Effect of high pressure processing in the formation of castings of aluminum alloys

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Abstract. The effect of high pressure on the formation conditions of aluminum castings has been investigated. It was established experimentally that the crystallization of castings under high mechanical pressure proceeds at a higher temperature difference across the cross section than at atmospheric pressure. The cooling rate of a cylindrical casting in various zones on the section, which is characteristic for cooling alloy in the crystallization range, is determined. The formula for calculating the solidification time of a casting and the time of its holding pressure during piston compression is recommended. The influence of the scale factor on the solidification time of cylindrical castings is considered. It is shown that with increasing height at a constant diameter of the casting, the relationship between the solidification time and diameter of the casting is linear. It has been experimentally established that the solidification coefficient of an alloy depends on its thermophysical properties of the alloy and the applied pressure. Its value increases with decreasing silicon content in the alloy and increasing pressure. The pressure significantly reduces the difference in the values of the solidification coefficient of castings from alloys of different compositions.

Keywords: aluminum alloys, casting with crystallization under pressure (CALS), front solidification, thermal conditions of formation, cooling rate.

1. Introduction

The process of CALS in aluminum alloys to obtain dense castings with a high utilization rate of metal, at a minimum machining allowance. Such works as [1-17] and others are devoted to the study of the influence of various factors on the conditions of formation of aluminum castings during injection molding. The review [18-19] States that the majority of studies in the metallurgy of aluminum alloys are devoted to the following aspects: multiscalar, mesoscopic and granular modeling of the casting process; phase field modeling of al alloy solidification; modeling of alloyed al melts; in situ observations of solidification; research of nucleation mechanisms for the primary phase, primary phase morphology; research of nucleation and growth of intermetallics; synthesis of selection mechanisms in al alloys solidification; alloy design for additive manufacturing; role of fluid flow in solidification.

The purpose of this paper is to study the effect of high pressure on the pressing conditions of formation of a wide range of castings from aluminum alloys.

2. Materials and method

Studies of the casting with crystallization under pressure process were carried out on cylindrical castings with a diameter of 50 mm and a height of 40...110 mm.
Aluminum and its alloys prepared in a shaft furnaces resistance without protective atmosphere. Crucible alloys were not degassed, refined or modified, to assess the effect of mainly mechanical pressure. In accordance with the objectives of the experiments, the melt was poured into the die with different overheating above the liquidus temperature (crystallization) — 50 ... 200°C.

The remaining technological regimes were taken as follows: the initial temperature of the die $T_0 = T_m = 20 \ldots 200 \text{°C}$; nominal pressing pressure $P_N = 0.1$ (atmospheric), 50, 100, 150, 200, 300 and 400 MPa; the holding time of the melt in the die before the application of pressure $\tau_h = 3 \ldots 5 \text{ s}$ and the forming casting under pressure $\tau_0 = 25 \ldots 30 \text{ s}$. Die and punch were greased with graphite oil or engine oil before each pouring. The accuracy of temperature measurement was $\pm 7 \text{°C}$; pressing pressure $\pm 10 \text{ MPa}$; punch displacement $\pm 0.1 \text{ mm}$. Crust growth (or displacement of liquidus and solidus temperatures of alloys having a crystallization interval) was evaluated by the cooling curves of the casting at the end of solidification (or reaching liquidus and solidus temperatures) at the corresponding casting points - at distances of 3, 6, 12.5 and 25 (center) mm from the surface. This allowed it possible to determine and study the kinetics of crust growth from the moment when the melt was poured into the die until the casting was removed from the latter.

The layout of the installation for the study of the thermal conditions of the formation of the casting is shown in figure 1.

Figure 1. Installation scheme for the study of thermal conditions of the formation of a cylindrical casting: 1 – pressure sensor (mesdose); 2 – punch; 3 – die; 4 – hodograph (punch displacement sensor); 5-13 – thermocouples.

To determine the pressing force, strain gauges 1, located in the cavity of the punch 2, are provided, and to determine the amount of movement of the punch during consolidation of the solidifying casting - rheochord (or inductive) displacement sensors 4. The temperature of the forming casting was measured by three (sometimes four) thermocouples 6 ... 8. Thermocouples were injected into the working cavity of the die to a distance of 50 mm from the bottom through the holes in the lower plate. The temperature of the matrix was measured by several chromel-aluminum thermocouples 9...13, located in specially made holes (either from the upper end or from the side surface).
3. Results and discussion
The cooling graphs of cylindrical castings are obtained, which are shown in figure 2. Their analysis showed that crystallization of the metal under high mechanical pressure occurs at a higher temperature difference over the cross section than at atmospheric pressure and the time of solidification of castings decreases with increasing pressure in all areas where thermocouples were installed. However, the closer to the casting axis is located zone, the substantial decrease in the solidification time under pressure. Latter, the surface layers of the work-piece to a depth of 3 mm harden substantially during melt exposure in the die before pressure is applied. Layers deeper-lying, or harden under increasing pressure or under first increasing and then under nominal pressure [20].

Figure 2. The cooling graphs of cylindrical castings of aluminum A7:
cooling curves of the casting 1, 2, 3, 4 - at a distance of 25 (center), 12.5, 6 and 3 mm from the outer surface;
heating curves of the die at a distance of 1 mm from the working surface near the upper end (1B), at an equal distance from the ends (1C) and near the lower end (1H),
and also at a distance of 5, 10, 15 and 20 mm from the working cavity at equal distance from the ends.

With the increase in the nominal pressure \( P_N \), the liquidus (crystallization) temperature of alloys (metals) increases. It should be noted, that it is observed not from the moment of application of pressure, and when reaching the value of 50...80 MPa. This can be explained by several reasons:

1) Changing the thermodynamic parameters of the system— the application to it of the law of Clausius-Clapeyron, according to which
\[ \frac{dT_m}{dp} = \frac{T_m}{L} (V_2 - V_1) , \]  

where, \(dT_m\) is the change in melting temperature (crystallization) due to the change in pressure by the value of \(dp\); \(T_m\) is the melting temperature; \(V_2, V_1\) is the volume of 1 kg of liquid and solid phases, respectively; \(L\) is the melting heat (crystallization) of the metal (alloy).

2) The discrepancy between the rates of crystallization heat release and heat removal form.

3) The release of heat during deformation of the vertical crust under pressure.

Latter can be confirmed by the fact, that the value of \(dT_m/dp\) in aluminum A7 is less than alloys AK12, AK9 and AL24P. Aluminum has less thermal conductivity than industrial aluminum alloys. Aluminum has a lower thermal conductivity than industrial aluminum alloys. The generalized dependences of the change of some parameters on the nominal pressure are shown in figure 3.

Figure 3. Influence of pressure casting harden time \((\tau_h)\) on investigated aluminum alloys, changes in the surface temperature of casting \((T_s/T_c)\), temperature difference across the casting section \((\delta T_0)\) and at the boundary "casting-die" \((\delta T_{Sf})\).

It is seen, that with increasing \(P_N\) decreases the solidification time of castings and the value of the temperature difference at the interface casting-shape, and increases the cooling rate of the casting and the temperature difference in its cross section. It should be noted that with increasing alloying degree of the alloy with silicon or other elements, and, consequently, with a change in thermal and mechanical properties, the parameter values move from the lower boundary to the upper boundary of the A7 aluminum. From the above relations (Fig. 3) shows that the greatest change in the investigated parameters observed at atmospheric pressure 0.1 to 100 MPa, with subsequent pressure increase measured parameters also vary but to a much lesser extent. This can be explained by the fact, that in the first pressure area there is a tight pressing of the growing crust against the walls of the die and, as a
result, reduction (and even elimination) of the gap between the casting surfaces and the mold (this is evidenced by a noticeable decrease in the value of $\delta T_{o/}$ (fig. 4)), as a result, increase the rates of removal of heat of overheating and crystallization. At a pressure of more than 100 MPa, it is possible to reduce the gap due to the pressing of the metal into the working surface microrelief of the mold and increase due to this cooling surface with all the ensuing consequences. However, the increase in the cooling surface is much less than in the pressure range up to 100 MPa, and therefore less influence of pressure on the studied parameters. The relative change in the casting surface temperature $T_s$ at the end of solidification can be calculated by the formula:

$$T_s/T_c = A - B \sqrt{P_N}.$$  

(2)

where, $T_c$ – the temperature of the casting center; $A$, $B$ – coefficients, respectively equal to 0.85...0.87 and 0.0175...0.0185; $P_N$ – nominal pressure pressing, MPa.

The influence of the scale factor (reduced size) on the solidification time of cylindrical castings with a diameter of 50 mm and a height of 25...100 mm at pressures of 50...200 MPa was studied. When determining the reduced thickness, not only the forming side surface $S_o$ was taken into account, but also the square ends $S_e$.

$$R = V / (S_o + 2S_e) = \frac{RH}{2H+R},$$

(3)

where, $V$ – volume of the casting; $H$ – height; $R$ is the radius.

Calculation according to the formula (3) showed that in the experiments the value of $R$ varied within 6.25...10 mm. The Processing of the results showed that with increasing $R$ (with increasing height at a constant diameter), the relationship between the time of reaching the solidus temperature of the alloy $\tau_s$ and $R$ is linear.

$$\tau_h = \tau_c = KR,$$

(4)

where, $K$– reduced solidification coefficient, numerically equal to $-1.12$ s/mm.

Analysis the graphs changes in $\tau_s$ and $\tau_c$ (Fig. 4) shows, shows that the lifetime of the two-phase zone increases with increasing the reduced thickness of the casting (all other things being equal). An increase in pressure (at $R$=const) leads to a decrease in the lifetime of the two-phase zone in the casting during solidification and the solidification time. This is confirmed by the data obtained on the basis of an analysis of the cooling curves and the relative displacement of the solidification front - the displacement curves of the liquidus and solidus temperatures of the studied alloys with a narrow crystallization interval (Figure 4).

The nature of the dependences obtained can be expressed as the equation of a parabola:

$$x/R = K_0 \cdot \tau^2,$$

(5)

where, $x$– the value of the advancing front of solidification, mm; $R$– the radius of the casting, mm; $K_0$– coefficient of relative hardening, $1/s^2$; the value ,which depends on the thermophysical properties of the alloy, and the compacting pressure; $\tau$ – time, s. The equation (5) can be expressed as follows:

$$x = K \cdot \tau^2,$$

(6)

where, $K$– solidification coefficient $(mm/s^2)$, the values are shown in Table 1.

The coefficient $K$ depends on the composition, and consequently, on the thermo-physical properties of the alloy and pressure. Its value increases with decreasing silicon content in the alloy and increasing pressure. Pressure significantly reduces the difference in the values of the coefficient of solidification of castings from alloys of different composition. Thus, with increasing pressure, the character of the dependences (3) and (4) does not change, but the lifetime of the two-phase region decreases. This indicates that the nature of the solidification of castings from alloys having a crystallization interval varies from bulk to sequential. Formula (5) is recommended to use for calculating the time of solidification of the casting and the time it is held under pressure (with piston pressing).
The effect of pouring temperature \( T_{pour} \), mold temperature \( T_d \) and \( \tau_b \) on the duration of solidification of castings \( H/D=2 \) was investigated. The results are shown in Table 2.

It is seen, that the process of determining parameter CALS is pressing pressure. The cooling rate of a cylindrical castings in various zones on the section, which is characteristic for cooling alloy in the crystallization range, is determined. It is found, that it increases as it moves from the periphery to the center, its value is greater, the higher the pressing pressure \( P_N \), the lower the pouring temperature of \( T_{pour} \), \( T_d \) and \( \tau_b \).
Table 2. Effect of the technological parameters of CALS on the solidification time of cylindrical castings \((D=50\ mm)\) of aluminum A7 and alloy of Al-4\% Cu

| \(T_{\text{pou}, ^\circ\text{C}}\) | \(T_{\text{s}}, ^\circ\text{C}\) | \(t_\text{s}, \text{s}\) | \(P_{\text{N}, \text{MPa}}\) | \(t_\text{b}, \text{s}\) |
|----------------|----------------|--------|--------|--------|
| aluminum A7    |                |        |        |        |
| 710            | 20             | 4      | 50     | 10.8   |
|                | 20             | 8      | 50     | 10.2   |
|                | 180            | 8      | 250    | 15.5   |
|                | 180            | 4      | 250    | 10.6   |
|                | 20             | 8      | 50     | 13.5   |
|                | 20             | 4      | 250    | 7.4    |
| alloy of Al-4\% Cu |                |        |        |        |
| 860            | 180            | 4      | 50     | 16.0   |
|                | 180            | 8      | 250    | 10.8   |
| 700            | 20             | 4      | 250    | 5.8    |
|                | 20             | 8      | 50     | 11.5   |
|                | 180            | 8      | 250    | 12.0   |
|                | 180            | 8      | 50     | 14.1   |
| 715            | 100            | 6      | 150    | 8.6    |
|                | 20             | 4      | 50     | 12.6   |
|                | 20             | 8      | 250    | 11.8   |
| 850            | 180            | 8      | 50     | 15.0   |
|                | 180            | 4      | 250    | 10.7   |

4. Conclusions
Studies of the effect of high pressure on the conditions of the formation of castings with CALS. It has been established experimentally that under CALS conditions, mechanical pressure has determining effect on the processes of solidification and cooling of castings. It is shown that crystallization under high mechanical pressure occurs at a greater temperature difference across the cross section than at atmospheric pressure. It was established experimentally, that with the increase of pressing pressure decrease the solidification time and the value of the temperature difference at the casting-mold interface, but the cooling rate of the casting and the temperature difference along its cross section increases. The formula for calculation of time of solidification casting and time of its endurance under pressure (at piston pressing) is recommended.

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