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The influence of the melt cooling rate on shrinkage behaviour during solidification of aluminum alloys

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Abstract. A comprehensive analysis of the shrinkage process during the crystallization of aluminum alloy castings was carried out. An assessment was made of the general nature of changes in filtration and shrinkage rates, as well as the width of the mushy zone, depending on the rate of crystallization of the melts. An analytical expression was proposed for determination of the critical value crystallization rate of the alloy from the standpoint of the probability of hot tearing in castings. The method of influence on crystallizing melts by vibration with the aim of reducing hot tearing is considered and experimental data confirming the effectiveness of this approach are given.

1. Introduction

The shrinkage processes occurring during the crystallization of alloys in the liquidus-solidus temperature range largely determine the quality of the cast products [1]. One of the widespread defects caused by shrinkage processes in cast aluminum alloys are crystallization cracks (hot tears). Despite the rather extensive theoretical and experimental material on the hot tearing of alloys accumulated in recent years (in particular, [2–5]), certain provisions continue to be debatable and topical. Especially it concerns the analysis of the reasons and factors for their formation in castings and the search for ways to reduce the tendency of alloys to hot tearing during crystallization.

Experimental facts show that at other constant factors the probability of hot tears in castings is greatly influenced by the cooling rate or temperature gradient in the solidified surface crust [6–8]. The most dangerous are the average cooling rates. At low and high intensity of heat removal from the surface of



the casting, the probability of surface hot tears is practically small. The latter originate as a result of hindered shrinkage of the casting elements in the crystallization range, but these effects can be compensated by healing with liquid of average composition from the central volumes of the casting. It has been suggested [9] that the formation of hot tears occurs when fluid from neighboring areas can no longer feed the deformed casting zone. Prediction of the formation of hot tears is complicated by the multifactorial nature of this process. The investigations carried out in the direction of the theoretical description of the phenomenon of hot tearing, focused mainly on the development of various criteria for assessing the tendency of alloys to the formation of hot tears [10-12]. Despite the fact that ideal correlations between predictive estimates and experimental data were not obtained yet, such criteria are a good methodological tool for explaining the processes of hot tears formation in castings [13].

The aim of this work is to theoretically evaluate the shrinkage processes and the formation of hot tears in aluminum alloys castings at different cooling rates during crystallization.

2. Methods

The analysis was carried out on the basis of the following hypothetical model of the shrinkage process during the crystallization of the casting. Shrinkage of the sample or casting begins to develop when a continuous framework of solid crystals is formed in the mushy zone. In the intergranular spaces there may be liquid or liquid from the heat centers of the casting. It enters the intergranular space due to the hydrostatic pressure of the melt from the riser or the central parts of the casting.

The shrinkage rate v_{sh} , which is responsible for the formation of hot cracks, will be proportional to the crystallization rate v_{cr} :

$$v_{sh} = \alpha_v \Delta T_{ks} \cdot v_{cr} \quad (1)$$

where α_v – volumetric coefficient of crystallization; ΔT_{ks} – temperature interval between the freezing point of the crystal framework (T_k) and the solidus temperature (T_s), $\Delta T_{ks} = T_k - T_s$.

Melt filtration rate v_f to the hot crack through the crystal framework is determined by the Darcy equation:

$$v_f = K_n \Delta P / \eta l \quad (2)$$

where ΔP – pressure of the melt in the heat center at the level of hot crack formation; η – dynamic melt viscosity; l is the width of the mushy zone; K_n – permeability of the mushy zone:

$$K_n = n^2 d^2 (1 - \varphi) / 48 \quad (3)$$

where $n = 0.0931$; d – diameter of the secondary axes of the dendrite or the average size of round crystals; φ – the relative fraction of the solid phase at the formation of a continuous framework of solid crystals, $\varphi = 0.259$.

According to M.C. Flemings [14], the value of d is related to the cooling rate of the casting by the ratio

$$d = b \cdot v_c^{-0.5} \quad (4)$$

where b – empirical coefficient with dimension $[m \cdot K^{0.5}/s^{0.5}]$; for aluminum $b = 1.2 \cdot 10^{-5} m \cdot K^{0.5}/s^{0.5}$. The dependence of the width l of the transition mushy zone is exponential:

$$l = l_0 \exp(-v_c \tau / \Delta T_{LS}) \quad (5)$$

where l_0 is the width of the two-phase mushy zone at $v_c \rightarrow 0$, in this case $l_0 = R/2$, (R denotes the radius of the cylindrical and ball castings or the thickness of the flat casting), that is, the zone extends to the center of the casting; $\Delta T_{LS} = (T_L - T_S)$ is the interval between liquidus and solidus temperatures; τ – crystallization time.

The cooling rate of the casting in the interval ΔT_{LS} is determined by the equation:

$$v_c = v_{cr}L / c\Delta T_{LS} \quad (6)$$

where L is the heat of crystallization; c –heat capacity of the alloy.

Hot tears will be healed with hot filtrate if the following condition is met:

$$v_f \geq v_{sh} \quad (7)$$

The shrinkage rate v_{sh} in expression (1) is proportional to the crystallization rate in the interval ΔT_{kS} . After substituting (3) – (6) into equation (2), assuming $v_f = v_{sh}$ in condition (7), we determine the critical value of the crystallization rate:

$$v_{cr}^0 = [A_1 / v_{cr} A_2 [\exp(-A_3 v_{cr} \tau)] / A_0] \quad (8)$$

where

$$\begin{aligned} A_0 &= \alpha_v \Delta T_{kS} \\ A_1 &= n^2 d^2 \Delta P c \Delta T_{LS} (1 - \phi) \\ A_2 &= 48 L \eta l_0 \\ A_3 &= L / c \Delta T_{LS} \end{aligned}$$

Equation (8) is transcendental and can be solved by a numerical iterative method. When deriving the equation, the following assumptions were made: 1) at the rupture of a continuous dendritic framework, all shrinkage is localized at the point of rupture with the formation of one or several hot tears; 2) changes in crystallization conditions when imposing various physical effects on liquid and crystallizing melts are not taken into account.

3. Results and discussion

To assess the general nature of the change in filtration and shrinkage rates, as well as the width of the two-phase mushy zone, figure 1 shows their dependences on the crystallization rate in a dimensionless form. From the presented dependences it follows that at a low crystallization rate $v_{sh} \rightarrow \min$, dendrites or equiaxed crystals have large transverse dimensions (parameter d in the formula (3)), permeability and filtration rate of the mushy zone reaches the limiting values, crystallization proceeds according to the bulk variant. At high cooling rates $v'_{cr2} > v'_{cr1}$ the mushy zone is practically wedged out, crystallization proceeds according to the frontal variant both in pure metals and in eutectic alloys. The filtration rate increases rapidly due to a sharp decrease in the width of the mushy zone in accordance with the expression (5).

The most dangerous are the average cooling rates or, in accordance with equation (6), the average crystallization rates in the interval $v'_{cr} < v_{cr} < v''_{cr}$, in which the filtration rate is insufficient to heal all casting defects of shrinkage origin. The “dangerous” region $v'_{cr} < v_{cr} < v''_{cr}$ is influenced by two temperature ranges ΔT_{LS} and ΔT_{kS} .

The greater the distance between the liquidus and solidus lines on the phase diagram (crystallization interval of the alloy), the slower decreases the width l of the mushy zone (formula (5)), the lower the filtration rate (formula (2)) due to the pressure gradient

$$dP / dx = \Delta P / l.$$

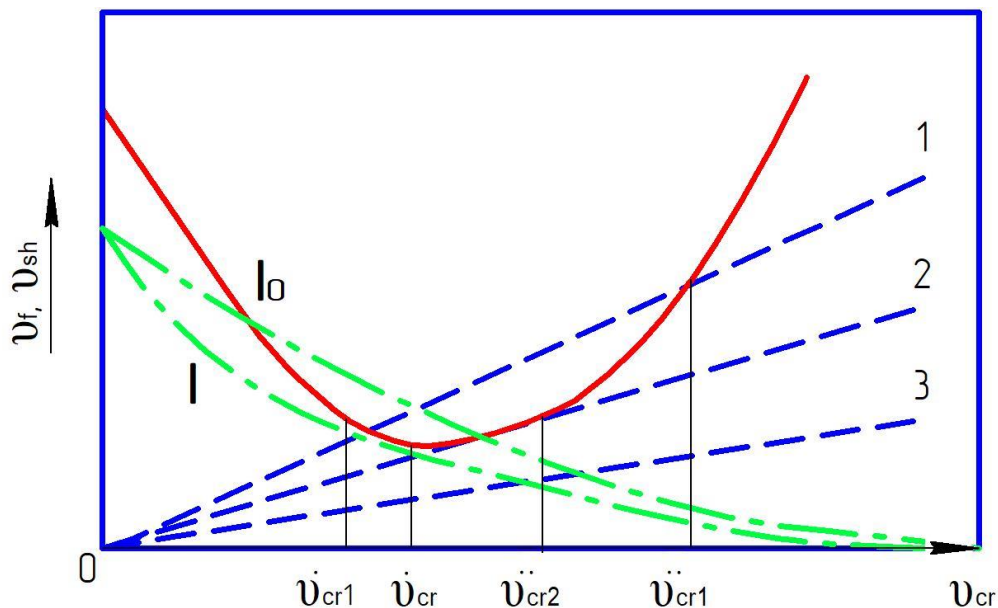


Figure 1. The nature of the change in filtration rate (—) and shrinkage rate (---), as well as the width of the mushy zone (---) depending on the melt crystallization rate: 1 – casting without the use of vibration; 2 – with vibration in the vertical plane; 3 – with volumetric vibration.

The positive influence of vibration on the refining of the structure, as well as on the mechanical and technological properties of alloys, is known [15]. It should be assumed that the vibration destroys the set framework of solid crystals at the initial temperature T_k (casting technology without applying vibration), the setting temperature decreases to T'_k , the interval ΔT_{ks} decreases, the rate of the shrinking process decreases in this interval (figure 1, curve 2), the less dangerous area of hot tearing and other shrinkage defects is becoming less. The optimal vibration parameters (A is the amplitude, ν is the frequency) or the effect of volumetric vibration for this alloy generally contributes to the healing of all defects of shrinkage origin (figure 1, curve 3), since the formation of a solid frame occurs near the solidus temperature at $\varphi = 0.5 \dots 0.55$. Without vibration $\varphi = 0.2 \dots 0.3$ according to the data of Ju.A. Nehendzi and L.S. Leibenson gives the average value $\varphi = 0.259$, based on the geometric analysis of the stacking of rounded crystals.

These positions were verified experimentally on a model Al – 5% Cu alloy by implementing vibration in a vertical plane. The alloy was melted in a resistance furnace. Hot tearing was determined on the annular technological sample, which was a casting molded into the sand form, in the configuration of flat rings filled from one molding channel. The inner surface of the rings was made in all cases using steel rods. Due to this, favorable conditions were created in the casting for the formation of shrinkage stresses due to mechanical deceleration of linear shrinkage from the side of the rod. The width of the rings in the radial direction can vary from 5.0 to 47.5 mm by means of metal rods of various diameters. The criterion for hot tearing is the maximum width of the ring (in mm) at which a hot tear appears. The larger this critical width of the ring, the more the alloy is prone to hot tearing. Vibration of ring samples for hot tearing was carried out on a specially manufactured vibrating table with an amplitude of 1.2 mm and a frequency of 50 Hz. We started vibrating the mold immediately after pouring the samples at a temperature of 720 ... 730 °C and finished after the end of the crystallization process. The results showed that the use of this technique reduces hot tearing (ring width) from 27.5 ... 30 mm for the initial alloy (without treatment) to 12.5 ... 17.5 mm (with vibration during crystallization).

It should be noted that that good results in reducing hot tearing tendency can also give various melt processing methods that change the state of the melt and allow to increase the fraction of the solid phase falling out near the solidus temperature during crystallization, which can contribute to the healing of

crystallization cracks. Such methods can be thermo-temporal treatment, thermal-rate treatment of melts and their varieties [16–19].

In general, the proposed method for calculating the critical rate of crystallization can be used in foundry-metallurgical practice for solving tasks of predicting the shrinkage behavior of alloys and estimating the probability of hot tearing tendency, if the corresponding experimental parameters will be accumulated for each group of industrial alloys.

4. Conclusion

The analysis shows that hot tears and microcracks and other defects of shrinkage origin in castings are formed in the range from the temperature at which solid crystals form a continuous framework to a temperature of $0.9T_s$. At low cooling rate, the rate of the shrinkage process is much less than the filtration rate and capillary feed, and shrinkage defects are effectively healed. High rates of heat removal from the surface of the casting lead to the frontal nature of crystallization, the mushy zone is practically wedged out, and the rate of healing of hot tears due to filtration again exceeds the rate of their opening due to the shrinkage process. Average crystallization rates and a large interval between liquidus and solidus temperatures are especially dangerous from the point of view of the formation of hot surface cracks. An effective technological approach, leading to a reduction in hot tearing of alloys, can be a vibration of a casting mold during the crystallization process and other physical methods of melt treatment.

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