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Research Article

Application of lost foam casting method to improves the surface quality of casting products

Hung Le Duong[*], **An Van Le, Chan Thanh Bui, Hung Thai Trinh**

ABSTRACT

The gearbox housing is a large and geometrically complex component, making it highly susceptible to common defects during the Lost Foam Casting (LFC) process, such as incomplete filling, shrinkage cavities, and gas porosity. These defects not only compromise the mechanical integrity and surface quality of the casting but also significantly increase production time, material costs, and energy consumption due to the necessity for multiple experimental castings. Therefore, it becomes crucial to apply advanced numerical simulation techniques to optimize the manufacturing process, enhance casting quality and efficiency, and minimize the environmental footprint of production.

This study employs numerical methods to predict the filling behavior and potential casting defects associated with different filling system configurations. By systematically analyzing and comparing various pouring system designs, the objective is to identify the most effective configuration that ensures complete mold filling, minimizes internal and surface defects, reduces material waste, and maintains an efficient and controlled casting speed. The simulation work was conducted using ProCAST Visual-Cast 17.4 software, a robust tool for simulating complex casting phenomena, including molten metal flow, heat transfer, solidification, and defect formation.

Multiple filling system setups were developed and evaluated, with their performance assessed based on key criteria including filling time, temperature distribution, defect prediction (such as shrinkage porosity, pitting, and gas entrapment), and overall flow behavior during mold filling. The simulated results were cross-validated with analytical solutions and empirical data to ensure high reliability and predictive accuracy.

Through this comprehensive analysis, the study successfully identifies an optimal filling system design that meets industrial standards for quality and dimensional precision. The findings provide critical insights into designing efficient, cost-effective, and environmentally sustainable LFC processes for large, geometrically complex components like tractor gearbox housings.

Key words: LFC, Lost Foam Casting, Casting Optimization, Procast, numerical analysis

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INTRODUCTION

The method of lost foam casting was first used in the US in 1970, but much later in Europe. Until the late eighties of the 20th centuries, there was no significant development in the application of casting method in Lost Foam Casting (LFC)[1]. By 1990, less than 1% of cast iron parts and less than 5% of aluminum alloy casting parts were cast by this method. However, since 1990, there have been many positive changes in the application of this method. The BMW foundry, one of the world's leading aluminum alloy parts foundries, has its own large workshop specializing in casting L-6 cylinders in LFC[2]. General Motors (GM) has been using LFC technology since 1982 and has since undergone many improvements[3]. GM has used this technology to cast many complex parts such as automatic transmission oil pumps. engine, A256 aluminum alloy body, cylinder cover… GM's Saginaw Metal Casting Operation (SMCO) is casting the body and cover for the Vortex by LFC. As illustrated in Figure 1, the market share of cast iron and aluminum alloy products produced using the LFC method has shown significant growth over time. The data highlights that by 2020, approximately 30% of aluminum alloy castings and 18% of cast iron parts were manufactured using LFC, indicating a steady trend of adoption and expansion of this advanced casting method worldwide[4].

Currently, Vietnam has up to 500 Company, casting establishments. For example: Dong Anh Mechanical Company, Mai Dong Casting, Tan Long Casting, Viet Nhat ... produce a series of casting products, such as: engine casting, steel pipe. But most of the Company apply traditional casting methods as well as outdated equipment. Molded products with poor surface quality need to be reprocessed, leading to inflated costs. There are fewer than 10 Company applying advanced casting methods, but they focus on metal casting, pressure casting, and flow casting. In Vietnam,

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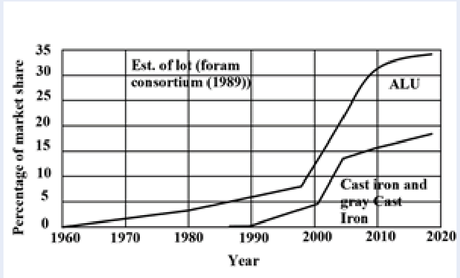

Figure 1: Market share of cast iron and aluminum alloy products cast in LFC

there are not many Company producing castings by the method of LFC, and there are not many topics focused on this research, most of the topics focus on the flow casting method.

To meet the demand for replacement machine gearbox covers, and at the same time reduce the burden of repair costs for user in Vietnam, the authors seek to manufacture gearbox covers in the country, and at a reasonable cost without losing quality. Using the reverse method to get the parameters of the gearbox, after that applying the numerical simulation method by Procast [5] to minimize the costs of testing. Here, the authors apply the Procast program to analyze the application of LFC for gearbox housings with different pouring systems to find the optimal pouring method for casting.

LFC CASTING PARAMETERS

The details of the gearbox are reverse-engineered, and 3D modeled with the basic dimensions as shown in Figure 2. From the figure, we see that the casting has a large size (528.05mm x 317.08mm x 114.26mm), thin and irregular walls (8.05mm thinnest and 62.14mm thickest), complex structure and many load-bearing structure.

The gearbox housing is a large and geometrically complex component, making it highly susceptible to common defects during the Lost Foam Casting (LFC) process, such as incomplete filling, shrinkage cavities, and gas porosity. These defects not only compromise the mechanical integrity and surface quality of the casting but also significantly increase production time, material costs, and energy consumption due to the necessity for multiple experimental castings.

To characterize the material used in this study, Table 1 presents the chemical composition of the GX15-32 alloy, which is a key component in the casting process. The detailed chemical composition of this alloy is as follows.

Table 1: ***Chemical Composition of GX15-32***

	C %	Si %	Mn %	P %	S %
GX 15-32	3.6	2.2	0.7	0.025	0.1

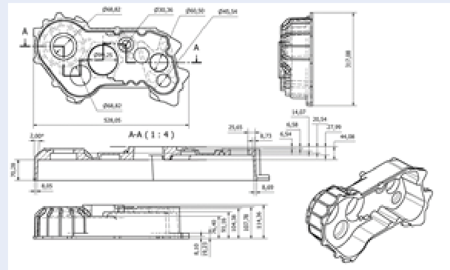

Figure 2: Gearbox detail

METHODS

This study, a numerical simulation approach was employed to analyze and optimize the Lost Foam Casting (LFC) process for a tractor gearbox housing. The methodology included the following steps, as shown in Figure 3.

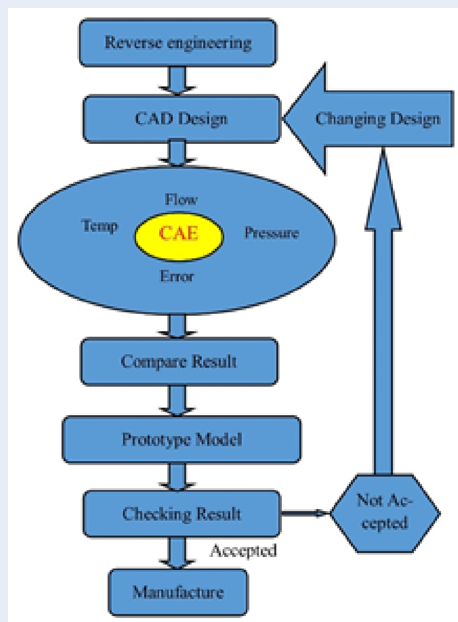

Figure 3: Diagram of the casting simulation process

Reverse Engineering and CAD Modeling

The gearbox housing was reverse-engineered to extract key dimensions and geometrical features. A 3D model was constructed using commercial CAD software such as SolidWorks or Inventor. The final model measures approximately 528.05 mm × 317.08 mm × 114.26 mm, with complex internal structures and wall thicknesses ranging from 8.05 mm to 62.14 mm.

Simulation Setup in ProCAST

The 3D CAD model was exported in STEP format and processed using ProCAST Visual-Cast 17.4. The geometry was cleaned and converted to VBD format using GenMesh for meshing. The simulation included:

- Molten metal flow dynamics
- Heat transfer
- Solidification

Prediction of casting defects such as shrinkage porosity and gas entrapment
A non-uniform mesh strategy was used: finer elements in high-gradient areas like ribs and walls, and coarser elements in low-variation mold regions, optimizing accuracy and computational cost.

Pouring System Configurations

Four gating system configurations were studied, as shown in Figure 4:

- Vertical pouring from the outer bottom
- Vertical pouring from the inner bottom
- Vertical pouring from the top
- Horizontal pouring from the inner bottom

Each setup was analyzed based on its influence on filling quality, flow behavior, and defect formation.

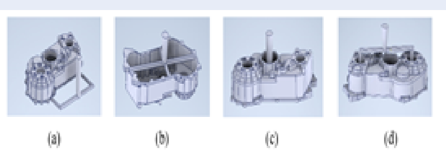

Figure 4: Pouring system

Boundary and Process Conditions

Simulation boundary conditions and casting parameters are summarized in Table 2.

Evaluation Criteria

Simulation outcomes were assessed using the following metrics:

- Time to complete mold filling

Table 2: Main Simulation Parameters

Parameter	Value
Pouring velocity (V)	1.5 m/s
Heat transfer coefficient (h)	10 W/m^2·K
Heat transfer coefficient (h)	0.05 MPa
Pouring height (h)	0.05 – 0.15 m
Initial metal temperature	As per ProCAST setting
Initial metal temperature	GX15-32 (see Table 1)

- Temperature distribution during mold filling and solidification
- Solid phase ratio development during solidification
- Occurrence and location of casting defects (shrinkage, porosity, incomplete filling)

Meshing model

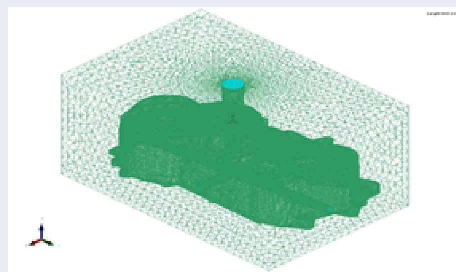

Figure 5: Gearbox, pouring system and mold mesh

Before using the software, the 3D solid model completed has been transformed into step format and exported. Then it needs to be analyzed and repaired by genomes software and output to vbd format file. Finally, it is imported into the mesh cast module of Procast software for meshing, so that the assembly position and geometric characteristics of mold and casting can be displayed completely and accurately; Importing the step format file directly into mesh cast will result in the loss of the assembly position of the mold and the casting and the complete separation of the components of the assembly.
The software has simple modeling and meshing functions, but it is difficult to complete the complex modeling and meshing of sand casting LFC gearbox. Its inspection, repair and format conversion functions can simplify the meshing in the process of casting simulation. Procast can read the three-dimensional solid models in step, IGS, STL and other formats, and check

and repair the free edges and overlapping edges of the geometric models of sand mold casting mud pump body, gating system, and sand mold in the assembly (as shown in Figure 5). After the repair of the geometric model is completed, Hide other parts in the assembly and export sand mold casting body, gating system, and sand mold one by one in vbd format.

Procast first divides the geometric model into face meshes, then checks and repairs the generated face meshes, and finally divides and optimizes the volume meshes. During casting simulation calculation, the grid parameters of sand-casting casting LFC gearbox and gating system are required to be higher, while the grid requirements of sand mold are lower. At the same time, due to the complex structure of sand casting LFC gearbox, it is necessary to adopt uneven grid division for casting LFC gearbox, gating system and sand mold, Dense grids are used to deal with the parts with large geometric change gradient such as the Gearbox, so as to truly retain the geometric characteristics of the sand casting LFC gearbox as much as possible. When dealing with the parts and molds with small geometric change gradient of castings, they should be divided into relatively sparse grids. In this way, the calculation accuracy and accuracy can be improved, and the calculation time can be reduced. The divided finite element mesh is shown in Fig. 5.

RESULT AND DISCUSSION

Analysis of vertical pouring from the outer bottom

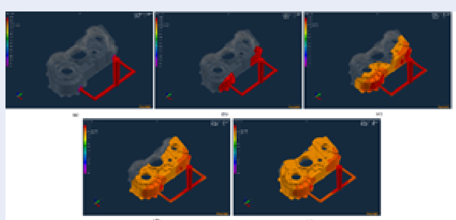

Figure 6: Temperature fieldduring filling process of vertical pouring from the outer bottom: (a) t =0.7090s, filling = 11,7%; (b) t = 1.1090 s, filling = 20,4%; (c) t = 2.7512s,filling = 50.3%; (d) t = 3.9036s, filling = 71.1%; (e) t = 5.0683s, filling =89.2

During filling process of molten metal into the lost foam casting, foam pattern is pyrolyzed layer by layer because the amount of heat transferred from liquid metal when molten metal meets it, and molten metal gradually replaces it. Between molten metal front and foam pattern forms a gas layer (decomposition product from the foam pattern), the mold exiting process of this gas also affects the filling process of molten metal. The amount of this gas leaving the mold depends on the coating and the permeability of sand mold.

Figure 6 shows the temperature field changes at the mold filling stage during molten metal poured into the mold. Colors are used to indicate temperature changes at various positions of molten metal. In the initial stage of 0.709s, the molten metal fills the whole pouring system (filling = 11.7%), the filling speed in this stage is slow because the molten metal has a high temperature at this time, the amount of gas from decomposition products generate a lot, the direction of the gas exiting the mold in this stage is opposite to the filling direction of molten metal, leading to an increase in the gas gap pressure at molten metal front and slowing down the filling rate of molten. From Figure 6 a and c, we see that the molten metal fills 38% with only time t = 2.0422s, at this stage the filling process takes place at fast rate due to the direction of decomposition gas escaping along with the filling direction. FromFigure 6 d and e show that it takes time t = 2.3171 to fill 38%, at this stage the filling process takes place at slow rate because molten metal front is far away from the heat source, the temperature of molten metal is further reduced, the foam in the cavity is basically pyrolyzed leading to a lot of gas products that increase the back pressure. Thus, the filling process of molten into the mold when vertical pouring from the outer bottom varies from slow to fast and then slow. The end of filling process is only achieved 89% because molten metal is far away the heat source, so the heat lost in the pyrolysis process of the foam is not supplement to reduce the fluidity of molten, and some casting area have thin walls so molten metal will cool rapidly down to the liquidus temperature and solid crystals appear first there interferes with the filling of molten metal on the opposite side of pouring system, as seen inFigure 6 a, it's the gray area. To solve this problem, we arrange an additional pouring system on the opposite side to supplement molten metal, but doing so leads to a huge waste of metal for the pouring system.

Figure 7 shows the change in temperature field and solid phase ratio during crystallization. The color is used to indicate the solid phase ratio at different areas in the casting as molten metal crystallizes. FromFigure 7 a, we can see those locations away from pouring system or thin walled will crystallize first, so there is a high solid phase ratio. When the crystallization process reaches from 50.3% to 70.3% as shown inFigure 7 b and c, most of casting section has been solidified, only upper and lower flanges and reinforcing ribs have

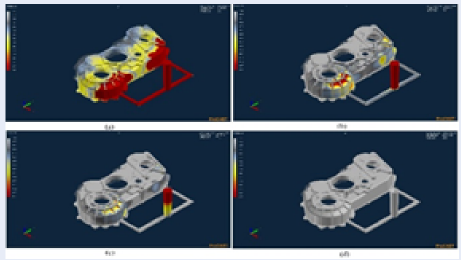

Figure 7: Solid phase ratio during solidification process of vertical pouring from the outer bottom: (a) solid phase ratio at 21.3% solidification, (b) solid phase ratio at 53.1% solidification, (c) solid phase ratio at 70.3% solidification, (d) solid phase ratio at 100%

a low solid phase ratio of the liquid. The entire casting solidification is completed in about 417s, as shown inFigure 7 d, casting with the external defects due to incomplete filling.

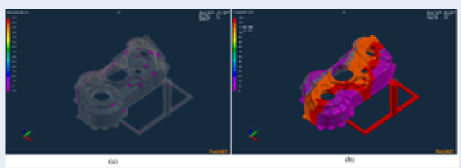

Figure 8: (a) Distribution of shrinkage porosity, (b) Temperature field at filltime

Figure 8 a shows the distribution of shrinkage and porosity inside the casting under vertical pouring from the outer bottom. The isolated liquid phase region during the solidification process is easy to form shrinkage cavities and decomposition gas products do not escape from the mold which will form porosity.Figure 8 b shows the temperature field distribution inside casting at full filling. We see the appearance of regions where both liquid and solid phases exist, these regions are also causes of shrinkage. It is an undesirable pouring method.

Analysis of vertical pouring from the inner bottom

Figure 9 is a schematic diagram of the temperature field change during mold filling under vertical pouring from the inner bottom. The entire filling process is relatively fast, and a large amount of heat from molten metal is lost during the pyrolysis of foam, so the filling rate will be significantly affected. In essence, the filling speed in this case is quite like vertical pouring from the outer bottom (at first the filling speed is

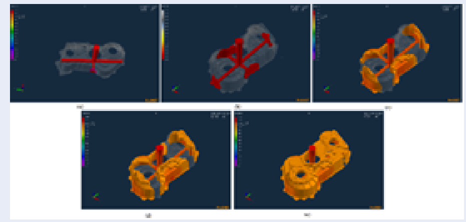

Figure 9: Temperature fieldduring filling process of vertical pouring from the inner bottom: (a) t =0.3920s, filling = 13.4%; (b) t = 0.6446s, filling = 20.5%; (c) t = 1.4824s,filling = 50.4%; (d) t = 2.0831s, filling = 70.6%; € t = 2.9359s, filling = 98%

low, then the filling speed is quite fast, then it slows down), as shown in Figure 9. But in this case, the molten metal flows from the four runners, so the filling is faster, and the filling is better than in the case of vertical pouring from the outer bottom. The filling process completes 98% within t = 2.9359, as shown inFigure 9 e. The filling reaches 98% in the simulation due to the influence of the sprue and sprue cup.

Because the molten metal enters the mold cavity from four different internal runner, the time and temperature are different, resulting in the instability of the filling process, vortex, splashing, and the decomposition gas products difficult to escape the mold due to tend to get trapped in the vortex of molten metal.

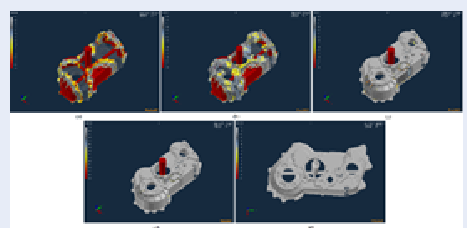

Figure 10: Solid phase ratioduring solidification process of vertical pouring from the top (a) solid phaseratio at 10.7% solidification, (b) solid phase ratio at 20.5% solidification,(c) solid phase ratio at 52.5% solidification, (d) solid phase ratio at 72.1% solidification.

Figure 10 shows the solid phase ratio during the filling process under vertical pouring from the inner bottom. In the initial stage, the temperature in some locations away from the pouring system is lower than the liquidus temperature will begin to solidify first. When the molten metal was filled to 50.4%, the solid phase ratio reached 2.1%, as shown inFigure 10 a, and achieved a solid phase ratio of 10.5% at filling 70.5%, as shownFigure 10 b. Several areas are far away from the heat source, the liquid metal temperature drops there, the fluidity of molten metal is poor, the molten metal front is not easily supplemented by subsequent molten metal during the solidification process, resulting in appearance of external non-filling defects, as shownFigure 10 d and e. Another explanation for these external defects (Figure 10 e) is that since the entire filling process in foam lost casting is conducted under negative pressure, molten metal will preferentially spread along the cavity wall rather than the horizontal liquid level rising. This results in the cavity wall to be filled when the filling process is complete, but the interior may still be empty or even insufficiently poured areas.

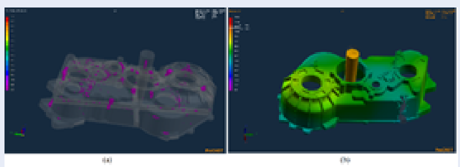

Figure 11: a) Distribution ofshrinkage porosity, (b) Temperature field at fill time

Figure 11a shows the distribution of shrinkage porosity inside the casting during crystallization under vertical pouring from the inner bottom. The shrinkage porosity defect is concentrated on the upper and lower flanges of gear box housing and a few defects on the corner of the reinforcing ribs and a few defects at the thicker wall of casting. The shrinkage porosity is concentrated at about 13%. The temperature field distribution inside is uniform, so it will limit the generation of thermal stress during the crystallization process, as shown inFigure 11 b. It is an undesirable pouring method.

Analysis of vertical pouring from the top

Figure 12 shows the temperature field variation during the filling of the vertical pouring casting from the top. This is a top-down pouring process, and the metal enters the mold cavity by four locations, so it has the advantage of filling due to the gravity of the liquid metal, so the filling process takes place quickly compared to other cases. In the first stage as inFigure 12 a and b, the filling process takes place a bit slowly due to the proximity of the heat source, so the gaseous products decompose a lot, this stage the gas exit direction is opposite to the filling direction of the liquid metal.Figure 12 c and d show that the mold filling capacity is significantly increased due to the greater amount of liquid metal and gas generated by gravity escaping through the mold wall. The deeper the liquid metal, the further away from the source, the melting temperature of the liquid metal decreases and some of the liquid metal loses heat due to the pyrolysis reaction, so the filling process slows down a bit as shown inFigure 12 (e-d).

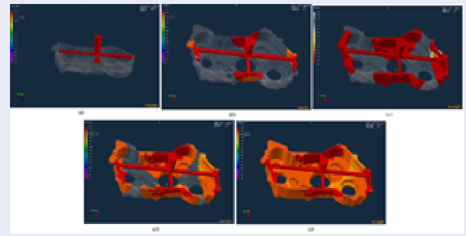

Figure 12: Temperature field during filling process of vertical pouring from thetop: (a) t = 0.3046s, filling = 10.8%; (b) t = 0.8714s, filling = 20.3%; (c) t= 1.4451s, filling = 50.7%; (d) t = 2.0147s, filling = 70.6%; (e) t = 2.8185s,filling = 98%

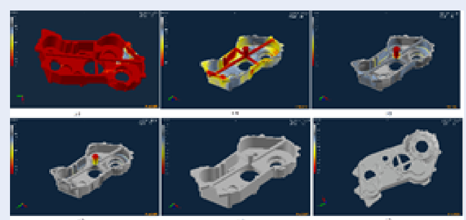

Figure 13: Solid phase ratioduring solidification process of vertical pouring from the top: (a) solid phaseratio at 1.6% solidification, (b) solid phase ratio at 21.3% solidification,(c) solid phase ratio at 50.2% solidification, (d) solid phase ratio at 70.7% solidification

Figure 13 shows the proportion of solid phases formed during crystallization.Figure 13 a, b show that the position of the bottom of the casting far from the base of the pouring tube will crystallize first at this position, the liquid metal is far from the pouring system and rapidly heats up through the mold. FromFigure 13c, and d, we see that the stable crystallization process in the direction from the bottom to the top takes place quickly about sixties, the rate of solid phase crystallization increases to more than 20%. The end of crystallization has almost no defects in the outer and inner surfaces of the casting as shown in Figure 13 e and f.
Figure 14 a shows the distribution of shrinkage and porosity inside the casting during crystallization, most of them distributed along the mold wall at the

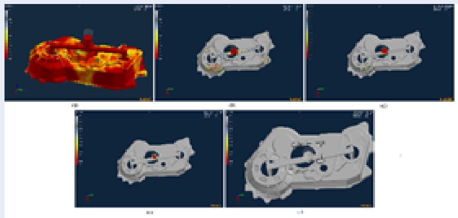

Figure 16: Solid phase ratioduring solidification process of horizontal pouring from the inner bottom: (a)solid phase ratio at 5.2% solidification, (b) solid phase ratio at 51.6% solidification,(c) solid phase ratio at 70.8% solidification, (d) solid phase ratio at 90,9%solidification, (e) solid phase ratio at 100% solidification.

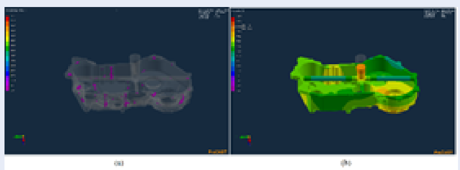

Figure 14: (a) Distribution of shrinkage porosity,(b) Temperature field at fill time

intersection of the two flows from the metal channels due to the eddy currents. or decomposition gas concentration, without the addition of liquid metal and in the thick-walled location of the casting. But the number of shrinkage pits is much lower than in the other two pouring cases.Figure 14 b shows that the distribution of the temperature field when fully filled is even among the values on the casting, so it also limits the occurrence of heat stress when crystallizing.

Analysis of horizontal pouring from the inner bottom

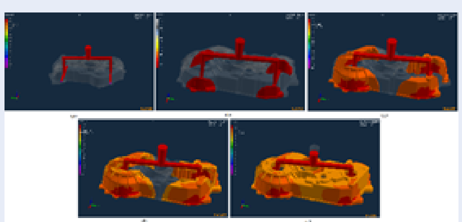

Figure 15: Temperature field during filling processof horizontal pouring from the inner bottom: (a) t = 0.3649s, filling = 12.5%;(b) t = 0.6910s, filling = 21.6%; (c) t = 1.4808s, filling = 50.5%; (d) t =2.0818s, filling = 70.9%; (e) t = 2.9197s, filling = 98%

As per Figure Figure 15 and Figure 16, the obtained result is fairly like the vertical pouring from the top. The only difference is the mass of the pouring system in this setup is heavier than the previous.

CONCLUSIONS

From the results obtained from the simulation on Procast software, we see that the vertical pouring system from the top (Figure 3 c) and the horizontal pouring system from the bottom inside (Figure 3 d) have the best casting surface quality. There is almost no surface defect formation nor complete filling as the two filling systems from the outer bottom (Figure 3 a) and the vertical filling system from the inner bottom (Figure 3 b). The clear distribution of shrinkage and porosity of the top-down vertical filling system is much less than that of other filling systems. Therefore, the top-down vertical pouring system is considered as an optimal choice for casting gearbox housing parts.

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COMPETING INTERESTS

The authors declare that they have no conflicts of interest with respect to the research, authorship, and/or publication of this article.

AUTHORS' CONTRIBUTIONS

Duong Le Hung: Conceptualization, methodology design, ProCAST simulation setup, data analysis, original draft preparation, Literature review, experimental parameter determination, cross-checking analytical equations, and final proofreading.
Le Van An: Supervision, validation of simulation results, manuscript review and editing.
Bui Chan Thanh: CAD modelling, mesh generation, boundary-condition specification, and result visualization.
Trinh Thai Hung: Development of gating system configurations, interpretation of defect prediction outputs, and critical revision of intellectual content.

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Ứng dụng phương pháp đúc mẫu hóa khí nhằm nâng cao chất lượng bề mặt sản phẩm đúc

Dương Lê Hùng*, Lê Văn An, Bùi Chấn Thạnh, Trịnh Thái Hưng

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TÓM TẮT

Vỏ hộp số là một chi tiết lớn và có hình dạng hình học phức tạp, dễ gặp phải các khuyết tật phổ biến trong quá trình đúc mẫu xốp (Lost Foam Casting - LFC) như: điền đầy không hoàn chỉnh, co ngót, và rỗ khí. Những khuyết tật này không chỉ làm giảm độ bền cơ học và chất lượng bề mặt của sản phẩm đúc mà còn làm tăng đáng kể thời gian sản xuất, chi phí vật liệu và tiêu hao năng lượng do phải tiến hành nhiều lần đúc thử nghiệm. Do đó, việc áp dụng các kỹ thuật mô phỏng số tiên tiến là cần thiết nhằm tối ưu hóa quy trình sản xuất, nâng cao chất lượng và hiệu suất đúc, đồng thời giảm thiểu tác động đến môi trường.

Nghiên cứu này sử dụng phương pháp mô phỏng số để dự đoán quá trình điền đầy và các khuyết tật có thể xảy ra khi áp dụng các cấu hình hệ thống rót khác nhau. Bằng cách phân tích và so sánh một cách hệ thống nhiều phương án bố trí hệ thống rót, mục tiêu là xác định được cấu hình hiệu quả nhất, đảm bảo điền đầy khuôn hoàn chỉnh, hạn chế tối đa khuyết tật, giảm lượng vật liệu thừa, và duy trì tốc độ đúc ổn định, kiểm soát tốt. Công tác mô phỏng được thực hiện bằng phần mềm ProCAST Visual-Cast 17.4, một công cụ mạnh mẽ trong việc mô phỏng các hiện tượng phức tạp của quá trình đúc như dòng chảy kim loại lỏng, truyền nhiệt, quá trình đông đặc và sự hình thành khuyết tật.

Nhiều phương án bố trí hệ thống rót đã được xây dựng và đánh giá, với các tiêu chí chính bao gồm: thời gian điền đầy, phân bố nhiệt độ, dự đoán khuyết tật (như co ngót, rỗ khí, và bẫy khí) và hành vi dòng chảy trong quá trình điền khuôn. Kết quả mô phỏng được kiểm chứng chéo với các phương pháp phân tích lý thuyết và dữ liệu thực nghiệm nhằm đảm bảo độ tin cậy và độ chính xác cao. Thông qua phân tích toàn diện này, nghiên cứu đã xác định được thiết kế hệ thống rót tối ưu, đáp ứng các tiêu chuẩn công nghiệp về chất lượng và độ chính xác kích thước. Các kết quả thu được mang lại những hiểu biết quan trọng trong việc thiết kế quy trình đúc mẫu xốp hiệu quả, tiết kiệm chi phí và thân thiện với môi trường cho các chi tiết lớn, có hình dạng phức tạp như vỏ hộp số máy kéo.

Từ khoá: LFC, đúc mẫu xốp, tối ưu hóa quá trình đúc, Procast, Phân tích số

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