side of the die) and $0.45 - 0.60$ mm/sec^2 (on the side of the internal surface, i.e., on the side of the plunger). A change in the composition of the alloy and hence in its thermophysical characteristics causes a change in factor K_i).

When the wall thickness of the casting is increased from 5 to 20 mm and the content of silicon in the silumin is increased to 18%, the time of solidification of the casting increases (other conditions being equal), though not very significantly. In the former case this is connected with the growth in the heat content of the casting and in the second case with the change in the thermophysical properties of the alloy (growth in the content of silicon is accompanied by decrease in the thermal conductivity of silumins).

Formula (7) is applicable for computing the time of solidification and the hold under pressure for castings subjected to plunger pressing.

PISTON-PLUNGER PRESSING

In the case of piston-plunger pressing (Fig. 1*c*) the melt is poured freely into the die of the press mold and then (after touching the end of the pressing plunger) a doze of the melt is squeezed into one or several cavities located in the plunger. The end of the plunger touches the crust formed at the side walls of the die and acts on it, i.e., deforms it.

We studied the processes of solidification and cooling of elements of castings formed in the cavity of the plunger and having the following sizes: $d = 10$, 15, and 20 mm, height $h = 60$ mm. The diameter of the internal cavity of the die $D = 60$ mm. The height H was varied depending on the volume of the cavity in the plunger. For good shaping of the protruding parts of the casting the cavity of the plunger had grooves for removing air and gases. The castings were produced from alloys AK7ch and A356.2.

We determined the effect of various parameters on the quality of the castings. It turned out that the flaws arising during shaping of the castings and hence during filling of the cavities of the press mold (primarily in the plunger) were of the following kinds: (1) poor forming of the contours of the casting in the cavity of the plunger due to the absence or insufficiency of ventilation of the press mold, (2) blisters (in the absence of ventilation of the press mold), (3) presence of foldings propagating from the external surface into the body of the casting (or the butt-end) due to deformation of the vertical "crust."

The flaws connected with poor forming of the contours of the casting are removed by using a prefabricated plunger with ventilation clearances between its components.

Studying the mechanism of formation of foldings at the places of deformation of vertical crust we established that this defect is most typical for castings produced in an insufficiently heated press mold ($t_m < 100°$C). Excess lubrication (for example, black-lead-oil one) on the vertical surfaces of the die also promotes formation of foldings. The vertical crust forming at the walls of the die is deformed, and its upper part displaces into the body of the casting, where it is fused partially under the action of the superheated alloy. The foldings can be removed by reducing the thickness and the strength of the crust using the following measures: raising the initial temperature of the die, shortening the time of holding of the melt in the die before applying the pressing pressure, increasing the allowance for mechanical treatment, changing the design of the casting by introducing an additional component, i.e., a flange with a size exceeding that of the preform, which may serve as a butt-end.

The quality of castings produced by the variant of piston-plunger pressing depends not only on the conditions of shaping of the casting but also on the pressure. It is recommended to compute the pressure by the formulas used for the case of piston pressing.

FORCE PROCESSES IN CASTING WITH PRESSURE CRYSTALLIZATION

We studied the force conditions of the formation of castings in CPC. We have already mentioned that in piston pressing the pressure acts on the vertical crust formed over the side walls of the die. Friction at the "casting – mold" contact surfaces arises at virtually any operation of treatment of a metal with the use of pressure. The friction forces and the resulting tangential stresses on the contact surfaces depend on many factors. Most researchers solve practical tasks concerning determination of the strain state of the metal due to various process operations under an assumption that the tangential stresses τ_t have a maximum absolute value (the Mises condition), i.e., $\tau_t = \sigma_s/\sqrt{3}$, where σ_s is the yield strength of the alloy at the deformation temperature. In the opinion of Professor E. P. Unskov, et al. this provides the strictest mathematical solution of technological problems for any method of computation. We have used such an assumption in our work too.

We considered the balance of forces acting on the forming casting at the moment when the solidification finishes and determined the pressure required for compaction of a solidifying preform of the type of a solid cylinder with diameter D and height H, i.e.,

$$p = K_u \sigma_s \left[1 + \frac{2}{\sqrt{3}}\left(1 + \frac{2H}{D}\right)\right], \tag{8}$$

where $K_u = 1 - K_{sh}$ is a coefficient depending on the shaping factor of the casting (for piston pressing $K_u = 1$).

The relative loss of pressure to external friction ($\Delta p = p_{fr}$) can be determined from the following expression:

$$\frac{\Delta p}{p} = \frac{2}{\sqrt{3}}\frac{\sigma_s}{p}\left(1 + \frac{2H}{D}\right), \tag{9}$$

where p is the applied pressure.

Analyzing Eq. (9) we can draw a practical conclusion that it is necessary to reduce the ratio H/D (at a constant σ_s) in order to obtain castings with elevated quality. Let as assume that the casting will be dense when over 60% of the pressure applied is spent on its densification (for example at $p > 0.6p_r$). Then, as it can be seen from Fig. 7, the values of $\Delta p/p < 0.4$ will be obtained at $H/D < 1$ if $p > 100$ MPa (domain *II*). At a pressure of 50 MPa and $H/D > 0.5$ (domain *I*)

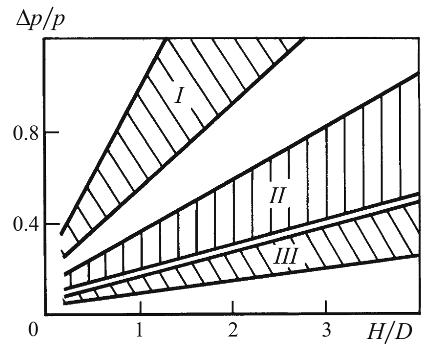

Fig. 7. Relative loss of pressure to external friction ($\Delta p/p$) as a function of the ratio of height H to diameter D of the casting: *I*, *II*, *III*) rated pressure of 50, 100, and 200 MPa (the lower boundary of each domain at $\sigma_s = 5$ MPa, the upper boundary at $\sigma_s = 10$ MPa).

quality castings without shrinkage flaws cannot be obtained, which is confirmed by numerous experimental data. At a pressure of 200 MPa, quality castings can be obtained with H/D of up to 3 (domain *III*).

The values of σ_s were determined from reference data. Knowing the temperature field of the casting at the moment when the solidification stops we chose $\sigma_s = 5 - 20$ MPa. The results of the computation of the loss of pressure to external friction by formula (9) are given in the Table 1 (at $\sigma_s = 8$ MPa).

At $H/D \gg 1$ we may assume that the loss of pressure to the friction on the vertical surfaces of the casting are much higher than the similar losses on the end surfaces, and the latter may be neglected. Then expression (9) assumes the form

$$\frac{\Delta p}{p} = \left(1 + 2.31\frac{\sigma_s}{p}\right)\frac{H}{D}. \tag{10}$$

At $H/D \ll 1$ (castings shaped as a collar or a disc) the external friction on the end surfaces is higher than on the side (vertical) surfaces (these may be neglected), and Eq. (9) assumed the form

$$\Delta p/p = 1.56\sigma_s/p. \tag{11}$$

An experimental study to the efficiency of the action of pressure on a solidifying casting was performed using a fa-

TABLE 1. Relative Losses of Pressure to External Friction

Alloy	$\Delta p/p$ at p_r, MPa		
	50	100	200
A7	0.91/0.80	0.55/0.62	0.32/0.35
AK7ch	0.64/0.62	0.60/0.61	0.52/0.55

Note. The numerators present computed data; the denominators present experimental data.

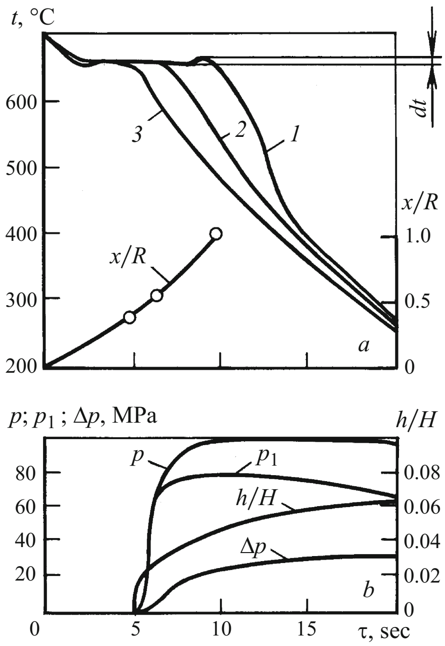

Fig. 8. Cooling curves (*1* – *3*) of a casting from aluminum A7, relative growth of crust x/R (*a*), and variation of the force parameters in the cooling process (*b*): *1*, *2*, *3*) temperature of the casting at a distance of 6, 12.5 and 25 mm (center) from the surface; p) pressure applied by the plunger; p_1) pressure created by the lower load cell; Δp) loss of pressure to friction; h/H) relative displacement of the plunger.

cility that allowed us to detect the temperature of the preform, the variation of the applied pressure and of the pressure transferred by the casting to the bottom of the die, and the relative displacement of the pressing plunge.

The results of one of the tests are presented in Fig. 8. It can be seen that the castings from aluminum A7 solidified for about 4.5 sec after application of pressure (t_{pour} = 700°C, t_m = 50°C). Pressure applied 5 seconds after the pouring is finished attains the specified value in about 4.5 sec, so that the casting solidifies under growing pressure (from atmospheric one to 100 MPa). After the application of pressure, its value for the first second $p = p_1$. This continues until the content of the solid phase does not exceed 50% and the pressure through the liquid phase is transferred to the bottom of the die and to the lower load cell. Then the value of p_1 starts to decrease, stabilizes at a content of the solid phase equal to 75%, and remains virtually constant ($p_1 \approx 75$ MPa) until the end of the solidification; the value of Δp corresponds to 20 – 30% of the applied pressure.

Thus, the loss of pressure to external friction increases upon solidification of the casting. This means that the last regions in the thermal center of the casting solidify at a pressure much lower than the applied one.

We have proved experimentally that the higher the height and the H/D ratio, the higher the relative loss of pressure to external friction (Fig. 9). This is confirmed by the results of

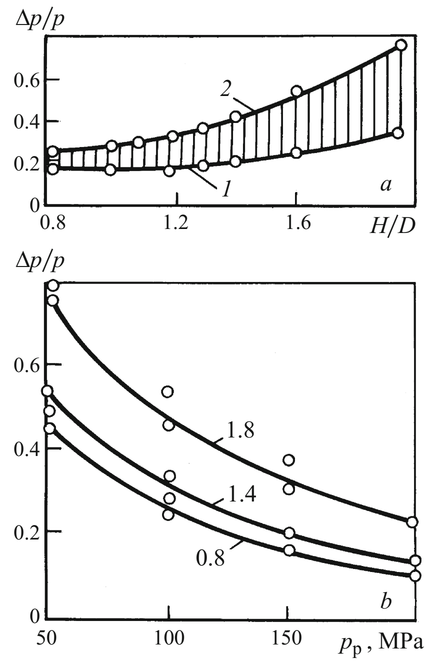

Fig. 9. Dependence of the relative loss of pressure to external friction $\Delta p/p$ on the ratio of the height H to the diameter D of the casting upon attainment of the liquidus (*1*) and solidus (*2*) temperatures (*a*) and on the pressing pressure p_p at different ratios H/D (indicated at the curves) (*b*).

the computation presented above. If the central zone of the casting still bears a liquid phase, the relative loss of pressure depends little on the height of the casting at $H/D < 1.2$. At $H/D = 1.6 – 2$ the values of $\Delta p/p$ increase somewhat. At the moment when the solidification stops, the ratio $\Delta p/p$ increases noticeably, especially in castings with $H/D > 1$.

We determined the values of σ_s for aluminum alloys with the use of the experimental estimates of the loss of pressure to external friction and established that σ_s = 8 – 18 MPa.

Our tests have shown that growth in the pressing pressure, in the friction factor at the "casting-die" interface, and in the height of the casting (other conditions being equal) is accompanied by increase in the force of withdrawal of the casting from the die. This means that the regimes of CPC should be optimized before each pouring of the melt and after lifting the plunger to the initial position; lubrication of the die of the mold is also a necessary condition.

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