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Research Article

Experimental Analysis of Gating Desing for Rapid Investment Casting of Aluminium Dies

Muhammad Shehbaz [1*] and Muhammad Sajid[1]

[1]*Department of Industrial Engineering, University of Engineering and Technology, Taxila, Pakistan*

(*muhammad.shehbaz@students.uettaxila.edu.pk)

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Abstract – This study examined how three different gating systems impacted the quality of aluminum dies developed through rapid investment casting. Gating System A, which featured a vertical setup with two ingates and effective venting, achieved a surface roughness of 3.2 µm, a minimal dimensional deviation of ±0.4 mm, and the highest hardness value of 35 HRB, demonstrating better performance. It also had the fewest surface defects, displaying an excellent finish with no signs of porosity or cold shut. Gating System C used the bottom fill technique and lacked a top ingate, resulting in moderate outcomes: a surface roughness of 4.5 µm, a dimensional deviation of ±0.8 mm, and a hardness of 31 HRB. Minor defects such as localized shrinkage marks and waviness were observed. Conversely, Gating System B proved to be the least effective, as it used only a top ingate and had improper venting. It had the lowest hardness at 28 HRB, with a surface roughness of 6.5 µm, and the highest dimensional error of ±1.2 mm. It also exhibited many surface defects, including air entrapments, cold shuts, and uneven surfaces caused by turbulent flow and insufficient feeding. These findings underscore the importance of optimizing gating design to achieve desirable mechanical properties, accurate dimensions, and smooth surface finishes in the production of aluminum dies via rapid investment casting.

Keywords – Rapid Investment Casting; Die Development; Aluminum; Gating System; Surface Roughness; Dimensional Accuracy.

I. INTRODUCTION

The foundry industry plays an essential role in the manufacturing industry, particularly when it comes to economic development, especially in those nations whereby caster products such as machinery, automobiles, and industrial components are produced. The advantage of casting techniques is that they have useful applications in the production of complex shapes that are not easily formed through other mediums thus playing a critical role in the current manufacturing sector [1]. Investment casting (IC), also known as the lost-wax method, has become increasingly popular due to its superior surface finish, remarkable precision, and capability to produce complex shapes [2]. Rapid Investment Casting (RIC), which uses 3D printing, especially FDM, to build patterns, is a recent development of investment casting. RIC offers speed, flexibility, and cost savings by doing away with traditional tooling, which lowers production time and costs, making it perfect for prototypes and low-volume aluminum products. Since the early 2000s, additive manufacturing (AM) has made significant strides in producing intricate metal, polymer, and ceramic components. AM-based rapid investment casting is now often used in foundries because it can generate designs fast without the need for tooling [3]. These two are more efficient than traditional methods in regards to material use and complexity, both AM and RIC [4]. Nevertheless, the main issue is defects development in aluminum RIC. Among the common defects are being porous, shrinkage cavities, oxide inclusions, roughness and improper dimensions. Inappropriate selection of gating system designs will exacerbate these problems due to the influence of liquid metal filling and solidification in the mold. Geometry of the gating system plays a role in temperature gradients, turbulence, and metal flow characteristics in the course of the casting process [5], [6].

The affinity of aluminum to oxygen explains very quick growth of oxide layers on the surface of the melt. As gas flows turbulently through the gating system, such oxide layers may be swept up and form double oxide layers resulting in gas porosity, which in turn weakens mechanical integrity [7],[8],[9],[10]. Also, the ingress of hydrogen in aluminum enhances the extent of porosity, particularly in the process of reoxidation [11],[12],[13]. To ensure that defects in casting are minimal, it is important to optimize the design of the gating system to facilitate laminar flow, minimize turbulence and facilitate directional solidification. Naturally pressurized gating system would assist in limiting the amount of reoxidation upon mold filling by ensuring a controlled flow of pressure and thus avoiding trapping of the oxide in the process [14],[15]. The correct gating setup assures proper metal flow, solidification, defect reduction, and yields. On the other hand, poorly developed gating system may lead to turbulence, control shrinkage porosity blistering, hot tears, rough surface, among other defects which indicates the need to effectively gating design [16].

Considering these elements, it is essential to investigate and put into place appropriate gating systems for RIC-based aluminum die production. This paper has conducted an experimental study of three alternatives of gating design used to compare their performances on casting quality. The controlled conditions of developing aluminum die out of each design were used and the castings evaluated in terms of surface defects, surface roughness, dimensional accuracy and hardness. It is aimed at finding that gating system that presents the overall best in terms of result thereby increasing the quality of in-aluminum dies developed through the rapid investment casting. Through the examination of the results, this study offers actionable recommendations for improving rapid investment casting methods in both low-volume and prototype production.

II. MATERIALS AND METHOD

In this research, Rapid Investment Casting (RIC) was employed to produce Aluminum LM30 dies by introducing and assessing three distinct gating systems, identified as systems A, B, and C. The entire manufacturing process, as shown in **Fig. 1**, commenced with a 3D computer-aided design model of the die created in SolidWorks. This CAD model was fabricated using a Prusa 3D printer with PLA filament through the Fused Deposition Modeling (FDM) method. A room-temperature vulcanized (RTV) silicone mold was created utilizing the printed pattern, which then enabled the production of wax patterns. The wax patterns were arranged into wax trees based on the configurations of the three gating systems, with their design specifications provided in **Table 1.** Each wax assembly underwent multiple coatings of ceramic shells through a process involving layers of slurry and stucco. After the shells were cured, dewaxing was performed in a burnout furnace, and the resulting molds were preheated in preparation for pouring the castings. The molten aluminum, made from the LM30 alloy, was poured using gravity casting, and the solidified castings were later extracted through a mechanical method due to the ceramic nature of the mold.

The post-casting operations included cleaning and shot blasting. The aluminum dies produced were subsequently evaluated using the stylus method to assess surface roughness, with dimensions measured using Vernier calipers and micrometers, and hardness tested on the Rockwell HRB scale. The most effective gating solution for die production with RIC was determined by comparing the three gating systems based on the final die surface quality, occurrence of defects, correctness of die dimensional parameters, and mechanical strength.

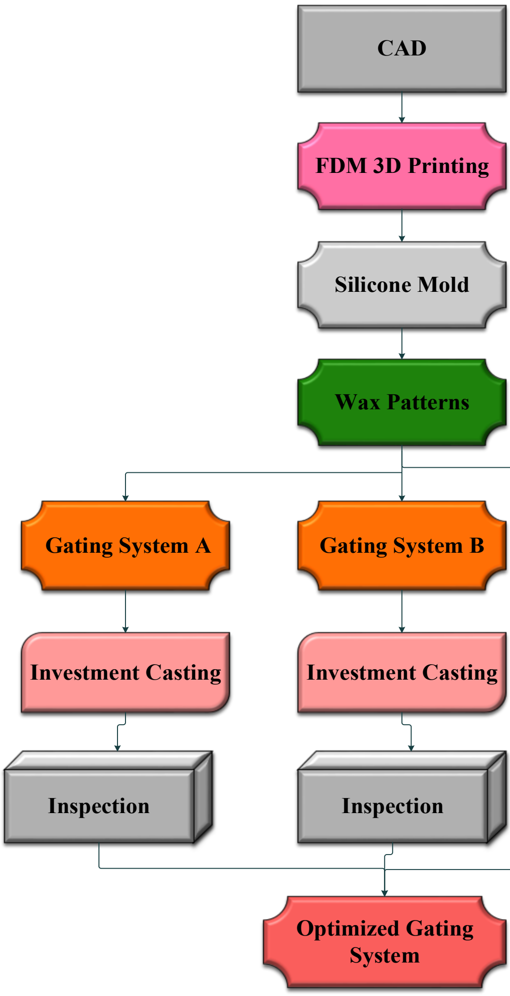

Fig. 1 Process Flow Diagram

Table 1. Gating System Classification

Gating System	Configuration Type	Part Orientation	Key Gating Elements
System A	Vertical, both cope and drag in one tree	Vertical position, cavity side outward	Pouring cup, sprue, top and bottom ingates, renting riser runner, end choke
System B	Radial(Branched wax tree) cope and drag are in different tree	Horizontal position part at bottom, cavity side upward	Pouring cup, 4 vertical wax runner connected to 45° inclined runners
System C	Vertical, both cope and drag in one tree	Vertical position, cavity side outward	Pouring cup, sprue, bottom ingates, renting riser runner, end choke

III. RESULTS AND DISCUSSION

This section will give a comparative account about three gating mechanisms in terms of surface quality, mechanical properties and dimensional accuracy of an aluminum LM30 dies formed using rapid investment casting. The results underline the importance of gating design on overall performance of casting.

The inspection of the aluminum dies cast using rapid investment casting work of three gating systems (Fig 2) revealed a considerable difference in terms of quality of surface finishing and creation of defects. Surface finish with even metal flow, smooth surfaces as well as minimal porosity, or evident defects, was the best in system A. This improved performance is attributable to its well centered sprue and neat gating design, which enhanced laminar flow and reduced turbulence in the steel mold during mold fill. On the contrary, the quality of surface in System B was considerably lower, with the incomplete filling, deep burn marks, as well as significant shrinkage holes. The main cause of these defects was due to high turbulence caused by the stitching and ragged gating design making the flow of molten metal to be altered resulting in premature solidification along with entrapment of air. In addition, defects related to gas were worsened by poor venting. System C produced surfaces of moderate quality but displayed a rough texture with scattered porosity and small blowholes. These complications are associated with an oversized sprue and an unbalanced runner arrangement, which led to uneven flow rates and localized overheating, resulting in trapped gases and inconsistencies during solidification. In summary, the analysis underscores the vital role of gating system design on the integrity of casting surfaces, where a well-optimized and balanced system like System A minimizes turbulence, promotes directional solidification, and ultimately decreases surface defects in aluminum dies.

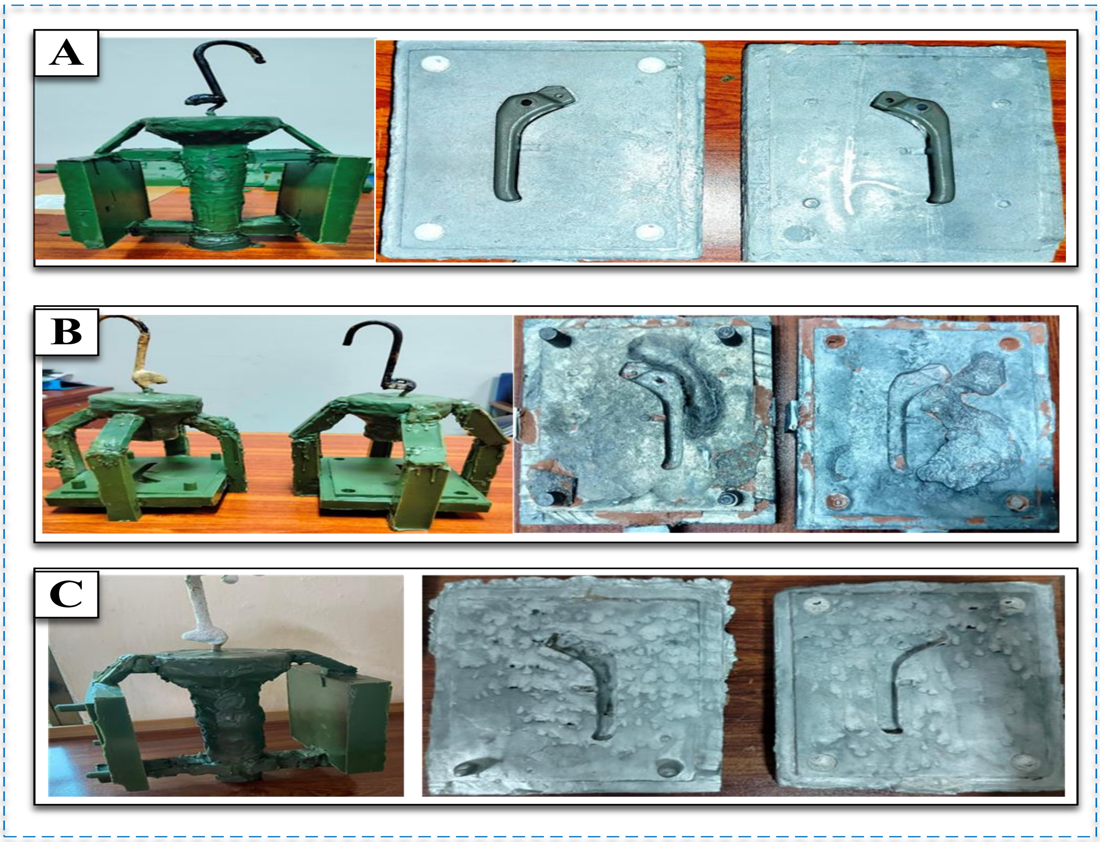

Fig. 2 Gating system Analysis

All three gating design system were evaluated along the surface roughness, hardness and dimensional deviation their results are listed in **Table 2** and graphically shown in **Fig 3**. Gating System A demonstrated superior performance overall, exhibiting the least surface roughness (~3.2 μm) due to its balanced dual ingate design and effective venting system that facilitated laminar flow with minimal turbulence. This configuration also improved dimensional accuracy, as there was reduced shrinkage and minimal trapped air due to even metal flow, resulting in deviations of less than 0.4 mm. The achieved hardness (~35 HRB) was the highest among all systems, primarily due to the finer grain structure stemming from stable thermal gradients and consistent cooling. Conversely, Gating System B yielded the poorest outcomes across all measurable parameters. The uneven metal flow resulting from its single ingate led to turbulence, splashing, and air entrapment, which contributed to increased surface roughness (~6.5 μm), greater dimensional deviations (~1.2 mm), and diminished hardness (~28 HRB) because of internal porosity and coarser grain formation. Gating System C produced moderate quality results, achieving intermediate filling via bottom-top flow with its bottom ingate and vent, leading to a more stable flow and providing an average surface roughness (~4.5 µm), dimensional deviation (~0.8 mm), and hardness (~31 HRB). Although it lacked a top ingate, the addition of a vent offered some relief by allowing gases to escape, thus improving the overall quality of the casting compared to System B.

Table 2. Comparative Values for Surface Roughness, Hardness, and Dimensional Deviation

Gating System	Surface Roughness (µm)	Hardness (HRB)	Dimensional Deviation(mm)
System A	3.2	35	±0.4
System B	6.5	28	±1.2
System C	4.5	31	±0.8

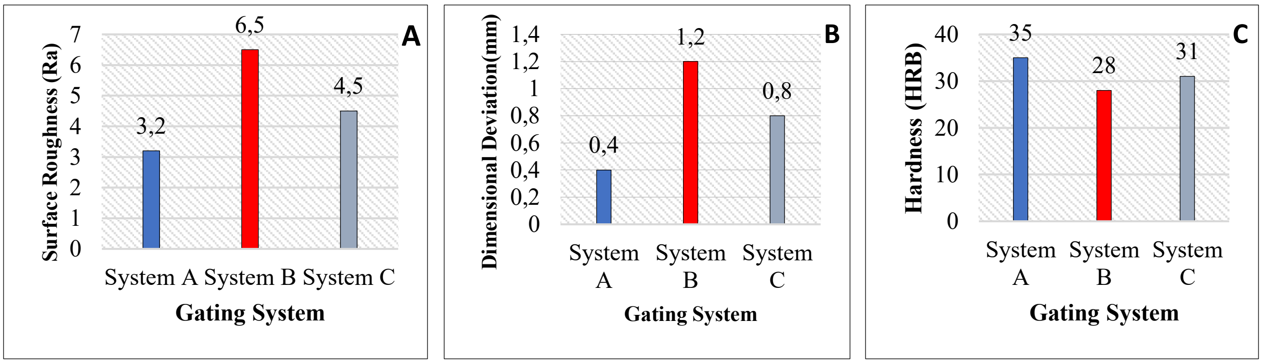

Fig. 3 Comparative Values Plots, (A) Surface Roughness, (B) Hardness, and (C) Dimensional Deviation

IV. CONCLUSION

This study thoroughly examined how three different gating system designs impacted the quality of aluminum dies produced using the rapid investment casting (RIC) process. The research focused on key quality parameters such as surface roughness, dimensional accuracy, hardness, and surface defects. Among all the configurations tested, Gating System A, which included two ingates and top feeding, showed superior performance with minimal dimensional variation (±0.4mm), the lowest surface roughness (Ra = 3.2 µm), and the highest hardness (~35 HRB). Additionally, its optimized molten metal flow and effective venting mechanisms resulted in the fewest casting defects. In contrast, Gating System B produced the poorest results, with the highest surface roughness (Ra= 2.5 µm), the lowest hardness (~28 HRB), and the greatest dimensional deviations (±1.2 mm) due to its single side ingate and inadequate venting. This setup also faced significant issues such as porosity, turbulence-induced holes, and incomplete filling, indicating that this design was not suitable for precision casting. Meanwhile, System C, which used a bottom feeding method, achieved moderate results across all quality indicators because of its controlled upward flow and slower filling rates. Overall, the results clearly show that gating design significantly influences the success of the RIC process. Optimizing gating not only improves mechanical and dimensional properties but also reduces surface defects, decreasing the need for additional processing. These findings can help researchers and professionals develop better, more efficient, and reproducible die production methods through rapid investment casting. The next step in improving gating configurations could involve using computational fluid dynamics (CFD) simulations and techniques for in-process defect detection. These approaches will support fine-tuning gating designs more accurately and predicting casting outcomes.

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