Using knowledge-intensive technologies to master magnesium alloy casting for surface-to-air missile bodies of the S-400 Triumf anti-aircraft weapon system

For the first time ever, the paper presents an original scientifically informed approach to manufacturing process design for magnesium alloy casting of large body parts using combined moulds (a permanent mould with an internal sand core). This approach involves solving a system of problems to ensure directional solidification and a steady feeding rate. To solve these problems at each stage of mould filling and casting formation, we used methods of foundry hydraulics and thermal theory of casting to derive expressions for computing the necessary manufacturing parameters, from the pouring temperature to the duration of keeping the finished casting in the mould. We combined these computational techniques into a single software package, which was successfully tested in practice at the JSC Moscow Mechanical Engineering Plant AVANGARD and Public stock company “Dolgoprudy Research Production Enterprise” while manufacturing surface-to-air missile compartments for the S-400 Triumf and Buk-M3 anti-aircraft weapon systems.

Keywords: cast magnesium bodies, permanent mould, core, feed system, pouring temperature, heat transfer in the casting, heat transfer in the mould, directional solidification, steady feeding rate, runner, chill, simulation.

One of the basic design features of special-purpose products included in modern Russian missile systems is the use of cast products made of high-strength magnesium alloys.

Application of magnesium alloys allows to ensure the best suitable product power-to-weight ratio and therefore the best product performance at large.

Development of casting process is a multifactor problem, and its solution is decisive not only for the quality of casting, but also for its production costs, including primarily the cost of tooling, labour intensity related to production process, and specific amount of metal. Risk of error is low for small-size and low-duty cast products. However, it dramatically increases when we talk about cast products, which require a long-term preproduction cycle.

Such cast products include large-sized cast bodies for guided surface-to-air missiles (SAM) of the S-400 Triumf anti-aircraft missile system (AAMS).

Nowadays, many companies are using multiple computer-aided engineering (CAE) systems in development of casting processes. Application of such systems allows to reduce costs of testing and modification of tooling, as well as the total time of production cycle to manufacture a pilot lot of cast products.

However, none of modern CAE systems allow for estimation of the expedience of a designed cast process.

Basic criteria for estimation of each CAE system is proper mould filling and absence of shrinkage cavities (or presence of tolerable defects).

Of course, the iteration method may help eliminate or reduce the effect of such defects on the casting quality and to reduce the specific amount of metal. However, a more efficient and reliable technique is to run preliminary computations of the required process control parameters for manufacturing cast products in order to meet specification requirements with a minimum specific amount of metal.

To implement this approach in development of production control processes for casting large-sized body parts made of magnesium alloys into a combined mould (permanent mould with internal sand core), a computer-aided design system has been developed to solve a system of problems to calculate the following parameters:

- design dimensions of the feed system (FS);
- pouring temperature;
Fig. 1. Diagram showing a thin-wall cast body with a vertical slot feed system when the vertical slot is directly adjacent to the outer side of the casting (a) and when casting serves as a vertical slot (b):
1 – hot top; 2 – casting wall; 3 – process lap; 4 – lugs on inner surface of casting; 5 – pouring gate; 6 – runner gate; 7 – pit; 8 – vertical slot

- distribution of pouring temperatures in the mould at the end of its filling;
- steady feeding of vertical walls of casting and required process laps;
- hot tops and cooling plates.

The first problem can be solved if the FS structural parameters are predetermined. For castings that belong to the said class, the obvious design solution is a vertical slot feed system (Fig. 1) [1]. This design allows to use two configurations:

1) the vertical slot is directly adjacent to the outer wall of the casting (Fig. 1, a);
2) the casting itself serves as a vertical slot. This allows to prevent heat transfer through the side wall of the vertical slot and eventually to reduce the superheat temperature of the metal poured into the mould (Fig. 1, b).

The feed system parameters are calculated based on the Bernoulli equation [2] with known recommended ratios of total areas of the FS elements, taking into account critical values of the Reynolds criterion and empirical values of flow coefficient.

To calculate the pouring temperature, the feed system and the mould’s working cavity are divided into $N$ sections with an approximately uniform cross-section area towards the metal flow.

In this case, we can calculate pouring temperature $t_{\text{зал}}$, which prevents admissible reduction of the molten metal temperature in the mould, using the solution to the heat-balance equation [3]. The following factors shall be considered:

- melting rate in the mould (regarding reduction of metallostatic pressure);
- superheat transfer to permanent mould (regarding a variation of heat-resistant paint layer thickness on its working surface);
- convection flow heat transfer when molten metal is discharged into casting lugs with regard to the Nusselt number and the Peclet number;
- heat transfer to sand core.

As a result, the pouring temperature can be calculated as follows [4]:

$$t_{\text{зал}} = t_{\text{пн}} + (t_{\text{max}} - t_{\text{пн}}) \exp \left( b_{\text{пн}} \left( \frac{\alpha_c F_c + \alpha_{\text{жж}} F_{\text{жж}}}{c' \rho Q_b \left( b_{\text{пн}} + b_{\text{жж}} \right)} \right) \right),$$

where $t_{\text{пн}}$, $t_{\text{max}}$ – initial mould temperature and molten metal temperature at vertical pit inlet, °C;
\( b_{\text{pm}}, b_{\text{pk}} \) – heat accumulation coefficients of permanent mould and sand mould, pouring gate and runner gate respectively, \( W \cdot c^{1/2}/(m^2 \cdot K) \);
\( \alpha_c, \alpha_{xx} \) – coefficients of heat transfer from molten metal flow to the surface of pouring gate and runner gate in the mould, respectively, \( W/(m^2 \cdot K) \);
\( F_c, F_{xx} \) – surface areas of pouring gates and runner gates, respectively, \( m^2 \);
\( c', \rho' \) – specific thermal capacity, \( J/kg \cdot K \), and density, \( kg/m^3 \), of liquid alloy, respectively;
\( Q_{\phi} \) – molten metal flow rate during mould filling, \( m^3/s \).

According to [2], it is important to ensure flow-through and cross flow when filling the cavity of the mould in the vertical slot feed system. For this purpose, we shall calculate the value of molten metal cross flow on each dedicated level of the casting height, which shall not be less than a certain preset geometrical parameter (for this type of castings – 1/4 of length of circumference).

Molten metal temperatures in the upper and lower layers of the mould’s working cavity at the end of its filling at flow-through and cross flow shall be calculated, taking into account that the lower layer will be filled before the upper one is filled.

That is why, while filling a large-sized mould \( (h > 1 \, 000 \, \text{mm}) \) up to the upper cross-section, solidification of molten metal may begin after filling.

At the phase of filling of the mould with molten metal, the wall of the permanent mould can be considered as a semibounded body in terms of heat rate due to short duration of the process. Based on the problem solution [4] for a semibounded body under the boundary conditions of the third kind, a temperature variation in the mould from the casting base to its top can be calculated by solving the equations for the specific heat flow rate through the surface of the permanent mould.

Knowing the preset pouring temperature, we shall take into account the following:

- initial temperature of permanent mould and its heat accumulation coefficient;
- coefficient of heat transfer from molten metal flow to permanent mould (taking into account the paint layer thickness on it);
- convection heat transfer coefficient;
- average rate of metal level rise in the mould.

If we know the casing base inlet temperature \( t_{\text{min}} \) and calculate it for upper layers \( t_{\text{min}} \), we can determine the average molten metal temperature by height:

\[
 t_{\text{sh}} = 0.5(t_{\text{min}} + t_{\text{min}}).
\]

The calculated parameters of temperature distribution by the casting height at the end of its filling are included in initial data for calculating the steady feed rate of vertical walls of casing and required process overlapping.

The casting solidification sequence is calculated based on the known analytical solution to the problem in the theory of solidification [5].

The difference is the determination of heat exchange in a combined mould represented as the sum of heat accumulation coefficients of the permanent mould and sand core. The effective heat accumulation coefficient for the permanent mould is calculated by replacing the permanent mould with a semibounded body in terms of heat rate and by using a mathematical model of its temperature field [6]:

\[
 b_{\text{eff}} = \frac{\sqrt{\pi F_0 \tau}}{2 \Theta (1+1/K + 1/B_i)}.
\]

where \( b_k \) – heat accumulation coefficient of permanent mould, \( (W \cdot c^{1/2})/(m \cdot K) \);
\( F_0, K, B_i \) – Fourier number and Biot number for permanent mould;
\( F_0 = a_k \tau / \delta_k \); 
\( \Theta = (t_{\text{pm}} - t_{\text{os}}) / (t_k - t_{\text{os}}), \); 
\( B_i = \alpha_k \delta_k / \lambda_k \);
\( a_k \) – temperature conductivity coefficient of permanent mould, \( m^2/s \);
\( \delta_k \) – permanent mould wall thickness, \( m \);
\( t_{\text{pm}} \) – average rated temperature of casting during solidification process, \( ^\circ C \);
\( t_{\text{os}} \) – ambient temperature, \( ^\circ C \);
\( \lambda_k \) – thermal conductivity coefficient of permanent mould, \( W/(m \cdot K) \);
\( t_k \) – initial temperature of permanent mould, \( ^\circ C \).
$f$ – permanent mould thermal condition disturbance function:

$$ f = 1 + \left[ \frac{\lambda_{mk} \Theta}{\delta_{mk} k_q} - 1 \right] \frac{1 - \exp(-A)}{A}, $$

$$ A = 1.67k^{0.85F}, \ F = F_{0.7}^0, $$

where $\lambda_{mk}$ – thermal conductivity coefficient of permanent mould coating (paint), W/(m·K);
$\delta_{mk}$ – coating thickness, m;
$k_q$ – coefficient of heat transfer through permanent mould wall, W/(m²·K).

The results of the casting wall solidification sequence analysis are the basis for calculating the process lap that provides its feeding. For this calculation, the filtered feed continuity criterion is used [7]:

$$ K_q = \frac{G^2}{V_t}, $$

where $G$ – average gradient of temperature in casting wall relative to its length, K/m;
$V_t$ – average rate of wall chilling during solidification, K/s.

Steady feeding rate of casting is available if the following condition is satisfied

$$ K_q \geq (K_q)_{kp}, $$

where $(K_q)_{kp}$ – critical value of steady feeding rate criterion.

For castings made of alloy ML5 $(K_q)_{kp} = 2.4\cdot105$ K·s/m² if macroporosity is eliminated and microporosity is limited.

Based on the mathematical model of the solidified casting’s temperature field, we formulated a system of equations to calculate the hot top feeding distance $L_{sn}$ and lap thickness $\delta_{sn}$ (see Fig. 1):

$$ \frac{2(t_{sn} - t_{cos})^{3/2}}{\sqrt[6]{\alpha_{Sn} t_{sn}}} \exp \left[ -1.05 \left( \frac{h_0}{\sqrt{\alpha_{Sn} t_{sn}}} \right)^{1.2} \right] - \frac{b_q T_s (t_p - t_0)}{b_s \delta_0} \exp \left[ -0.72 \left( \frac{h_0}{\sqrt{\alpha_{Sn} t_{sn}}} \right)^{1.4} \right] = L_{sn} (K_q)_{kp}, $$

where $t_{sn}$ – equivalent initial temperature of molten metal in the upper cross-section of wall, °C;
$t_{sn} = t_{snk} + c' \left( t_{sn} - t_{tnk} \right) / c_a \rho$;
$t_{sn}$ – temperature of molten metal the mould is filled with, °C;
$t_{tnk}$ – liquidus and solidus temperature of alloy, respectively, °C;
$t_{cos}$ – solidus temperature of alloy, °C;
$\tau_n$ – average time of casting wall solidification, s;
$\tau_{sn}$ – time of hot top solidification;
$\alpha_{sk} = \lambda_a / (c_m b)$ and $b_a = \sqrt[2]{c_m b}$ – effective temperature conductivity coefficients, m²/s, and heat accumulation coefficients, (W · c¹/²)/(m² · K), of alloy in solidification range;
$t_p$ – average rated temperature of solidifying casting.

The length of process overlapping $l_n$ on the casing wall is $l_n = h_0 - l_{sn}$. The overlapping thickness $\delta_{sn}$ in the lower part is equal to machining allowance.

Calculation of casting sizes comes down to calculation of the conical hot top cross-section base dimension $B_n$ followed by calculation of the upper dimension of cross-section $B_{sn}$ and hot top height $H_n$ by relations with $B_n$ (see Fig. 1):

$$ H_n = K_1 B_n, \ B_{sn} = K_2 B_n. $$

For magnesium-based castings $K_1 = 1.9...2.0$ for open hot tops and $K_1 = 1.5...1.6$ for blind hot tops, $K_1 = 1.1...1.2$ [2].

Value $B_n$ is determined with the help of the unit-based method of calculation by solving the equation of hot top heat balance [8]:

$$ Q_{sn} = Q_{p} + Q_{sn} + Q_{to}, $$

Heat balance components are determined depending on $B_n$. The specifics of calculation of heat $Q_{sn}$, emitted during hot top solidification is that we shall take into account a decrease in the metal volume in the hot top caused by shrinkage during solidification of casting and hot top:

$$ Q_{sn} = A_1 B_n^2 - A_2, $$

where $A_1 = 0.5c_m \rho L_a (1 + K_1) (t_{sn} - t_{cos}) (1 - 0.5e);$
$A_2 = c_m \rho L_a V_0 (t_{sn} - t_{cos});$
Lₙ – hot top length equal to the length of the upper section of the casting wall with the hot top, m;

 εᵥ – relative volume shrinkage of alloy during solidification, for magnesium alloys εᵥ = 0.05 ... 0.06;

 Vₒ – casting volume (without pits), m³.

The heat transferred from the hot top into the mould (permanent mould) Qᵦ is calculated as follows:

 Qᵦ = A₃Bₙ² + A₄Bₙ,

where 

A₃ = \frac{2}{\sqrt{\pi}} bₘₚₙ K₁(1 + K₂)(t_p - tₘ)\sqrt{tₘ},

for open hot top:

A₄ = \frac{2}{\sqrt{\pi}} bₘₚₙ Lₙ(K₂ - 1)\sqrt{1 + + \frac{2K₁}{(K₂ - 1)}} \times \n� (t_p - tₘ)\sqrt{tₘ};

for blind hot top:

A₄ = \frac{2}{\sqrt{\pi}} bₘₚₙ Lₙ \left\{ (K₂ - 1)\sqrt{1 + \frac{2K₁}{(K₂ - 1)}} \right\} \times \n� (t_p - tₘ)\sqrt{tₘ};

bₘₚₙ – effective heat accumulation coefficient of hot top mould, (W · c⁴/2)/(m² · K).

The heat transferred from the open surface of the hot top:

Qₘₖ = A₅ = \frac{0.31Lₙδₘₖ(tₘₖ₇ₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖₖ₆ th
Fig. 2. Body part drawing
intended to manufacture the cast body, namely, simulation of the mould filling process (see Fig. 3), which indicates stable conformity with the requirements for continuity and laminarity of molten metal flow. This allows to maintain the desired parameters of the feed system. The analysis of temperature fields and solid phase formation (see Fig. 4) shows that requirements for directional solidification of the casting during its moulding are met thanks to the initial distribution of the molten metal temperature at the end of the process of mould filling, as well as due the initial gradient of permanent mould temperatures depending on its height and heat exchange conditions between the molten metal being solidified and the mould through the pre-calculated variable layer of heat-insulating paint. Formation of shrinkage porosity (see Fig. 6) in castings allows to identify locations of pore formation and a tolerable value. In case of deviation from the standard parameters set forth in specification requirements for casting, process-related equipment responsible for steady feeding of the relevant areas of a casting (hot tops, process laps, cooling plates, heat-insulating paint) is subject to re-design, based upon minimization of its specific amount of metal.
To determine the time for curing a casting in the permanent mould before extraction, the duration of crystallization process needs to be calculated (see Fig. 7), because it is important for minimizing the backlog of foundry tooling and for improving the performance of the casting process.

The analysis of results for this magnesium alloy-based casting as well as for other cast elements of the SAM structure for the S-400 Triumph AAMS has proven high efficiency of results of calculation of all process parameters.

As a result, we have prepared design documentation and manufactured foundry tooling. After refining production control processes, all the designed compartments made of alloy ML5 for products developed by JSC Moscow Mechanical Engineering Plant AVANGARD and those made of alloy ML10 for products developed by DNPP, PJSC have successfully passed Group I tests as per OST 1.90248–77. According to completed qualification tests, the manufactured compartments fully meet the specification requirements.

Therefore, the developed methods for calculating process control parameters to cast magnesium alloy-based body parts into a combined mould are highly efficient due to an integrated approach to problem solving and trustworthy results.
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Применение наукоемких технологий при освоении корпусного литья из магниевых сплавов для ЗУР ЗРК С-400 «Триумф»

Впервые рассмотрен оригинальный научно обоснованный подход к проектированию технологических процессов литья крупногабаритных корпусных отливок из магниевых сплавов, изготавливаемых в комбинированных формах (кокиль с внутренним песчаным стержнем). Данный подход включает в себя решение комплекса задач с целью обеспечения условий направленности затвердевания и непрерывности питания отливок. Для решения этих задач для каждого этапа заполнения формы и формирования отливки на основе методов литейной гидравлики и тепловой теории литья были получены выражения для расчета требуемых технологических параметров от температуры заливки расплава до времени выдержки сформированной отливки в форме. Данные расчетные методики были объединены в пакет программ, который прошел успешную апробацию в АО «ММЗ «АВАНГАРД» и ПАО «ДНПП» для изготовления отсеков зенитных управляемых ракет для зенитно-ракетного комплекса С-400 «Триумф» и «Бук-М3».

Ключевые слова: магниевые корпусные отливки, кокиль, стержень, литниковая система, температура заливки, теплообмен отливки, теплообмен формы, направленность затвердевания, непрерывность питания, прибыль, холодильник, моделирование.

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