On the Issue of Heat Balance of Molds for Injection Molding of Non-Ferrous Metal Alloys

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Abstract. The article presents a study of the thermal balance of injection molding molds. The main components of the balance equation are indicated, as well as the factors that affect them. It is revealed that the most important factor affecting the thermal balance is the material of the mold. The use of coatings applied by the method of physical vapor deposition on the forming surfaces of molds is proposed. These coatings provide a reduction in friction between the forming surface and the poured melt at the time of filling, which reduces the temperature of the forming surface by 10–12°C. Among the considered options, the most optimal indicators were for titanium and molybdenum metal nitride (Ti, Mo) N.

1. Introduction

When designing a mold for injection molding, an important issue is to ensure the pre-operation of heating or cooling the mold. This action allows you to obtain the best initial conditions for the interaction of molten metal with the mold, which ultimately improves the quality of the resulting castings, and also increases the service life of the mold. The solution to this problem is possible only by accurately determining the components of the heat balance equation. At the same time, it is necessary to take into account all factors that can directly or indirectly affect the components of the heat balance [1, 2].

2. Results

In General, there are two components of the heat balance of the mold under a steady thermal regime, one of them \( Q_{in} \) – input heat and \( Q_{out} \) – output heat. The equality of these values determines the thermal balance between the mold and the casting. The solution of this equation allows you to determine the need for pre-cooling or heating the mold. The heat input can be calculated with sufficient accuracy using a well-known method [3]:

\[
Q_{in} = Q_{oh} + Q_{cr} + Q_{c} + Q_{fr},
\]

where \( Q_{oh} \) – heat of metal overheating, \( Q_{cr} \) – heat of crystallization, \( Q_{c} \) – heat of solid casting, \( Q_{fr} \) – frictional heat.

In this case, the heat of friction and the heat of overheating together make up about 12% of the total value of the amount of heat supplied [4, 5].
Calculating the heat output is not an easy task, since there are many gaps in the mold. However, the heat released by the mold to the environment consists of two main components. One of them is $Q_{cl}$ – the heat withdrawn from the closed mold through the side surfaces, the other is $Q_{op}$ – the heat withdrawn from the forming surface in the open state of the mold. That is, in the end, the heat output can be calculated using the following formula [6]:

$$Q_{\text{out}} = Q_{cl} + Q_{op},$$

It is also worth noting that the heat released to the environment is about 3% of the total heat released in the mold [7].

The main factor determining the value of the components of the input and output heat is the material of the mold, which is almost impossible to significantly change the effect. However, there are ways that allow you to partially change the components of the heat balance. One of them is the use of various lubricants that can significantly reduce the temperature of the working surface. These lubricants can be liquid, powdered, or a mixture of liquid and powder. Their application is that after a certain number of cycles, the lubricant is applied to the work surface [8]. However, a significant disadvantage of using such lubricants is that they are washed off from sharp edges and corners, in addition, the destruction of molds begins with sharp edges and corners on the forming surfaces. In addition, for these lubricants, even on even flat areas, the temperature distribution will be uneven, this moment will depend on the distance to the gating system. Another important point is that the application of liquid lubricants must be carried out cyclically through a small number of cycles, depending on the size of the resulting casting [9, 10].

Thus, given the fact that in modern engineering almost all working parts have a complex configuration, it is necessary to better solve the problem of reducing the contact temperature on the working surfaces. Coatings applied by physical vapor deposition (PVD) can serve as a solution to this issue [11, 12].

A distinctive feature of this method is the ability to apply a coating with almost any metal as a base. This makes it possible to purposefully improve the pre-set performance characteristics of the surface layer, which ultimately increases the durability of the tooling, as well as the quality of the resulting castings. Another important feature of coatings applied by the PVD method is the presence of these coatings of a fine-grained densely packed structure, which provides increased resistance to destruction in conditions of high temperatures and stresses [13].

The thermal interaction between the mold and the molten metal after the PVD coating is applied changes for several reasons. One of them is due to the physical properties of the coating, the other is to reduce the coefficient of friction [14, 15].

Despite the possibility of using refractory metals as the basis of a multifunctional coating, their thickness of 3–10 microns is so small that the use of even such a metal as molybdenum, which has increased refractory properties, does not give any significant changes in the terms of the heat balance and is no more than 0.3% of the heat input [16, 17].

Another important point for studying the effect of coating properties on the thermal balance is the cooling of the mold between injections of molten metal. It can be assumed that between cycles, the coating should reduce the interaction rate between the mold and the environment. In turn, the preservation of heat inside the mold should reduce the influence on the magnitude of the amplitude change in the surface layer, which, ultimately, will increase the resistance index of the molds [18, 19]. However, experimental data disproved this hypothesis. The temperature difference for molds in the open state with different coatings in comparison with uncoated ones gave a difference of no more than 0.2%.

Thus, the only moment associated with coatings that can significantly affect the thermal balance is the change in the value of the heat flow from the friction between the molten metal and the surface layer of the forming surfaces by reducing the coefficient of friction between these surfaces. The value of this coefficient depends entirely on the composition of the coating, and a
study was conducted to determine the optimal one. For comparison, the following compositions of single-layer coatings applied by the PVD method were selected: TiN, MoN, TiCN, (Ti, Mo) N, and as a comparison with the classical technology of manufacturing molds, inserts with a nitrided forming surface were studied.

Determining the temperature of the mold TM in the molten metal casting zone was performed using thermocouples, one end of which was connected to the temperature indicator, the other end was fixed in blind holes located next to the forming surfaces. The temperature was measured at several points and at different heights from the forming surface. According to the tests, it was found that the highest temperature values correspond to a layer 8–10 mm from the forming surfaces (figure 1), which is confirmed by the existing theory [20].

![Figure 1. Mold temperature depending on the coating composition, a – nitrided surface, b – TiN (titanium nitride), c – MoN (nitride of molybdenum), d – TiCN (the titanium carbonitride), e – (Ti,Mo)N (the nitride of the metals titanium and molybdenum).](image)

The best values correspond to MoN coating, which is due to the fact that molybdenum is a good base for lubricants. Thus, MoN coating is able to reduce the operating temperature of the forming surfaces of the mold by 10–12 °C in comparison with the nitrided surface. This means that the preheating temperature of the mold before pouring molten metal will be lower by the specified 10–12 °C. It is also worth noting that among the studied coatings, the worst results were shown by coatings complex in composition, but better than the nitrided surface.

Despite the fact that different grades of steel can be used as the mold material, as well as the fact that the melting temperature of the poured alloys differs depending on their compositions, the curve of the dependence of the number of thermal cycles on the temperature difference in the mold material has approximately the same nonlinear character. Despite the possible different initial conditions of the injection molding process, it can be said that the smaller the temperature difference in the mold material, the greater the number of casting cycles until the destruction of the forming surfaces. Thus, even a slight decrease in the temperature drop can have a positive effect on the resistance of casting equipment. And in particular for the injection molding process of zinc alloys, the distinctive feature of which is a relatively small melting point of about 380°C, even such a small decrease in the maximum operating temperature will give a much greater effect than for aluminum or brass alloys.

3. **Conclusions**

The use of wear-resistant coatings applied by the PVD method, which consists in the condensation of a substance from the plasma phase in a vacuum with ion bombardment of the surface on a
special installation, allows you to reduce the temperature on the forming surfaces of the mold. The supplied heat flows are reduced due to an abnormally low coefficient of friction on the forming surfaces, which reduces the maximum heating temperature of the mold material. This leads to an increase in the operational stability of injection molding molds, as well as to an increase in the quality of the resulting castings.

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