Features of Design of Chill Molds for Casting of Non-Ferrous Metal

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Abstract. The article discusses methods for calculating the main parameters of the chill mold in the design process. Formulas for calculating the thickness of the working wall, as well as recommendations for choosing the material of the chill mold, depending on the size and shape of the resulting castings, are specified. Disadvantages of existing methods for calculating the chill mold parameters are indicated. Solutions for the use of multi-layer coatings applied by physical vapor deposition on the forming surface of the chill mold are proposed, which increases the efficiency of the casting process in the chill mold, regardless of the shape of the casting and the design of the chill mold.

1. Introduction

Compared to traditional casting methods, the chill casting process is an effective way to obtain blanks by reducing the consumption of molding materials, reducing sources of waste, improving the quality and performance of castings, high productivity, the ability to automate and mechanize the process, reducing capital costs, reducing the cost of castings. These advantages are due to the repeated use of metal foundries in comparison with sand and clay forms. However, the effectiveness of using the chill mold will depend on its design and material, which makes the design stage one of the most difficult at the pre-production stage [1].

2. Results

Based on the research [2], we can say that when designing chill molds, one of the main issues is the choice of the thickness and material of the working walls, since these parameters affect the operational stability of the chill mold. There are various methods for determining the wall thickness of the chill mold S. The most widely used method is based on the theoretical analysis of the stress-strain state of the working walls of chill molds of various designs (Figure 1a) [3, 4].

For single-layer and double-layer steel and cast-iron chill molds with liquid cooling, the wall thickness must be selected according to the schedule (Figure 1a), with the upper limit values being the most preferred options. An exception is the situation when the chill mold is used for casting castings of complex configuration with closely spaced protrusions. In this case, the values for the lower limit are used. In addition, in the case of casting castings using sand rods, it is necessary to choose a double thickness of the casting.
When choosing a cylindrical design of chill molds for hollow castings, it is necessary to use a graph (Figure 1b), in which the values of the parameters \( N \) and \( K \) are determined by the formulas [5]:

\[
K = \frac{S_1}{2R} ; \tag{1}
\]

\[
S = 2NR , \tag{2}
\]

where \( S_1 \) – the thickness of the casting; \( R \) – outer radius of the casting.

When casting solid cylindrical castings, the thickness of the profile walls can be determined with the ratio \( S = 1.4R \).

Figure 1. Interdependence of parameters of the chill molds.

According to the method [6], the wall thickness of the chill mold \( S \) when casting castings from ferrous and non-ferrous alloys must be determined according to the schedule (Figure 1c). In this case, values are chosen depending on the melting temperature of the molten melt for high temperature alloys is preferred upper limit, and for low temperature – lower limit.

Despite the fact that these methods have been tested for a long time in practice, they have a disadvantage due to the fact that the proposed graphs (Figure 1) are generalized for various designs of chill molds and therefore may have an error associated with averaging the operating loads. In this regard, additional methods for determining the thickness of the working walls are applicable for specific cases.

In [7], the wall thickness of flat chill molds is proposed to be calculated using the formula:

\[
S = \frac{k}{2} A \left[ 1 + \sqrt{1 + \frac{8\lambda_2}{A\alpha_1}} \right] , \tag{3}
\]

where \( k \) – empirical coefficient; \( \lambda \) – coefficient of thermal conductivity (indices “1” and “2” refer to the casting and chill mold, respectively),

\[
A = \frac{3Q_1}{c_2 \rho_2 (T_{cr} - T_p)} ; \tag{4}
\]

\[
\alpha_1 = \frac{\lambda_{cr}}{X_{cr}} ; \tag{5}
\]

\[
Q = X_1 \rho_1 \left[ c_1 (T_p - T_{cr}) + r_1 \right] , \tag{6}
\]

where \( X_1 \) – half the wall thickness of a flat casting; \( c \) – specific heat (the \( \langle \rangle \) symbol indicates a liquid state); \( \rho \) – density; \( r_1 \)– specific heat of solidification of the casting; \( T_p, T_{cr} \) – pour and crystallization temperatures; \( X_{co} \) – thickness of the paint layer (coating).
This method of calculating the wall thickness has passed laboratory and factory tests and can be successfully applied to enterprises that produce mainly flat castings. However, there are significant disadvantages associated with the restriction on the scope of use only for flat chill molds, as well as the need to determine a large amount of empirical and theoretical data depending on the material of the chill mold and casting, which makes the calculation quite complex and suitable only for experienced design engineers.

The calculation method is relatively simple [8]:

$$S = 11\sqrt{2S_1}$$  \hspace{1cm} (7)

This method has shown good results when casting cast iron castings, but if it is necessary to obtain castings from other alloys, its use becomes impossible.

The method developed on the basis of theoretical research is quite accurate [9]:

$$S = \frac{3B}{2K_p} \cdot X_1 \left( K_B + \frac{1 + K_B r_1}{T_p - T_{2n} c_1} \right)$$ \hspace{1cm} (8)

where \( B \) is the coefficient that takes into account the propensity of the chill mold to warping, and its material to oxidation;

$$K_p = \frac{2X_1}{R_{th}}$$ \hspace{1cm} (9)

$$K_B = \frac{b_2}{b_1}$$ \hspace{1cm} (10)

where \( R_{th} \) – given the wall thickness of the casting; \( b_1, b_2 \) – the coefficients of accumulation of heat to the casting material and form; \( T_{2n} \) – the initial temperature of the chill mould; \( r_1 \) – specific heat of solidification of the casting, \( c_1 \) – specific heat of the casting material.

Calculations using formula (8) are fairly accurate, but they require a large amount of preparatory work related to the definition of specific values of coefficients and parameters for each specific case, so its widespread use in practice is unlikely.

In addition to difficulties in calculating the size of the working wall, there is a problem of choosing the material of the chill mold, the method of its manufacture [10]. Gray cast iron, high-strength cast iron, cast steel, structural carbon steel, aluminum and copper alloys, as well as alloy steels and alloys with special properties can be selected as the material of the coil.

The choice of a specific brand of metal as a chill mold material is due to two factors – physical and mechanical properties that affect the strength, and economic efficiency. Thus, the option of expensive copper alloys or special alloyed steels is justified under the influence of intense thermohydrodynamic loads or with a mass volume of castings production. The use of cast iron or steel is due to the size of the casting, as well as the version of the coil and the type of cooling (air or water). In special cases, chill molds made of aluminum alloys are used with the use of anodizing, most often for small castings [11, 12]. At the same time, there is no unambiguous method for evaluating the suitability of materials for manufacturing the working walls of the chill mold. There are various design parameters of the special assessment.

For brittle materials, depending on the presence of a heat-protective coating, the following formulas are used [13]:

$$Z_0 = \frac{\sigma_B \lambda}{\alpha_T E}$$ \hspace{1cm} (11)

$$Z_0' = \frac{\sigma_B}{\alpha_T E}$$ \hspace{1cm} (12)

where \( \sigma_B \) – the limit of the tensile strength; \( \lambda \) – thermal conductivity; \( \alpha_T \) – thermal expansion coefficient; \( E \) – elastic modulus.
For malleable materials, the parameters $K$ and $K'$ are used, depending on the failure mechanism under alternating loads:

$$K = \frac{\lambda \delta}{\alpha_E}$$

$$K' = \frac{\lambda a_{IS}}{\alpha_E}$$

(13)

(14)

where $\delta$ – elongation; $a_{IS}$ – impact strength.

$$P = \frac{a_{IS}}{\sigma_{YS}} \left( \frac{\alpha_T \theta_c - 2 \sigma_y}{E} \right)$$

(15)

where $\sigma_T$ – yield strength; $\theta_c = \theta_p \frac{b_1}{b_1 + b_2}$ – chill mold temperature at the time of filling; $\theta_p$ – the temperature of the metal at the time of casting, calculated from the initial temperature of the coil, as from zero.

The higher the values of the parameters specified in formulas 11–15, the higher, under equal conditions, the operational stability of the chill molds [14, 15].

The considered theoretical and practical methods of calculation and assessment of suitability show the complexity of the design process of chill molds, so it is important for designers to use universal methods to improve the performance of the chill mold in order to increase the number of castings obtained.

Based on the results of the study [16, 17], it was found that coating the forming surface by physical vapor deposition will reduce the coefficient of friction between the form and the interacting metal, reduce the pressure on the forming parts and reduce the temperature on the forming surface at the time of pouring the molten metal, which should improve the quality of the resulting castings. These factors will reduce the magnitude and amplitude of vibrations of tensile stresses in the forming parts both in the closed and open state of the form, which will increase the period of operation until the formation of cracks of the 1st type. In addition, the formation of compressive stresses in the coating applied by the physical vapor deposition method can contribute to slowing the growth of type 1 cracks in the material of forming parts and the formation of cracks in the coating itself. Coating by physical vapor deposition will slow down the growth of cracks, as well as increase wear resistance, which will increase the operational life of chill molds and the quality of the resulting castings [18].

It is possible to use simple single-layer coatings, such as titanium nitride (TiN) or molybdenum nitride (MoN), as well as complex multi – layer coatings (titanium carbonitride (TiCN) – titanium nitride (TiN) – molybdenum nitride (MoN)) [19, 20]. The proposed coatings have positive properties, namely: a small thickness (up to 10 microns), which will not affect the accuracy of the resulting castings; high adhesive ability, which contributes to a strong adhesion to the chill mold material; the ability to slow down the growth of cracks formed both on the forming surface and in the chill mold material; the chemical inertness of the coating after application, which will provide protection from sticking of the poured melt to the forming surface, especially when casting aluminum alloys; relative ease of coating application; high microhardness of the coating, providing a long service period of the coating.

3. Conclusions

Thus, there are a large number of methods for selecting the material and calculating the thickness of the chill mold walls, obtained as a result of generalization of experimental data, taking into account various specific conditions of the casting process. However, each method has disadvantages that limit the scope of application. Designers face a difficult practical task to determine all the conditions of the
developed casting process that affect the specific values of the chill mold parameters. In this regard, given the relative complexity of these methods, there are promising universal ways to improve the performance properties of the chill mold, which will allow for a wider use of most methods for selecting materials and calculating the wall thickness of the chill mold using any of the methods. One of these solutions is a method for applying nitride and carbonitride coatings by physical vapor deposition on the forming surface of a coil or metal rod.

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