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Optimization of Aluminum Casting Process Using PLA-Based Casting Patterns and Analysis of their Thermal Behavior

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ABSTRACT

This paper presents the results of experimental and numerical studies of the casting process of 99.85% pure aluminum using investment-casting technologies with patterns produced by additive manufacturing. The influence of pouring temperature, mold-filling time, and gating-system design on porosity formation and casting quality was analyzed. It was established that increasing the pouring temperature within the range of 700–800°C leads to increased porosity due to higher gas solubility and intensified turbulence of the melt flow. It was shown that the separating gating system ensures a minimum number of defects compared to top and bottom metal-feeding systems. In addition, thermal analysis of PLA and a glass-fiber-reinforced PLA composite was carried out. Pure PLA was found to burn out almost completely (residue about 2.4%), whereas the composite was characterized by a high residual content (~43.6%), which may negatively affect mold quality. The simulation results obtained using the AutoCAST software package showed good agreement with the experimental data and confirmed the effectiveness of numerical modeling for optimization of casting processes. It was established that the optimal pouring-temperature range for aluminum is 720–760°C. The obtained results confirm the potential of using PLA in investment casting technology and make it possible to improve the quality of aluminum castings under industrial production conditions.

Keywords: 3D printing, investment casting, aluminum alloys, additive manufacturing, industrial manufacturing, innovative manufacturing processes.

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Introduction

Porosity is one of the most critical defects in foundry production, significantly affecting the mechanical properties, tightness and fatigue life of aluminum castings [[1, [2], [3]]. The main mechanisms of pore formation are gas saturation of the melt and shrinkage processes during solidification [[4], [5], [6]]. Aluminum alloys are characterized by high solubility of hydrogen in the liquid state and a sharp decrease in its solubility upon transition to the solid phase, which leads to intense gas evolution and the formation of gas porosity [[7], [8]]. Additional factors that influence the formation of defects include flow turbulence, air entrainment during pouring, and inefficient operation of the gating system, which can lead to the formation of oxide films and inclusions [[2] [9], [10]]. As noted in the works of Campbell [2] and Stefanescu [10], disruption of flow laminarity promotes the capture of double oxide films (bifilms), which are potential centers for the initiation of pores and cracks. Shrinkage porosity develops due to insufficient compensation for volumetric shrinkage, which is approximately 6% for aluminum, and is directly dependent on the efficiency of feeders and directional solidification [[5], [11]]. According to classic research by Flemings [11], the formation of shrinkage defects is determined by local temperature gradients and casting feeding conditions. Therefore, optimizing the design of gating and feeding systems is a key factor in improving casting quality [[12], [13]]. Modern research confirms that the use of numerical modeling allows for the effective prediction of defect formation zones and optimization of process parameters prior to conducting actual experiments [[6], [12], [14]]. The use of software packages such as Auto-CAST improves the accuracy of casting process design and reduces production costs [[6], [14]]. Modern methods for reducing porosity include optimization of gating systems, melt degassing, and the use of numerical modeling [[9], [10], [11]]. In particular, the use of modified gating system designs (bottom, top, and divider) allows for controlling the nature of the melt flow and minimizing turbulence, which reduces the likelihood of air entrainment and oxide film formation [[2], [9], [15]]. Effective degassing is achieved by using fluorine- and chlorine-containing salt fluxes, as well as inert gas bubbling methods (Ar, N_2), which ensure the removal of dissolved hydrogen through diffusion and coalescence of gas bubbles [[7], [16], [17]]. Additionally, filtration systems (ceramic filters) are used to remove non-metallic inclusions and stabilize the melt flow [[18], [19]]. The use of numerical modeling allows for considering the thermal, hydrodynamic, and phase processes occurring during casting [[12], [13], [14]]. Software packages such as Auto-CAST, ProCAST, and MAGMASoft predict temperature distribution, flow rates, shrinkage zones, and potential porosity regions, enabling optimization of gating system design and pouring modes at the design stage [[6], [12], [20]]. The use of defect formation criteria, such as the Niyama criterion, further improves the accuracy of shrinkage porosity prediction and enables evaluation of casting quality at the early stages of development [[21], [22]]. In recent years, particular attention has been paid to the integration of digital modeling, additive technologies, and intelligent defect prediction methods. Current research shows that the use of integrated thermohydrodynamic modeling and digital analysis methods can significantly improve the accuracy of porosity prediction and reduce the number of production tests [[23], [24], [25]]. In addition, the effect of additively manufactured polymer models on the quality of cast parts is being actively studied, including the thermal degradation characteristics of PLA composites, their gas evolution, and the formation of a residual phase.

Studies demonstrate the effectiveness of integrating modeling methods with experimental data and machine learning approaches, which allows for the consideration of real production factors and increases the reliability of predictions [[23], [24], [25]]. Thus, the integrated use of degassing, rational design of gating systems, and digital modeling is the most effective approach to reducing porosity and improving the quality of aluminum castings. With the development of additive technologies, the use of polymer models for investment casting is of particular interest, allowing for a significant increase in accuracy and a reduction in the cost of manufacturing complex-shaped castings [[15], [16]]. In particular, FDM and SLA technologies provide high-precision prototypes with specified geometry and controlled surface roughness [[23], [24]]. PLA (polylactide) is widely used due to its biodegradability, low processing temperature, and ability to undergo almost complete thermal decomposition without the formation of significant residues [[17], [18], [19]]. Thermal destruction of PLA occurs primarily through the depolymerization mechanism with the rupture of ether bonds and the formation of volatile products, which makes this material promising for casting using burnt models [[18], [25]]. The thermodynamic approach demonstrates that both in sulfurizing roasting of Pb–Zn ores and in aluminum alloy casting, the controlling factor is the regulation of phase transformations through changes in gas atmosphere and temperature, which ultimately governs the formation of material structure and defect development [[26], [27]]. The obtained results indicate that the use of 3D-printed PLA models in aluminum investment casting is associated with a significant influence of polymer thermal decomposition, the mold–pattern interface, and heat and mass transfer conditions on defect formation, including porosity, which requires consideration of material anisotropy, gas evolution behavior, and thermal processing regimes to improve the accuracy and quality of cast products [28].

However, the introduction of composite materials such as glass fiber-reinforced PLA requires further analysis, since the presence of an inorganic phase significantly alters the mechanism of thermal degradation and heat and mass transfer [[20], [21], [22]]. In particular, glass fiber increases thermal stability and shifts the temperature maxima of decomposition, but simultaneously leads to the formation of a residual phase that can impede the removal of decomposition products, impair the gas permeability of the mold, and contribute to the formation of casting defects [[21], [22]]. Furthermore, the interaction of the polymer matrix with the surface of the reinforcing fibers can lead to multistage decomposition kinetics and changes in gas evolution [20].

Despite numerous studies devoted to reducing the porosity of aluminum castings and the use of PLA patterns in investment casting, the complex relationships between pouring parameters, gating system design, thermal degradation of PLA composites, and defect formation remain poorly understood. Most existing studies examine either the hydrodynamic properties of the mold filling process or the thermal behavior of polymer patterns separately. However, the influence of residual PLA composite mass on the quality of aluminum castings and the mechanisms of defect formation have not been fully explored.

The scientific novelty of this study lies in the comprehensive combination of experimental research and numerical modeling of the aluminum casting process using additively manufactured PLA models of varying compositions. This study, for the first time, combinedly evaluates the influence of pouring temperature, gating system design, and the thermal behavior of PLA/PLA composites on the formation of porosity in aluminum castings. Additionally, a relationship was established between the high residual mass of the PLA composite, the characteristics of outgassing during thermal degradation, and the likelihood of defect formation in the cast structure. The obtained results allow us to expand our understanding of defect formation mechanisms and substantiate the selection of optimal materials and process modes for investment casting.

The aim of this study is to comprehensively investigate the influence of process parameters (pouring temperature, pouring time, and gating system design) on the porosity of aluminum castings, as well as to evaluate the thermal behavior of PLA and PLA composite materials for their applicability in investment casting technologies. Particular attention is paid to the relationship between the mechanisms of thermal degradation of polymer patterns and defect formation in metal castings, which allows for the substantiation of the selection of optimal materials and process conditions.

Materials and Methods

Experiments and Casting Simulation

Experimental and numerical studies of the casting process of high-purity aluminum (99.85%) were carried out to analyze porosity formation and optimize technological parameters. Numerical simulation was performed using the Auto-CAST software package, which makes it possible to predict temperature-field distribution, melt-flow velocity, and zones of probable defect formation.

During the study, the main technological parameters of the process were varied, including pouring time, melt temperature, and the design of the gating-feeding system. The pouring time for different types of gating systems was as follows: 12.5 s for the bottom system, 8.5 s for the separating system, and 5 s for the top system, which ensured different melt-flow patterns—from predominantly laminar to turbulent regimes. The geometric parameters of the sprues included diameters of 14 mm and 10 mm with lengths from 50 to 80 mm, which made it possible to regulate the flow rate and the hydrodynamic conditions of mold filling. The dimensions of the ingates were 10×12×15 mm, and those of the runners were 8×10×65 mm and 8×10×90 mm, respectively, ensuring uniform melt distribution and a reduction in local turbulent zones. The experimental conditions were further refined to ensure the reproducibility of the study. High-purity aluminum (99.85%) was used, and the melt was prepared in an electric resistance furnace. Before pouring, the melt was degassed to reduce the dissolved hydrogen content and decrease the likelihood of gas porosity. A sand-clay mold with controlled gas permeability and moisture content was used as the casting mold, providing stable heat-removal and solidification conditions. Temperature control was carried out using thermocouples and a digital data-recording system.

Table 1 - Design parameters and their calculated values for the feeding and gating systems.

No.	Parameter	Design value
1	Pouring time for the bottom, separating, and top gating systems	12.5 s, 8.5 s, and 5 s, respectively
2	Top and bottom sprue diameter and sprue length for the separating and top gating systems	14 mm, 10 mm, and 50 mm, respectively
3	Top and bottom sprue diameter and sprue length for the bottom gating system	14 mm, 10 mm, and 80 mm, respectively
4	Sprue: diameter and height	15 mm and 20 mm, respectively
5	Runner dimensions: width, height, and length for the separating gate system	8 mm, 10 mm, and 65 mm, respectively
6	Runner dimensions: width, height, and length for the bottom gate system	8 mm, 10 mm, and 90 mm, respectively
7	Ingate dimensions: width, height, and length for the top, separating, and bottom gating systems	10 mm, 12 mm, and 15 mm, respectively
8	Feeder design based on Caine's method; feeder diameter and height for the bottom and separating gating systems	25 mm and 25 mm, respectively
9	Height and diameter of the feeder neck for the bottom and separating gating systems	10 mm and 20 mm, respectively

In addition, the design of the riser (sprue) with a diameter of 15 mm and a height of 20 mm was optimized to ensure stable melt supply and reduce the likelihood of air entrainment. The feeding system was designed based on Caine's method, taking into account the formation of directional solidification; the feeder dimensions were 25×25 mm and the neck dimensions were 10×20 mm, which ensured effective compensation of shrinkage processes. Particular attention was paid to the placement of the feeder in the zone of maximum thermal concentration (hot spot), which contributed to a reduction in shrinkage porosity.

The choice of these parameters was dictated by the need to ensure an optimal balance between mold-filling rate, reduced flow turbulence, and effective feeding of the casting during solidification, which together are aimed at minimizing gas and shrinkage porosity. This is shown in Table 1.

The feeding system was designed with consideration for compensating the volumetric shrinkage of aluminum, which is about 6% during solidification. The feeder dimensions were 25×25 mm, which provided sufficient volume to feed the casting and prevent shrinkage defects. The system design was optimized using simulation results, including hot-spot analysis and directional solidification.

Analysis of the influence of gating-system type showed that when a bottom gate is used, the molten metal enters the lower part of the mold, ensuring a predominantly laminar flow regime and minimizing air entrainment; however, the mold-filling time increases. It was established that as the pouring temperature increases in the range of 700–800°C, a steady growth in porosity is observed, as clearly shown in Fig. 1. This effect is caused by the increased solubility of gases in the aluminum melt at higher temperatures, as well as by the decrease in viscosity, which leads to intensified turbulence and the entrainment of gaseous inclusions. According to the simulation results, porosity increases approximately from 960 to 1120 mm^3, whereas the experimental values change from 1030 to 1250 mm^3, indicating a higher level of defect formation under real conditions due to the influence of technological factors such as flow turbulence, air entrainment, mold gas permeability, and the limited efficiency of degassing. At the same time, the trends of the Simulation and Experimental dependencies coincide, which confirms the adequacy of the Auto-CAST model despite the presence of a quantitative discrepancy of about 50–130 mm^3 associated with the idealization of the calculation conditions. It was established that in the range of 700–740°C the increase in porosity is moderate, whereas at temperatures above 740–780°C a sharp increase in defect formation is observed, indicating the achievement of a critical temperature interval.

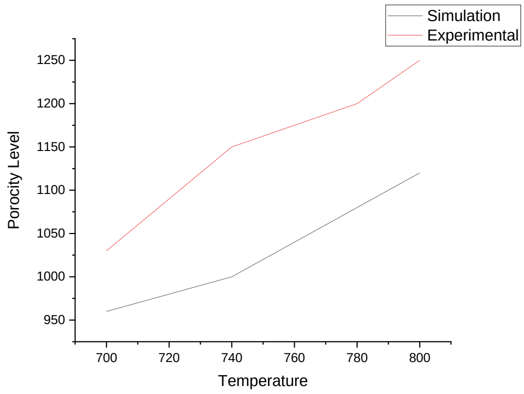


Fig. 1 - Change in porosity as a function of pouring temperature

When a top gating system is used (Fig. 2), the mold is filled in the minimum time; however, due to the free fall of the melt, a turbulent flow regime is formed, which leads to an increase in gas and shrinkage porosity. In this case, porosity increases from 1040 to 1300 mm³ according to simulation results and from 1180 to 1460 mm³ according to experimental data. The increased defect level is caused by intensified turbulence, air entrainment, and the formation of oxide films that serve as pore nucleation sites. A particularly intensive increase in porosity is observed in the range of 780–800°C, which indicates the critical influence of temperature on defect-formation processes.

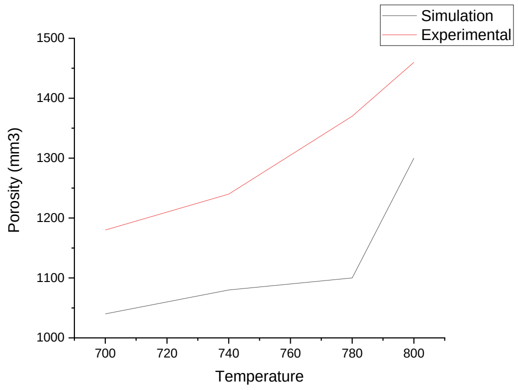


Fig. 2. Change in porosity as a function of pouring temperature

The separating gating system (Fig. 3) proved to be the most effective from the standpoint of minimizing porosity, combining the advantages of bottom and top melt supply. In this system, the sprue and gate are located in the same plane, which ensures an optimal temperature gradient and directional solidification. This promotes the transfer of the shrinkage cavity from the casting volume into the feeder and reduces the probability of defect formation. The analysis showed that porosity increases from 1030 to 1250 mm³ (simulation) and from 1090 to 1420 mm³ (experiment), while the lowest level of defect formation among all considered systems is observed. Similar to the other cases, a sharp increase in porosity is recorded at temperatures above 780°C, which is associated with intensified gas saturation and deterioration of solidification conditions.

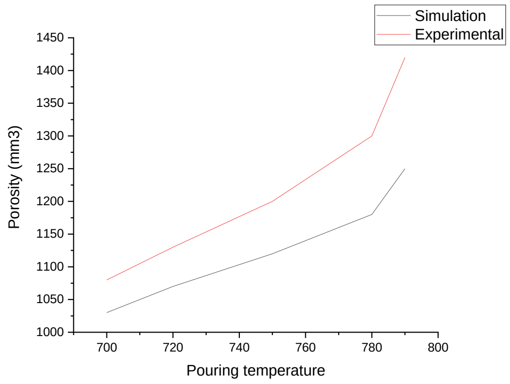
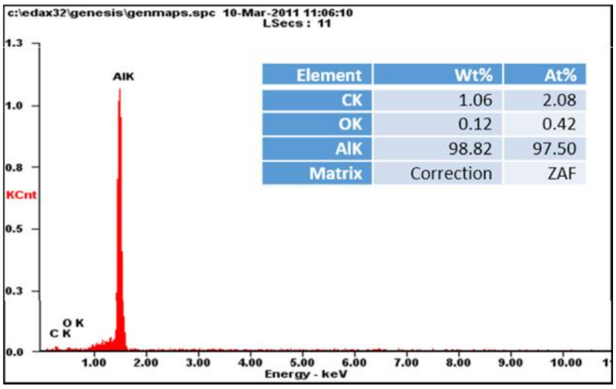


Fig. 3 - Change in porosity as a function of pouring temperature

In addition to the macroscopic analysis of porosity, a microstructural analysis of the samples was carried out using optical metallography methods. The investigations were performed on polished sections prepared by standard methods of mechanical polishing and chemical etching. The microstructural analysis made it possible to reveal the distribution of pores, the nature of the dendritic structure, and the localization of defects depending on the pouring temperature and the type of gating system. The obtained microstructural images further confirmed the results of numerical modeling and experimental porosity analysis. The obtained results demonstrate that the pouring temperature and the type of gating system have a decisive influence on the formation of porosity in aluminum castings. The optimal choice is the use of a separating gating system in combination with a controlled temperature regime (not higher than ~740–760°C), which ensures the minimization of turbulence, effective feeding of the casting, and a reduction in gas and shrinkage defects.

Energy-Dispersive Spectroscopy (EDS) Analysis

The chemical composition of the cast aluminum was determined by energy-dispersive spectroscopy (EDS), the results of which are presented in Fig. 4. It was established that the main phase is aluminum, while impurities of carbon and oxygen are also detected in the samples, which may be associated with oxidation processes and the interaction of the melt with the surrounding environment.



Element	Wt%	At%
CK	1.06	2.08
OK	0.12	0.42
AlK	98.82	97.50
Matrix	Correction	ZAF

Fig. 4 - EDS analysis of cast aluminum

An increased oxygen content in certain local areas may indicate the formation of Al_2O_3 oxide inclusions, which can act as nucleation centers for gas pores. From a physical point of view, porosity formation is associated with a decrease in gas solubility in the aluminum melt during crystallization and with the local accumulation of gaseous products of thermal degradation of the PLA pattern. During solidification, diffusive release of dissolved hydrogen occurs, as well as restricted removal of gases through the mold, which leads to the formation of closed pores.

The following relationship was used for quantitative evaluation of porosity:

$$P = \left(1 - \frac{V_p}{V_S}\right) 100\%$$

where is the sample volume, is the dense volume, M is the sample mass, and ρ is the material density.

The dense volume was determined by the expression:

$$V_p = \frac{M}{p}$$

The obtained experimental porosity values were compared with the results of numerical simulation. The average discrepancy between the experimental and calculated data was less than 8%, which indicates satisfactory adequacy of the model used. To increase the reliability of the results, measurements were carried out on at least three samples for each casting mode, after which the mean values and standard deviations were calculated. The error in porosity determination did not exceed ±2%.

The combination of macro- and microstructural analysis methods, energy-dispersive spectroscopy, and experimental determination of porosity made it possible to comprehensively assess the influence of technological parameters on defect formation in aluminum castings.

Thermal Analysis of PLA and PLA Composite

Thermogravimetric analysis (TGA), as well as derivative curves (DTG) and differential thermal analysis (DTA), were used to evaluate the thermal behavior of PLA-based materials employed in additive manufacturing. The results for pure PLA and for the PLA composite reinforced with glass fiber are presented in Figures 5 and 6.

As can be seen from Fig. 5, pure PLA demonstrates characteristic single-stage thermal degradation. In the temperature range up to 300 °C, the mass of the sample remains almost unchanged, which indicates the absence of moisture and volatile components. The main decomposition stage occurs in the interval of 320–380 °C, with a maximum degradation rate around 360 °C. In this range, intensive depolymerization is observed with rupture of ether bonds and release of gaseous products. The total mass loss is about 95–98%, and the residual mass does not exceed ~2.4% at 1000 °C (Fig. 5), which indicates almost complete burnout of the material.

From the standpoint of the casting process, the intensive release of volatile products in the range of 320–380 °C is accompanied by the formation of a gaseous environment inside the mold. If the mold has sufficient gas permeability, the degradation products are effectively removed, which reduces the probability of defect formation. The low residual mass of pure PLA indicates almost complete burnout of the pattern and a minimal probability of forming solid residues in the mold cavity. This contributes to obtaining a more homogeneous structure of aluminum castings and reduces the risk of gas porosity formation. In addition, the EDS analysis results show that in castings obtained using pure PLA, the oxygen and carbon contents are minimal, which indicates more complete removal of thermal degradation products and a lower probability of secondary oxidation of the melt during casting.

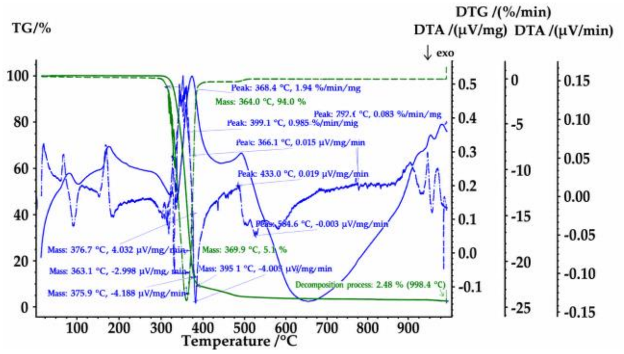


Figure 5 - TGA, DTG, and DTA curves for pure PLA material used in additive manufacturing, demonstrating single-stage thermal degradation and almost complete mass loss

From the standpoint of physicochemical processes, the intensive release of volatile products in the interval of 320–380 °C can lead to a local increase in gas pressure inside the mold. If the molding material has insufficient gas permeability, this contributes to the formation of gas porosity in the casting. Thus, the temperature range of the maximum PLA degradation rate is a critically important parameter when selecting pattern burnout modes.

In contrast, the glass-fiber-reinforced PLA composite (Fig. 6) demonstrates more complex thermal behavior. Up to 300 °C, no significant changes in mass are observed, which indicates system stability. The main decomposition stage is shifted to a higher temperature range of 350–420 °C, with a characteristic maximum around 410 °C, which is associated with the influence of the reinforcing inorganic phase. The presence of several peaks on the DTG and DTA curves (≈367 °C, 431 °C, 490 °C, and 541 °C) indicates a multistage degradation mechanism caused by the interaction of the decomposition products of the polymer matrix with the glass-fiber surface. The key difference is the significant increase in residual mass, which amounts to about 43.61% at 1000 °C, due to the presence of thermally stable glass fiber. This indicates that the material is not subject to complete burnout, unlike pure PLA. The high residual mass of the PLA composite has a direct effect on the quality of aluminum castings. Incomplete burnout of the composite material leads to the accumulation of residual inorganic particles inside the casting mold, which worsens the gas permeability of the molding system and hinders the removal of thermal degradation products. As a result, a local increase in gas pressure occurs in the mold cavity, promoting the formation of gas porosity and surface defects in the castings. Residual glass-fiber particles can become centers of local disturbance of the crystallization of the aluminum melt. This leads to the formation of microdefects, an increase in the number of non-metallic inclusions, and a decrease in the structural homogeneity of the material. The presence of such inclusions worsens surface quality and can reduce the mechanical properties of the finished products.

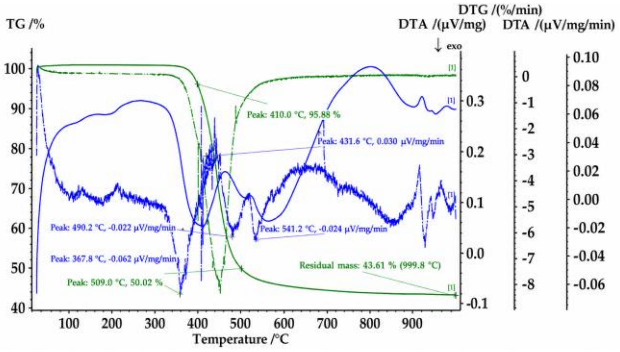


Figure 6 - TGA, DTG, and DTA curves for a PLA-based composite reinforced with glass fiber, demonstrating the multistage nature of thermal decomposition and a high residual mass (~43.6%) caused by the presence of an inorganic phase

A comparison of the thermal curves shows that the addition of glass fiber leads not only to increased thermal resistance but also to a longer duration of gaseous-product release. This may explain the increased probability of defect formation during casting, since more prolonged thermal degradation is accompanied by gas accumulation in the interfacial regions of the mold. In addition, the presence of a residual inorganic phase can worsen the removal of decomposition products and lead to local inclusions in the casting structure. The EDS analysis results confirm this assumption. In samples produced using the PLA composite, an increased content of oxygen and carbon is recorded, which may be associated with residual thermal decomposition products and local oxidation of the melt. This indicates insufficiently complete removal of the burnout products of the composite material and confirms the direct relationship between the high residual mass of the PLA composite and the deterioration in the quality of cast products.

A comparative analysis shows that the addition of glass fiber leads to increased thermal resistance and a shift in the temperature maxima of decomposition; however, it is accompanied by an increase in residual content and a more complex thermal-degradation mechanism. This is important for investment-casting processes: while pure PLA ensures complete material removal without the formation of significant residues, the composite material can lead to the accumulation of inorganic phases and the formation of defects in the casting mold.

To increase the reliability of the thermal analysis, all tests were performed in triplicate. The temperatures of the maximum decomposition rate were determined as average values, and the variation in the results did not exceed ±5 °C. The obtained data demonstrate good reproducibility of the experimental measurements and agrees with the results of numerical modeling of thermal-degradation processes.

Thus, the results of the thermal analysis (Figs. 5 and 6) confirm that pure PLA is a preferable material for investment-casting technologies, whereas PLA composites require additional optimization of burnout modes, including higher temperature and improved conditions for the removal of decomposition products.

Conclusion

As a result of the experimental and numerical studies of the casting process of aluminum with a purity of 99.85% using investment-casting technology, the following main conclusions were established: the pouring temperature is a key parameter determining the level of porosity of castings. As the temperature increases in the range of 700–800°C, a steady increase in porosity is observed due to the increased solubility of gases in the melt and intensified flow turbulence. It is shown that the experimental porosity values (≈1030–1250 mm^3) systematically exceed the simulation results (≈960–1120 mm^3) by 50–130 mm^3, which is caused by the influence of real production factors such as air entrainment, instability of thermal conditions, and the limited efficiency of degassing. It was established that the type of gating-feeding system has a significant influence on defect formation. The lowest level of porosity is achieved when a separating gating system is used, providing directional solidification and an optimal thermal gradient. When a top gating system is applied, the maximum level of porosity is observed due to the turbulent flow regime and the entrainment of gaseous inclusions, whereas the bottom system provides a more stable (laminar) flow but requires increased mold-filling time.

The modeling results obtained using the Auto-CAST software package showed a high degree of qualitative agreement with the experimental data, which confirms the adequacy of the applied model and its effectiveness for the engineering optimization of casting processes. Thermogravimetric analysis showed that pure PLA completely decomposes in the range of 320–380°C with a residual mass of less than 3%, which makes it a promising material for investment casting. At the same time, the glass-fiber-reinforced PLA composite is characterized by multistage decomposition and a high residual mass (~43.6%), which can lead to deterioration of mold quality. It was established that the optimal pouring-temperature range for aluminum should be within 720–760°C, ensuring a compromise between melt fluidity and minimization of porosity. At temperatures above 780°C, a sharp increase in defect formation is observed, which requires strict control of the technological regime. The combination of numerical modeling methods and experimental studies makes it possible to effectively optimize the technological parameters of the casting process and significantly reduce the level of porosity in aluminum castings.

The practical significance of the results obtained lies in the possibility of implementing them under real foundry-production conditions in order to improve the quality of aluminum castings and reduce the amount of scrap. The established optimal pouring-temperature regimes (720–760°C) can be used in the development of process sheets and regulations for investment casting of aluminum alloys. The use of a separating gating-feeding system makes it possible to reduce the probability of gas porosity formation and increase the structural homogeneity of products without a significant increase in production costs.

The study results can also be used in the design of technological processes employing additively manufactured PLA patterns. The use of pure PLA instead of glass-fiber-reinforced PLA composites provides more complete burnout of the pattern and reduces the risk of residual inclusions in the mold. This is especially important for the production of thin-walled and critical parts used in mechanical engineering, the aerospace industry, and the automotive industry. The use of software modeling in the AutoCAST environment makes it possible, at the design stage, to predict zones of probable defect formation, optimize the design of the gating system, and reduce the number of expensive experimental trials. The implementation of such an approach under production conditions contributes to reduced material costs, lower metal consumption, and increased overall technological efficiency of foundry production. The obtained results can serve as a basis for further industrial optimization of investment-casting processes, including automation of temperature-regime control, improvement of degassing systems, and development of new materials for additive casting patterns.

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PLA негізіндегі құю үлгілерін пайдалану арқылы алюминий құю процесін оңтайландыру және олардың термиялық әрекеттерін талдау

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ТҮЙІНДЕМЕ

Мақалада аддитивті өндіріс әдісімен дайындалған балқымалы үлгілер бойынша құю технологиясын қолдана отырып, тазалығы 99,85% алюминийді құю процесінің эксперименттік және сандық зерттеулерінің нәтижелері ұсынылған. Құю температурасының, қалыпты толтыру уақытының және құю жүйесі конструкциясының кеуектіліктің түзілуіне және алынатын құймалардың сапасына әсері талданды. Құю температурасының 700–800°C аралығында жоғарылауы балқымадағы газдардың ерігіштігінің артуына және ағын турбуленттілігінің күшеюіне байланысты кеуектіліктің ұлғаюына әкелетіні анықталды. Металды берудің жоғарғы және төменгі жүйелерімен салыстырғанда, бөлгіш құю жүйесі ақаулардың ең аз мөлшерін қамтамасыз ететіні көрсетілген. Сонымен қатар, PLA және шыны талшық қосылған PLA-композитінің термиялық талдауы жүргізілді. Таза PLA іс жүзінде толық жанып кететіні (қалдық шамамен 2,4%), ал композит жоғары қалдық құрамымен (~43,6%) сипатталатыны анықталды, бұл құю қалыптарының сапасына кері әсер етуі мүмкін. AutoCAST бағдарламалық кешенін пайдалану арқылы алынған модельдеу нәтижелері эксперименттік деректермен жақсы сәйкестік көрсетті және құю процестерін оңтайландыру үшін сандық модельдеудің тиімділігін растады. Алюминийді құюдың оңтайлы температура диапазоны 720–760°C екені анықталды. Алынған нәтижелер балқымалы үлгілер бойынша құю технологиясында PLA қолданудың перспективалы екенін растайды және өнеркәсіптік өндіріс жағдайында алюминий құймаларының сапасын арттыруға мүмкіндік береді.

Түйін сөздер: 3D-басып шығару, балқытылатын үлгілер бойынша құю, алюминий қорытпалары, аддитивті өндіріс, өнеркәсіптік өндіріс, инновациялық өндірістік процестер.

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Оптимизация процесса литья алюминия с использованием литьевых схем на основе PLA-материалов и анализа их термического поведения

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АННОТАЦИЯ

В статье представлены результаты экспериментальных и численных исследований процесса литья алюминия чистотой 99,85% с использованием технологий литья по выплавляемым моделям, изготовленным методом аддитивного производства. Проанализировано влияние температуры заливки, времени заполнения формы и конструкции литниковой системы на образование пористости и качество получаемых отливок. Установлено, что повышение температуры заливки в диапазоне 700–800°C приводит к увеличению пористости вследствие роста растворимости газов и усиления турбулентности потока расплава. Показано, что разделительная литниковая система обеспечивает минимальное количество дефектов по сравнению с верхней и нижней системами подачи металла. Также проведён термический анализ PLA и PLA-композита со стекловолокном. Установлено, что чистый PLA практически полностью выгорает (остаток около 2,4%), тогда как композит характеризуется высоким остаточным содержанием (~43,6%), что может отрицательно влиять на качество литейной формы. Результаты моделирования, полученные с использованием программного комплекса AutoCAST, показали хорошее соответствие экспериментальным данным и подтвердили эффективность численного моделирования для оптимизации литейных процессов. Установлено, что оптимальный диапазон температуры заливки алюминия составляет 720–760°C. Полученные результаты подтверждают перспективность использования PLA в технологии литья по выплавляемым моделям и позволяют повысить качество алюминиевых отливок в условиях промышленного производства.

Keywords: 3D-печать, литье по выплавляемым моделям, алюминиевые сплавы, аддитивное производство, промышленное производство, инновационные производственные процессы.

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