Parameterization of means to stabilize the structure in shaped castings

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Abstract The issues related to the management of the processes of formation of the crystal structure in shaped castings are considered. It is shown that the expediency of applying a specific technological means of managing the crystallization process depends on various factors and requires an individual approach in each specific case.

The heat exchange between the casting and the mold is the base which determines the process of cast bars solidification, namely, its temperature field, the sequence and the rate of solidification. The particular processes of castings forming are associated with these solidification parameters. These include the processes of filtration feeding, the crystalline structure formation, the alloy chemical heterogeneity formation, etc. These processes determine the basic properties of cast products.

The formation of shaped castings of columnar crystals in the crystal structure in some cases is not allowed for their manufacture according to the technical conditions. The dysfunctions of a homogeneous structure stable formation is associated with the castings geometrical features and with the change in heat-removal rate in different parts of the cast bar during solidification.

The formation of a homogeneous equiaxial structure in the solidified casting in accordance with the works [1, 2], occurs under the condition

$$\frac{G_L}{v_z} \leq m \frac{C_0}{D} \left[ 1 - \frac{k}{k} \right],$$

(1)

where $G_L$ is the temperature gradient at the crystallization front in the liquid phase; $D$ is the diffusion coefficient in the liquid phase; $m$ is the liquidus slope; $k$ is the distribution coefficient; $C_0$ is the composition of solid solutions in accordance with the state diagram; $v_z$ is the linear rate of solidification.

If the condition (1) is not satisfied in the initial period of the alloy solidification, the prerequisites for a columnar structure formation are created, and for equiaxial structure formation after some time as a result of a decrease in the temperature gradient at the crystallization front. Accordingly, the homogeneity of the structure in the cast bar may be impaired. The left side of expression (1) is essentially a criterion for the homogeneity of the structure, which can also be defined by the relation:

$$K_{gc} = G_L^2 / v_{ct},$$

(2)

where $v_{ct}$ is the cooling rate of the casting at the front of the insulating liquid.

The right side of expression (2) is determined by the alloy state diagram and its properties. It determines the critical value of the $K_{gc}$ criterion. As a result, condition (2) can be written as follows:
For a group of alloys, the value \((K_{gc})_{cr}\) is determined from experiments. For example, it is known that the critical value of \(K_{gc}\) for superalloys such as ZhS6U and TsNK-7 \((K_{gc})_{cr}\) is within \(5\times10^5-5\times10^7\) K⋅s/m². In the case of increase in the \(K_{gc}\) value, the probability of destabilization of the equiaxial structure formation appears, and the question arises of changing the casting modes parameters. However, this can be difficult due to the occurrence of other defects associated with disfunction in the mold filling, the feeding conditions of the shaped castings sections, etc. Therefore, the problem of eliminating the structure heterogeneity is often solved in a comprehensive manner. For example, in order to avoid the formation of non-fills and cast seams, the temperature of the melt pouring is reduced with a simultaneous increase in the initial temperature of the mold, or the elimination of the columnar structure by “warmth-keeping” the casting areas that are problematic in feeding with liquid metal.

![Schemes of sections of solid (a) and hollow (b) conical portions. I, II – the first and second parts of the conical portion.](image)

**Figure 1.** Schemes of sections of solid (a) and hollow (b) conical portions. I, II – the first and second parts of the conical portion.

As an example, let us consider thin-walled tapered portions of shaped castings without an internal cavity and with a cavity (figure 1), obtained by investment casting (IC) from heat-resistant alloys. The calculation of the homogeneous structure formation in them is carried out on the basis of condition (3). For this, the conical portion is divided into two parts I and II, which length is the same \((x' = 0.5\, x)\). Then their reduced sizes will be equal:

| Part of portion | Structure of portion | Effective size, m |
|-----------------|----------------------|------------------|
| I               | Solid                | \(R_1 = 0.125\, (3\, y + y_k)\); |
| II              | Hollow               | \(R_1 = 0.125\, [3\, (y - y_k) + y_k - y_{sk}]\); |
|                 | Solid                | \(R_2 = 0.125\, (y + 3\, y_k)\); |
|                 | Hollow               | \(R_2 = 0.125\, [y - y_k + 3\, (y_k - y_{sk})]\); |

If technological lap is performed at the top of the flattened cone, the \(y_k\) in formulas (6) and (7) increases by the lap thickness. The calculation of the \(K_{gc}\) criterion is performed according to (2). The value of \(G_L\) is defined as the average temperature gradient in the liquid phase in front of the isoleadus front in the part I of the conical portion of the element:

\[
G_L = 2\, (T_{liq} - T_{ti1})/x, \quad (8)
\]

where \(T_{liq}\) is the liquidus temperature of the alloy; \(T_{ti1}\) is the temperature in part I at the time of overheat removal in the part II.

The value of \(v_{tl}\) is defined as the average cooling rate at overheat removal in the part I:

\[
v_{tl} = 2\, ((T_{ti1} - T_{liq})/\tau_1, \quad (9)
\]

where \(\tau_1\) is the duration of overheat removal in the part I.

Based on (2), (8) and (9) we have:
K_{\text{gc}} = \frac{4\tau_1 ([T_1 - T_{\text{eq}}]/x)^2}{(T_{x1} - T_{\text{eq}})}.

(10)

If, as a result of the calculation, the condition $K_{\text{gc}} > (K_{\text{gc}})_{\text{cr}}$ is satisfied, the column structure is formed. To eliminate it, the following techniques and technological means are usually used:

– reducing the melt pouring temperature or the mold preheating furnace temperature before pouring;
– a decrease in the initial temperature of the mold due to a decrease in the temperature of the mold preheating furnace;
– additional thermal insulation of the mold at the tapered portion during casting without preheating the molds (figure 2(a));
– technological lap at the end of the flattened cone (figure 2(b));
– technological element of the cast in the form of a vertical roller (or a “pencil”) near the edge of a flattened cone (figure 2(c)).

In practice, it is advisable to use the considered technological means influencing on the homogeneous structure formation. Their effectiveness depends on the temperature conditions of the casting and the parameters of the means. For example, the use of additional thermal insulation on the shell of a thin-walled element is reasonable when the mold is cooled after it is unloaded from a tempering furnace before pouring. The maximum effect is achieved when the initial temperature of the portion II of the form is greater than the temperature of the portion I of the mold.

The efficiency of using a “pencil” to eliminate a non-uniform structure is relatively low, even with a short distance to the top of a flattened cone.

Figure 2. Schemes of the conical portion of the cast using the technological means:
1 – conical portion; 2 – mold shell; 3 – thermal insulation; 4 – technological lap; 5 – "pencil".

Therefore, it is used if the mold is heated before pouring and the $K_{\text{gc}}$ criterion slightly exceeds its critical value. This conclusion is also confirmed by the practice, when in the transition to the investment casting (IC) technology with thermal insulation, in all cases the “pencil” was replaced with additional thermal insulation. Calculations show that the most effective of presented means to eliminate the het-
erogeneous structure is technological lap at the top of a flattened cone. However, it is necessary to re-
member about additional machining of the cast.

The presented calculation methodology is implemented in automated analysis for designing the IC tech-
technological processes for shaped castings being fabricated from heat-resistant alloys, and is tested in pro-
duction.

References
[1] Flemings M 1977 Solidification processes (Moscow: Mir) 423 p
[2] Weingard U 1967 Introduction to the physics of metals crystallization (Moscow: Mir) 160 p