Advances in Science and TecŠology
Research Journal

Advances in Science and Technology Research Journal, 2026, 20(1), 104–120
https://doi.org/10.12913/22998624/210382
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.07.19
Accepted: 2025.09.06
Published: 2025.11.21

A validated framework for the development of low-cost aluminum dies through rapid investment casting

Muhammad Shehbaz[1], Muhammad Sajid[1], Muhammad Asad Ali[1*], Wasim Ahmad[1]

[1] Department of Industrial Engineering, University of Engineering and Technology, Taxila, 47050, Pakistan
* Corresponding author's e-mail: m.asad.ali24@gmail.com

ABSTRACT

The rising demand for agile, economical, and scalable manufacturing has driven the need for innovative approaches in tool and die development. Aluminum has emerged as a promising alternative to traditional die materials due to its low density, excellent castability, thermal conductivity, machinability, and recyclability. This study proposes and validates a structured framework for the development of low-cost aluminum dies using rapid investment casting (RIC). The framework, grounded in an extensive review of existing practices, is implemented through a real-world case study focused on the development of a die for an automotive door handle. A CAD model was designed with a 3%-dimensional tolerance, and the die was fabricated using LM30 aluminum alloy via RIC. The die was then tested using polypropylene (PP) in an injection molding process to evaluate its dimensional accuracy and surface roughness. Results revealed that in contrast to certain features, which exhibited strong dimensional consistency – such as the circle diameter along the large pin, front lengths, and upper slope depth (with deviations within ±0.1 mm to ±0.2 mm) some geometries, particularly sloped features, showed notable discrepancies. Small slope length 1 demonstrated a significant reduction of 0.66 mm during casting, likely due to angular mold erosion or material pullback. Additionally, the small and large mounting pin lengths, handle length, and small slope length 1 recorded the highest dimensional deviations. Despite these variations, the aluminum die achieved a surface finish near the industrial standard of 3.2 μm, while the molded PP part exhibited improved surface quality. Economic considerations reveal the saving of time (~7 to 3 weeks) and cost ($720 to $180). The results demonstrate that the proposed RIC-based framework provides a cost-effective, efficient, and flexible solution for producing customized or low-volume dies, offering reduced tooling costs and faster production cycles while meeting the industry standards.

Keywords: die manufacturing, surface roughness, dimensional accuracy, aluminum, rapid investment casting.

INTRODUCTION

Die manufacturing is believed to be the foundation of all industries. It is considered a vital factor in the success of product development [1]. Manufacturing die plays a crucial role in numerous industries by serving as a basis for producing high-quality components and products. The quality of dies directly influences the performance, durability, and overall reliability of the manufactured items [2]. Therefore, understanding the manufacturing processes that affect die quality is of paramount importance. The production of industrial goods requires manufacturing discrete components, which are then sub-assembled and assembled into finished products ready for sale. Dies and molds are used in production procedures, including forging, stamping, casting, and injection molding, to create almost all mass-produced discrete parts [3]. Tooling for die casting, forging, injection molding, and sheet metal forming applications is produced by the die and mold manufacturing sector [4].

The primary goal of today's manufacturing sector is to produce low-cost, high-quality goods quickly [5]. A cost-effective solution is crucial in this modern and demanding industrial environment together with the expected efficiency and quality of the final product [6]. Numerous industries, including automotive, aerospace, and consumer products, depend heavily on die manufacture. The quality, cost, and time to market a product can all be greatly impacted by the selection of the manufacturing process. Traditional die manufacturing techniques, including electrical discharge machining (EDM), and CNC machining, have served as the foundations of toolmaking. These subtractive methods, however, frequently have limited flexibility in responding to iterative design changes, expensive tooling efforts, and lengthy lead times [7].

As a result, there is a growing trend toward sophisticated die development techniques that can handle high complexity without compromising accuracy and are quicker and more economical. In addition, techniques such as additive manufacturing (AM) or rapid tooling (RT) are now considered reliable substitutes for traditional die making. With these methods, digital processes and material layering are used to quickly produce tooling directly from 3D designs. These technologies especially accelerate development and offer greater freedom in creating part shapes in smaller-scale manufacturing [4, 8]. When rapid prototyping (RP) methods are linked to downstream investment casting, they help to speed up the verification and tool validation process. For instance, one important integration is rapid investment casting (RIC), which benefits from the freedom of 3D printing as well as the accuracy of silicone molds for wax patterns in investment casting. The use of patterns made using fused deposition modeling (FDM) is replacing traditional wax in the RIC process [9, 10].

Rapid tooling (RT) is the term for this type of RP tooling manufacturing [11], which can manage low-volume manufacturing (≤5 items) accurately, precisely, and economically. RT represents a modern manufacturing technique allowing RP principles to directly produce tools with speed [12, 13]. An increasing number of RT approaches tend to be grouped together. Indirect and direct tooling are compared, as well as soft and hard tooling. It is still feasible to categorize RT techniques according to practical characteristics rather than rigid standards [14]. In this classification, "casting patterns" are considered an indirect RT method, utilizing RP-generated sacrificial models in both investment and sand casting. The use of rapid prototyping and rapid tooling techniques for creating master patterns leads to the formation of rapid investment casting (RIC) [15–17]. RIC refers to all situations where RP&T technology serves for IC production [18–21]. Due to the rapid production of patterns without tooling, RIC has become a widely accepted method in the foundry industry. According to Wang et al. [23], developing and using 3D printing patterns in the investment casting process can reduce lead time by 89% and manufacturing cost by 60%, while Wang et al. and Shah [16, 22] reported that additive manufacturing integrated investment casting and sand casting play a vital role to improve the capability of the foundry industry for various applications in 21st century. Cheah et al. [23] established several manufacturing chains that use technologies from additive manufacturing (AM) in recognition of the difficulties in IC to lower the lead time and cost. Direct rapid investment casting (DRIC) and indirect rapid investment casting (IRIC) are the two main types of rapid investment casting (RIC), which are based on how the pattern was developed. The main way these categories distinguish the methods is by the method used to prepare the ceramic shell and produce the pattern [24] (Figure 1).

Jiang et al. [25] discussed the procedure of deformation compensation and proposed a novel compensation model for the wax pattern die of a turbine blade. An efficient compensation model was created based on Taylor expansion to address the lack of available compensation techniques. Instead of section by section, the suggested approach accounts for casting deformation in three dimensions. After adjustment, the deformation was reduced by almost 80–90%, demonstrating that the suggested approach can greatly minimize deformation.

Particularly in RIC-based die production, aluminum is becoming the preferred material. Due to its advantageous qualities, including high heat conductivity, corrosion resistance, light weight, and ease of machining, it is an excellent choice for tooling applications requiring good dimensional stability and moderate strength. According to Altinbalik and Mutlu [26], aluminum dies can be manufactured at 30–40% lower cost than steel dies, primarily because of reduced material expenses and faster processing times. This makes aluminum an attractive option for low-to-medium production runs. Additionally, aluminum dies have found applications in injection molding, investment casting, low-pressure die casting, aerospace, and the automotive sector, positioning aluminum as a viable alternative to steel in die and mold manufacturing [27]. As industries increasingly prioritize cost reduction, sustainability, and

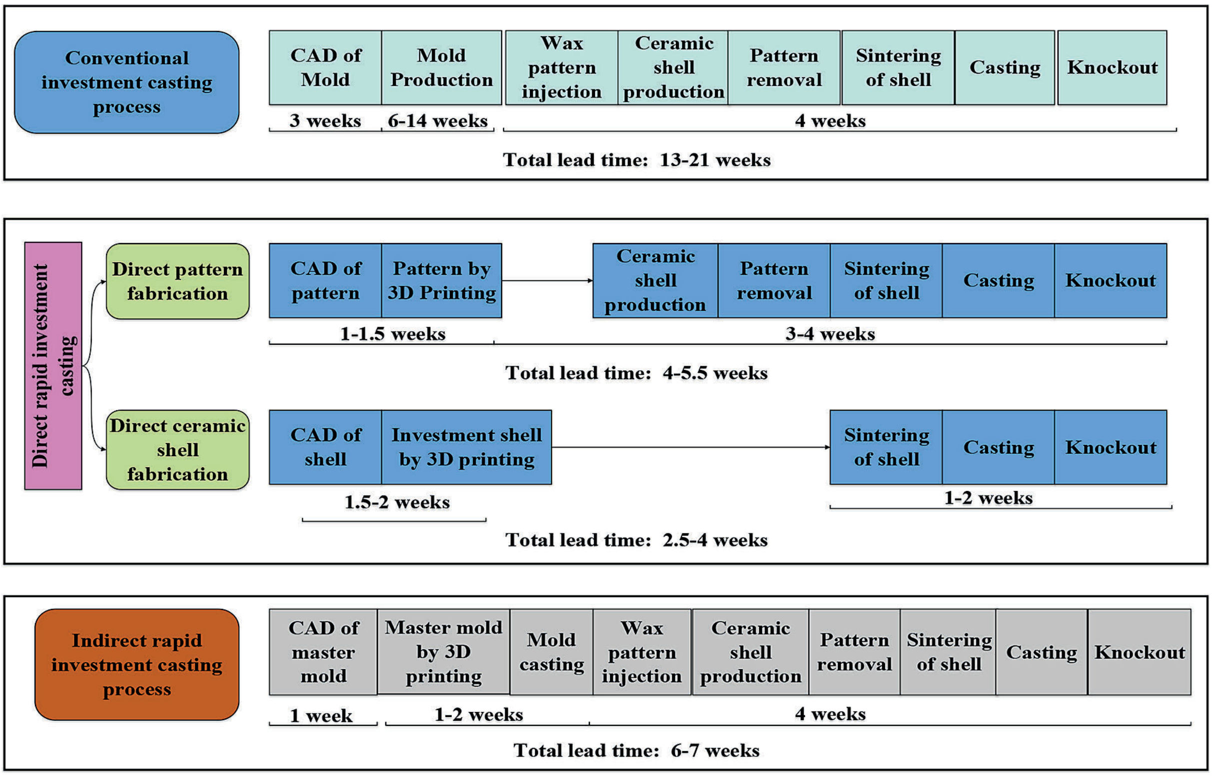

Figure 1. Type of rapid investment casting along with timeline comparison [24]

efficiency, the role of aluminum in mold manufacturing has expanded further [28]. Steel is typically used as the die material for long-term mass production (10–15 years), with traditional die manufacturing relying mainly on CNC machining and EDM. While suitable for high-volume markets, this approach becomes less economically viable in today's rapidly changing environment where client needs constantly evolve. Although advancements have been made in rapid prototyping and tooling (RP&T) and investment casting, most previous research has focused on discrete elements such as pattern materials, ceramic shell properties, or casting parameters. Few studies have explored the use of rapid investment casting (RIC) for producing inexpensive aluminum dies.

The novelty of this research lies in developing and validating a framework for economic cost modeling tailored specifically for the rapid investment casting of aluminum dies. Unlike traditional tooling methods, this framework employs FDM-based patterns, silicone molds, and RIC to create low-cost, short-lived dies suitable for small-scale or customized projects. Aluminum was chosen as the die material due to its affordability, recyclability, and compatibility with moderate tooling requirements, offering a practical alternative to the costly and time-consuming process of steel tooling. This study aims to develop and demonstrate a systematic approach for creating low-cost aluminum dies using RIC. The specific objectives are: (i) to design and produce a die utilizing FDM-based rapid prototyping and RIC, accounting for dimensional allowances to compensate for shrinkage; (ii) to evaluate the die's dimensional accuracy, surface finish, and functionality; (iii) to assess the economic viability of the proposed RIC framework compared to conventional die manufacturing methods; and (iv) to illustrate the framework's practical application through a real-world case study involving a commercial automotive component (Mehran door handle).

PROPOSED RESEARCH FRAMEWORK FOR THE DEVELOPMENT OF LOW-COST DIES THROUGH RIC

A review of traditional and advanced die development methods through machining, casting, and rapid prototyping processes leads to the proposed hybrid strategy – rapid investment casting for aluminum die development, as shown in Figure 2. This method combines rapid investment casting technology with aluminum die fabrication. The innovative approach unites three

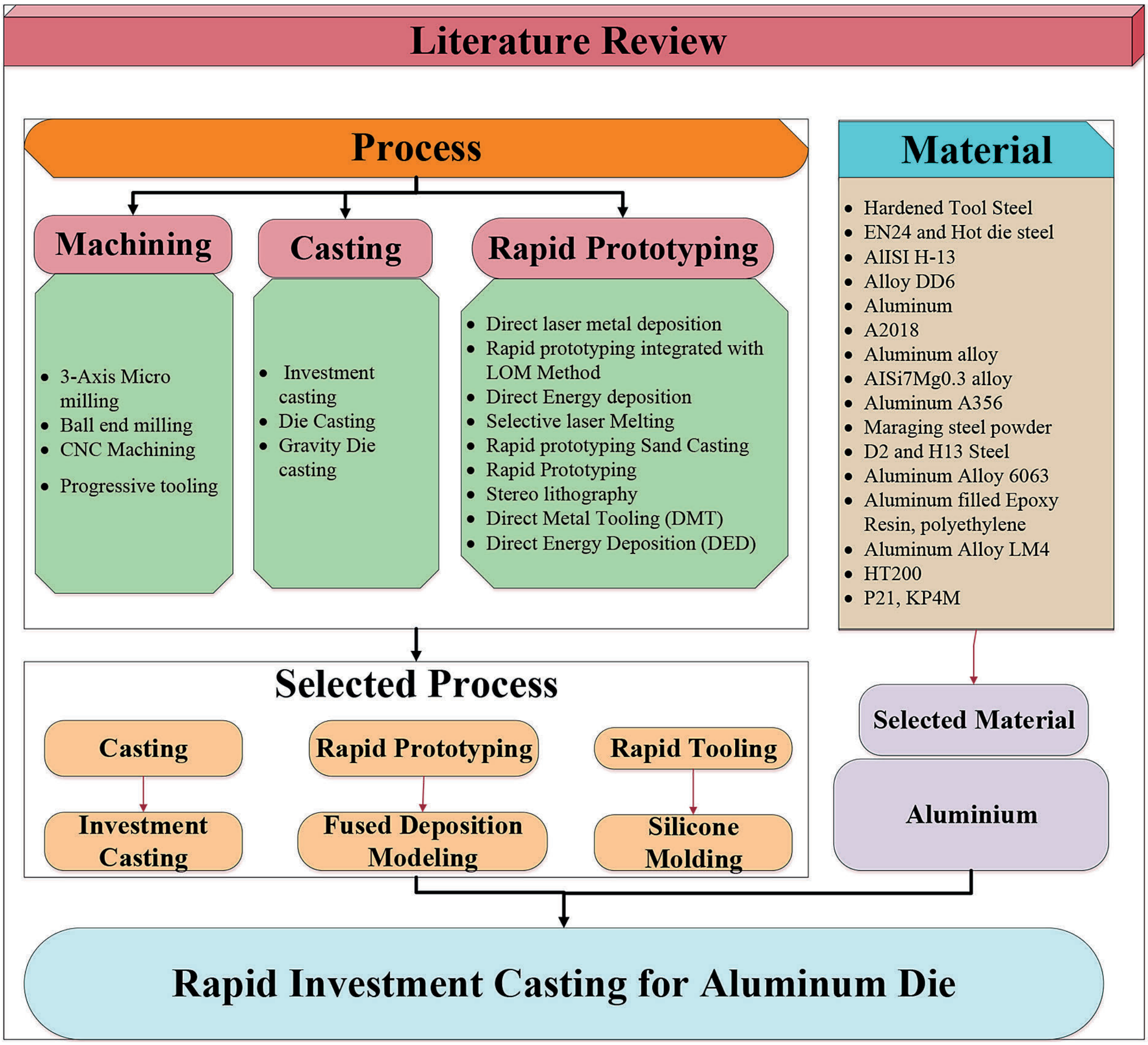

Figure 2. Sorting of processes for low-cost die development

modern technological solutions: the integration of investment casting with fused deposition modeling (FDM) and silicone mold generation from rapid tooling allows producers to precisely duplicate intricate shape details while achieving smooth surface finishes at budget-friendly prices and fast cycle times. Choosing aluminum for die production delivers optimal benefits by reducing weight and ensuring easy machinability alongside sufficient power requirements for manufacturing small- to average-volume runs. This makes aluminum the preferred material for industries seeking efficiency in tooling applications. These three technologies work together to create flexible production systems with fast processing times and reduced costs, while maintaining precise part details and enabling quick market adaptations.

The long-lasting, high-volume production capabilities of steel-based traditional die manufacturing systems extend for 10–15 years; however, these approaches create challenges in industries requiring regular design updates. The aluminum-based rapid investment casting method provides producers with design flexibility through its ability to respond quickly to model alterations while eliminating time-consuming production delays. This approach functions optimally in situations involving customized production volumes and dynamic product development cycles. The manufacturing process supports sustainability through its use of recyclable materials and cost-efficient elements, along with its rapid prototyping capability, which shortens development timeframes. The resulting organizational approach optimizes speed while simultaneously lowering expenses and enhancing accuracy and system adaptability, making it suitable for modern demanding market conditions.

The proposed method: rapid investment casting for aluminum die development process consists of five consecutive stages that integrate essential quality control checkpoints throughout to achieve accurate and functional aluminum dies. A systematic visual diagram (Figure 3) illustrates the stages and quality control measures for the entire method, providing clear structured details about the whole process. In the first phase, the CAD designer creates the patterns by incorporating features such as cope and drag, alongside detailed geometries. Quality technicians review the design at this stage to verify that it meets customer requirements. Conducting this quality inspection avoids costly future complications that may arise due to incomplete designs. The process continues after the design fulfills all necessary specifications. The design undergoes revisions until it meets required specifications for advancement.

In the second phase 3D printing using FDM technology builds the die pattern through a layer-by-layer process of slicing an STL file. A quality check monitors the printed part's dimensions and surface quality, with a focus on detecting physical defects after completion. Before starting silicone mold development, the quality check at this stage confirms that the 3D-printed part has achieved the prescribed precision. Any part that does not meet the required standards necessitates adjustments to the printing parameters before repeating the print cycle. A validated 3D-printed pattern serves as the foundation for the silicone mold production process in the third stage. A quality inspection verifies both the dimensions and surface quality

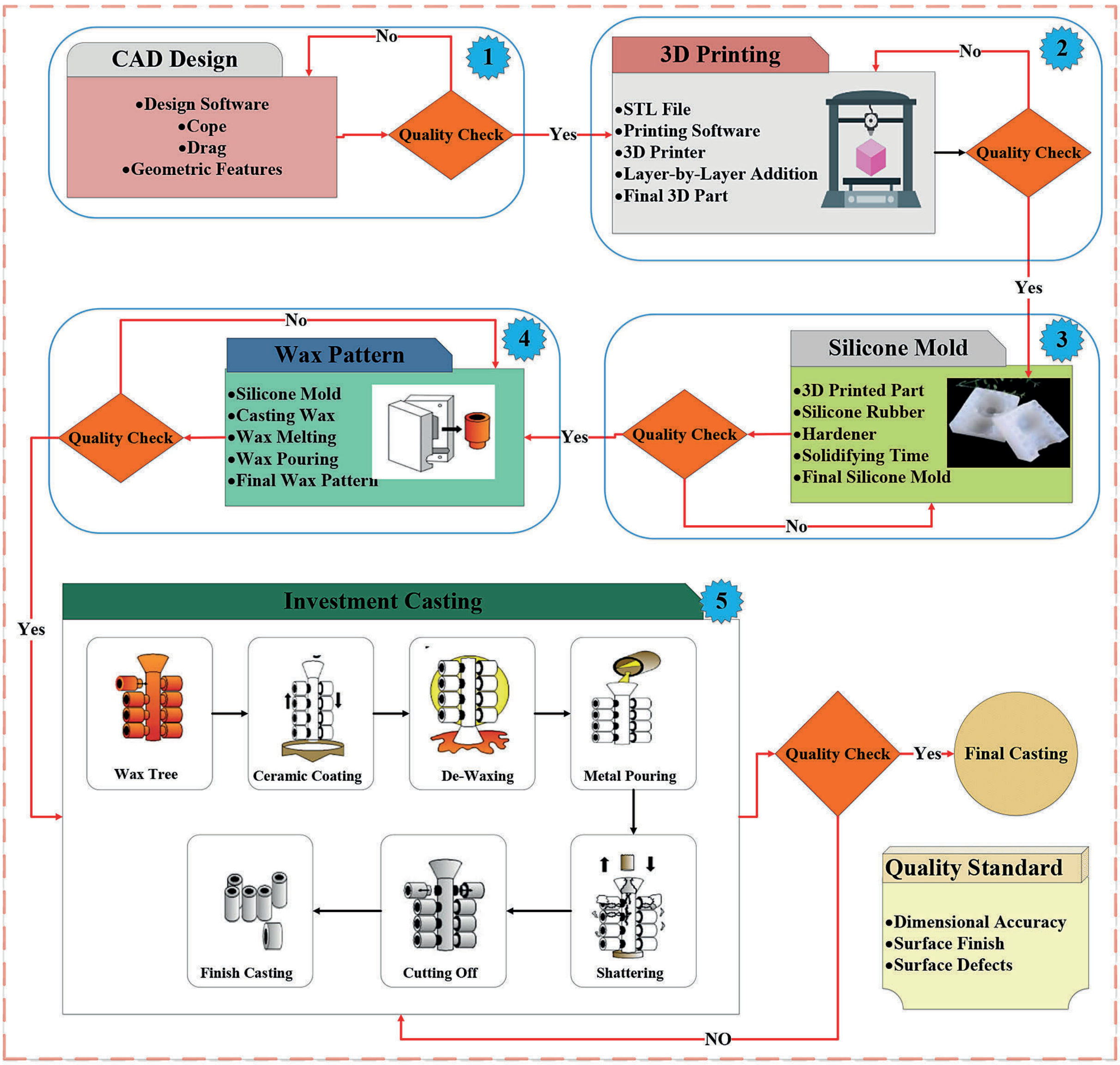

Figure 3. Systematic flow of rapid investment casting process

of the mold. This inspection is crucial because any imperfections detected now will lead to functional issues and finish degradation for both the wax pattern and the final casting. Production proceeds based on passing quality results from the mold inspection. The process continues only after the mold successfully meets the required specifications; however, manufacturing restarts if specifications are not satisfied.

Production of wax patterns occurs through silicone mold and investment casting wax operations during stage four. Experts thoroughly check these patterns for standardized dimensions and uniform surface appearance since nonstandard elements could lead to casting faults. The final process of investment casting comprises various sub-steps, including wax tree assembly, ceramic shell coating, dewaxing, and aluminum metal pouring, finishing the die with several quality checks. The efficient metal flow during pouring relies heavily on proper wax tree assembly, which influences the overall casting quality. The ceramic shell must be strong enough to withstand the metal pour, while the dewaxing operation must achieve complete wax removal to maintain mold quality. A proper understanding of aluminum melt temperatures during pouring is vital for precision in mold filling, while post-production operations that remove gates and sprues and perform surface finishing determine the final die product's dimensions and finish.

The final casting undergoes thorough quality examination before production resumes, followed by a root cause analysis to identify and address earlier-stage problems in cases of non-compliance. Different quality checks at each stage serve as essential components that preserve process efficiency while minimizing costs and delivering high-quality end products. The process achieves better results because early problem detection facilitates immediate resolution, reducing rework costs and waste while maintaining dimensional precision. The characteristics of aluminum die material support low-weight performance while providing excellent machinability and suitable strength properties, allowing this methodology to meet the needs of industries requiring flexible product demands at low to medium production volumes. The process enables high-speed manufacturing operations and flexible design adaptations that assist contemporary industries in rapidly creating personalized products at sustainable rates without compromising performance standards.

A systematic process framework detailing the crucial phases of RIC for aluminum dies supports the suggested model. The four main components of the RIC workflow are outlined in Table 1, which also highlights the tools utilized, process descriptions, technical issues, and related literature. Every stage is designed to consider the mechanical and thermal properties of aluminum while preserving manufacturing speed and cost effectiveness.

VALIDATION OF PROPOSED RESEARCH FRAMEWORK

The structured methodology framework used in this study is presented in this section, along with a summary of the major actions conducted during the investigation. The investment casting technique based on rapid prototyping and tooling (RP and TIC) was used to create a die for the benchmark part carefully. This method allows complex shapes by combining traditional investment casting with modern prototyping methods. The process is a systematic set of steps that begins with CAD modeling to design the benchmark part and proceed to rapid prototyping to generate the first

Table 1. Process breakdown in RIC

Step	Description	Key considerations	Tools	Reference
Digital design	Create a digital model of the aluminum die pattern using design software.	Compensate for 2–3% shrinkage, validate tolerances (±0.2 mm), ensure printability.	Design software (e.g., SolidWorks)	[29, 30]
Additive manufacturing (3D printing)	Produce a physical pattern using cost-effective 3D printing processes.	Use FDM with 0.2 mm layer height, 15–20% infill; inspect for defects, target roughness < 5 µm.	3D printers (e.g., FDM), calipers, roughness testers	[31, 32]
Investment casting	Create the aluminum die through shell building, dewaxing, and pouring.	Use 4–6 shell layers, preheat to 500 °C, pour at 700 °C, inspect defects with dye penetrant testing.	Basic furnace, pouring equipment, testing kits	[33]
Final die preparation	Clean, inspect, and document the cast die for evaluation.	Clean manually, inspect dimensions (±0.2 mm), document minimally for traceability.	Calipers, basic CMM, documentation systems	[34]

pattern. The wax part is then created using this pattern in the silicone mold making process. The wax part is then assembled and covered in ceramic material to create a strong ceramic mold. The ceramic shell must be dewaxed and fired before molten metal is poured into the ready-made mold. Following casting, the ceramic mold is removed to show the cast die, which is then finished to produce the appropriate level of accuracy and roughness on the surface. Several tests were carried out to assess the quality and features of the die after the casting and finishing processes. A vernier caliper was used to measure dimensional accuracy to make sure the finished product complied with design requirements. To assess the cast surface's quality, surface roughness was determined as shown in Figure 4.

Experimental details

The automobiles door inner handle's die is selected as a benchmark part, employed in this case study to investigate the feasibility of employing patterns created as sacrificial investment casting patterns to produce metal castings rapidly. In the case of the Mehran car door inner handle, the die plays a pivotal role in shaping the final product.

Extreme care of detail is necessary in the design and production of the die, considering material qualities, geometry, and functionality. The accuracy of the die directly affects the fit, longevity, and visual appeal of the injection-molded inner handles, as well as their overall quality and consistency. Achieving optimal outcomes in die designing and manufacturing requires exact dimensional accuracy. Strategically, an allowance is incorporated into the design to account for the expected shrinkage that happens during various production processes, such as 3D printing, waxing, and aluminum casting. To adequately account for this shrinkage, the die design typically adds a 3% (0.8% wax, 1.4% aluminum and 1% for 3D printing and silicone rubber molding) [35, 36] margin across all dimensions.

3D modeling

Using SolidWorks CAD software, the die was designed as the initial step in the Rapid Investment Casting (RIC) process. The component's geometry was first modeled, and the die halves—cope and drag—were extracted. The design included a 3% dimensional allowance to account for shrinkage, just the die's cavity portion was created and 3D printed for first examination to verify this modification. As shown in Figure 5, the entire die assembly (cope and drag) was completed in SolidWorks after the dimensional accuracy was verified using the imposed allowance. As seen in Figure 5, the entire die assembly (cope and drag) was completed in SolidWorks after the dimensional accuracy was verified using the prescribed allowance.

FDM 3D printing

The RP method used in the development of master pattern of die is FDM 3D printing method. Materials used in the RP method offer diverse properties, requirements, temperature, cost, and weight. In the FDM technique, polyamide (PA), polylactide (PLA), polycarbonate (PC), tough polylactide (tough PLA), polyethylene terephthalate) glycol (PETG), acrylonitrile butadiene styrene (ABS) and its copolymers are the most often used thermoplastic materials to make 3D objects. Based on literature review the material selected for the development of master pattern of die is PLA filament. The 3D printing condition used in this case study to 3D print the master patterns are listed Table 2. According to widely published values and equipment recommendations for FDM-printed pattern, the 3D printing conditions shown in Table 2 were chosen. An ideal compromise between accuracy and time efficiency was achieved with a print speed of 50 mm/s and a layer height of 0.2 mm. A 25% infill density further decreased material consumption without sacrificing pattern stability. A 15% infill overlap enhanced the bonding between neighboring layers, while shell and top/bottom thicknesses were selected to guarantee wall integrity and surface closure. These settings are consistent with previous research on investment casting using FDM [37–39].

Silicone mold fabrication

After 3D printing the next step is to develop the silicone rubber mold. In this case study, the three main steps were used in the precise process of making silicone molds. (i) To guarantee the best possible surface quality, the master pattern was first carefully prepared. This included careful cleaning and testing. To make pattern removal after molding easier, a mold release agent was also carefully applied. (ii) The mold was then sealed in place by carefully assembling mold frames around it. At the top of the mold frame, a central

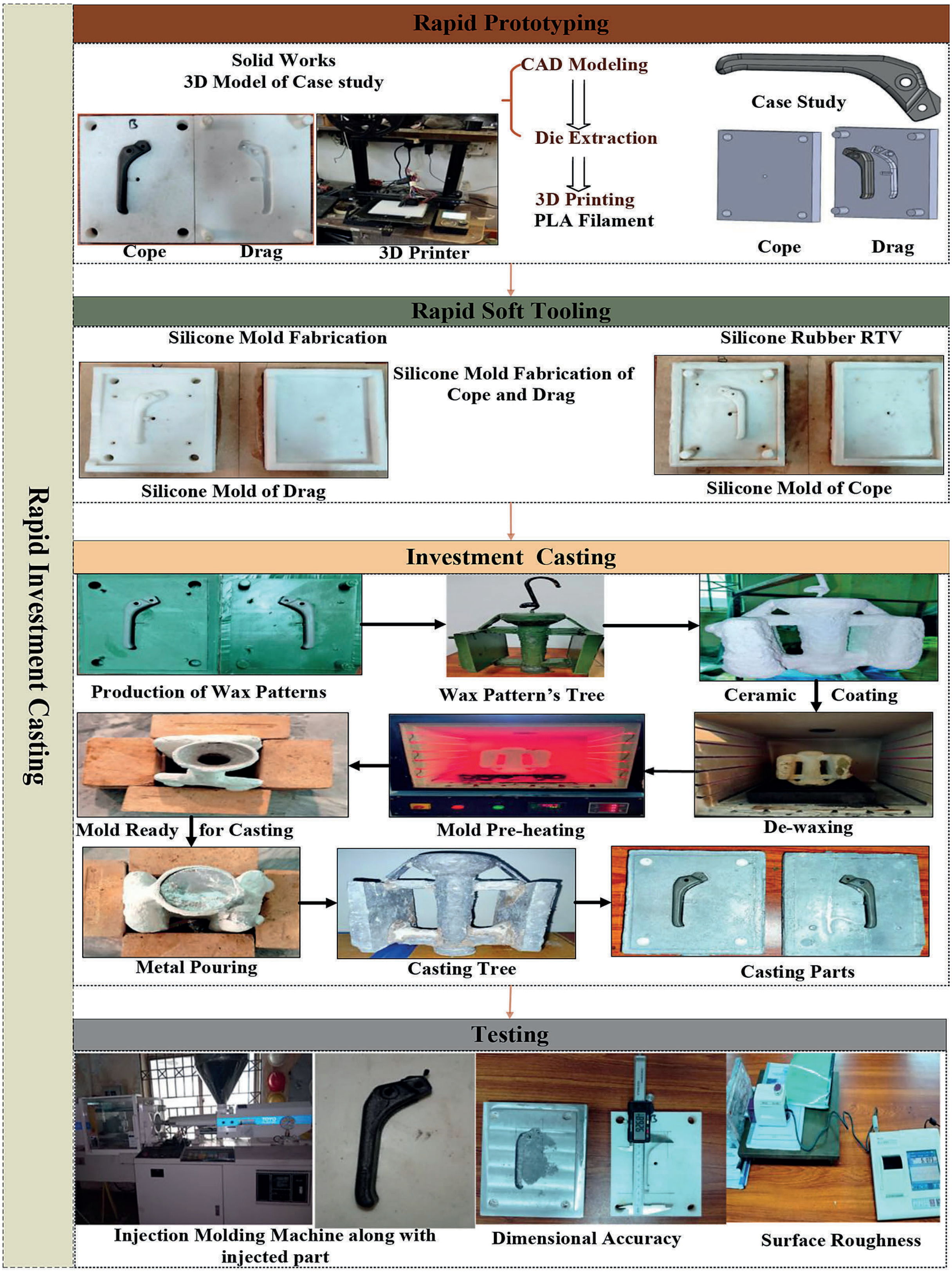

Figure 4. Experimental framework

pouring hole was purposefully placed to help with the waxing process and to make pouring wax easier. To make the procedure of waxing even easier, four bleeding holes were placed at different locations. (iii) Lastly, silicone RTV rubber was precisely combined with binder liquid (hardener) at a weight ratio of 100:3 and then poured into each mold frame to completely cover the design.

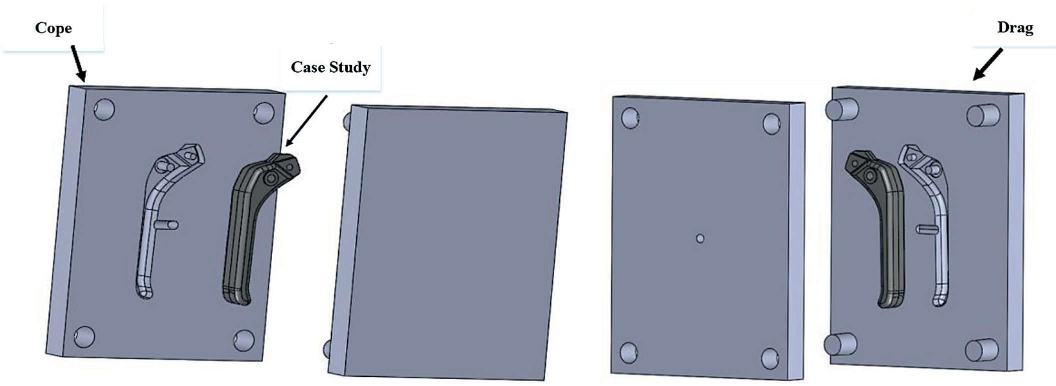

Figure 5. Final 3D model of case study with extracted cope and drag

Table 2. 3D printing conditions

Parameter	Value
Print speed	50 mm/s
Infill density	25%
Infill speed	80 mm/s
Layer height	0.2 mm
Shell thickness	0.8 mm
Top/bottom thickness	0.6 mm
Infill overlap	15%

Before curing, the silicone mixture was degassed to remove air bubbles. After curing, the cope and drag of molds were exposed when the mold casings were carefully disassembled. Proper mixing of hardener and rubber is very important in the development of silicone rubber mold. Curing time is also critical in this step. This silicone runner mold is normally used for customized pattern production not for mass production.

Investment casting

In this research four steps are involved in preparing the dies through investment casting. First, molds that had already been prepared with RTV silicone rubber were filled with wax to create wax patterns of die. These wax patterns were assembled in a tree shape, including the riser, runner, ingates, pouring cup and sprue, forming a wax tree. Second, ceramic shells were made by repeatedly applying ceramic coatings over the wax tree. The ceramic shell mold was made through a multi-step process involving dipping, stuccoing, and drying. First, the wax tree was immersed in a primary slurry composed of zircon and then coated with zircon sand that was finer than 100 mesh. This dipping and stuccoing cycle was repeated three times, with each layer drying for 12 hours, totaling 36 hours for the primary coat. Next, secondary coatings were applied using fused silica sand ranging from 30 to 80 mesh, with two coats each drying for 6 hours, adding up to 12 hours. To increase mechanical strength, three additional backup layers were added using coarser fused silica sand (16–30 mesh), with each layer drying for 6 hours, totaling 18 hours. Finally, a sealing dip was performed as the last coat in slurry without stuccoing, requiring 12 hours to dry. Overall, nine layers were applied, resulting in approximately 78 hours of drying time and creating a ceramic shell with sufficient thickness and strength for aluminum casting. A detailed outline of the ceramic coating process is shown in Table 3.

After ceramic coating the ceramic mold was de-waxed at 250 °C in electric furnace to remove the wax from the ceramic mold and make the mold hollow. De-waxing is one of most important step of investment casting uncontrolled de-waxing lead to the breaking of ceramic mold. The mold was baked at 750 °C for 10 hours to fully remove any remaining wax and moisture. Simultaneously, the aluminum alloy LM30 was melted in electric furnace 2 at 750 °C. The molten alloy was then poured into the de-waxed shell mold, and after cooling the ceramic shell was removed from the casting. Finally, cope and drag were cut from the casting tree and further finishing operations

Table 3. Chemical composition of LM30

Element	Al	Si	Mg	Fe	Cu	Mn	Ni	Zn	Cr	Ti
wt.%	80.35	9.64	0.12	1.26	2.43	0.06	0.15	5.92	0.03	0.04

were performed to achieve the final appearance. The chemical composition of the LM30 used in this study is listed in Table 4.

Results and analysis

This section outlines the findings from the die testing, assessment of dimensional accuracy, and evaluation of surface quality for the aluminum die created through rapid investment casting. The die underwent testing on an injection molding machine using PP to verify its functionality and performance. A dimensional analysis was performed at every stage of the process, from the CAD design to the final cast die and the injected part, to evaluate accuracy and deviations. Furthermore, surface roughness measurements were conducted for both the cast die and the PP component to assess quality of replication and finish. The results validate the die's capability in producing plastic components that are both dimensionally precise and of high quality.

Die testing on injection molding machine

The aluminum die developed through rapid investment casting was evaluated on a standard injection molding machine to assess its effectiveness in manufacturing the Mehran car door handle. PP was chosen as the molding material due to its excellent flow characteristics and dimensional stability. The die was firmly secured, and the machine was operated using the following optimized settings: a melt temperature of 220 °C, an injection pressure ranging from 100 to 120 MPa, a holding time of 8 seconds, and a cooling duration of 15 seconds. Molten PP was injected into the die cavity and allowed to solidify before being ejected. The die showed outstanding structural integrity with no evidence of flashing, leakage, or dimensional distortion. The final PP component displayed superior surface quality and dimensional precision, validating the functional adequacy of the cast aluminum die for producing plastic parts via injection molding. Figure 6 depicts the setup of the injection molding machine and the successfully molded PP door handle part.

Dimensional accuracy

Dimensional accuracy was assessed to evaluate deviations in key features at each stage of die fabrication. Precision measuring tools such as digital vernier calipers, outside micrometers, and depth gauges were used to record the dimensional values of each feature at various points. The assessment focused on 14 critical geometrical features, measured across five stages: the original CAD model (baseline), the 3D printed die, the wax die, the cast LM30 die, and the final injection-molded PP (polypropylene) part. The recorded values and absolute deviations between stages are listed in Table 5, with their progression shown graphically in Figure 7 and Figure 8 respectively.

Table 4. Ceramic coating

Coating	Slurry	Material	Coats	Mesh size	Drying time/coat (hour)	Total drying time (hour)
Primary	Yes	Zircon sand	3	<100	12	36
Secondary	Yes	Fused silica sand	2	30:80	6	12
Backup	Yes	Fused silica sand	3	16:30	6	18
Final Dip	Yes	Slurry	1	-	12	12

Figure 6. (A) Injection molding setup, (B) Injected part

Among the features evaluated, the handle length consistently decreased from 92.2 mm (CAD) to 90.2 mm (PP part), with the largest single reduction of 0.75 mm occurring between the 3D printed pattern and the wax die, followed by a 0.64 mm decrease from the cast die to the molded part. The handle width decreased overall from 36.5 mm to 35.2 mm, with a notable initial deviation of 0.5 mm during 3D printing. The width at the end of the handle showed minor fluctuations, indicating greater dimensional stability in that area. The lengths of the mounting pin features showed significant variation. The small mounting pin length drastically decreased from 6.02 mm (3D printed die) to 1.9 mm (wax pattern), with a deviation of 4.12 mm, then further dropped to 1.75 mm in the final PP part. Similarly, the large mounting pin length experienced the greatest deviation among all features, dropping from 10 mm to just 3 mm, with a notable 5.79 mm reduction during the wax stage. These major declines are likely due to wax shrinkage and mold deformation, especially in slender, elongated shapes. In contrast, some features like the

Table 5. Dimensional values and absolute deviation of die at each stages

Code with Feature	Dimensions (mm)					Absolute deviation (mm)			
	CAD (A)	3D print die (B)	Wax die (C)	Cast die (D)	PP part (E)	A-B	B-C	C-D	D-E
1- Handle length	92.2	91.85	91.1	90.84	90.2	0.35	0.75	0.26	0.64
2-Handle width overall	36.5	36	35.77	35.66	35.2	0.5	0.23	0.11	0.46
3-Handle width at the end	8.68	8.82	8.88	8.65	8.5	0.14	0.06	0.23	0.15
4-Mounting pin dia (small)	3.57	3.2	3.2	3.29	3.25	0.37	0	0.09	0.04
5-Mounting pin length(small)	5.91	6.02	1.9	1.8	1.75	0.11	4.12	0.1	0.05
6-Mounting pin dia (large)	4.95	4.35	4.34	4.67	4.6	0.6	0.01	0.33	0.07
7-Mounting pin length (large)	9.92	10	4.21	3.12	3	0.08	5.79	1.09	0.12
8-Circle along larger pin	9.12	9.1	9.09	9.04	8.95	0.02	0.01	0.05	0.09
9-Front length along large pin	11.65	11.65	11.65	11.65	11.6	0	0	0	0.05
10-Front length along small pin	8.8	8.7	8.7	8.6	8.5	0.1	0	0.1	0.1
11-Handle depth along small pin	6	5.87	5.55	5.55	5.5	0.13	0.32	0	0.05
12-Depth along upper slope	3.45	3.45	3.44	3.44	3.4	0	0.01	0	0.04
13-Small slope length 1	7.14	6.99	6.96	6.3	6.1	0.15	0.03	0.66	0.2
14-Small slope length 2	7.4	7.23	7.2	7.15	7	0.17	0.03	0.05	0.15

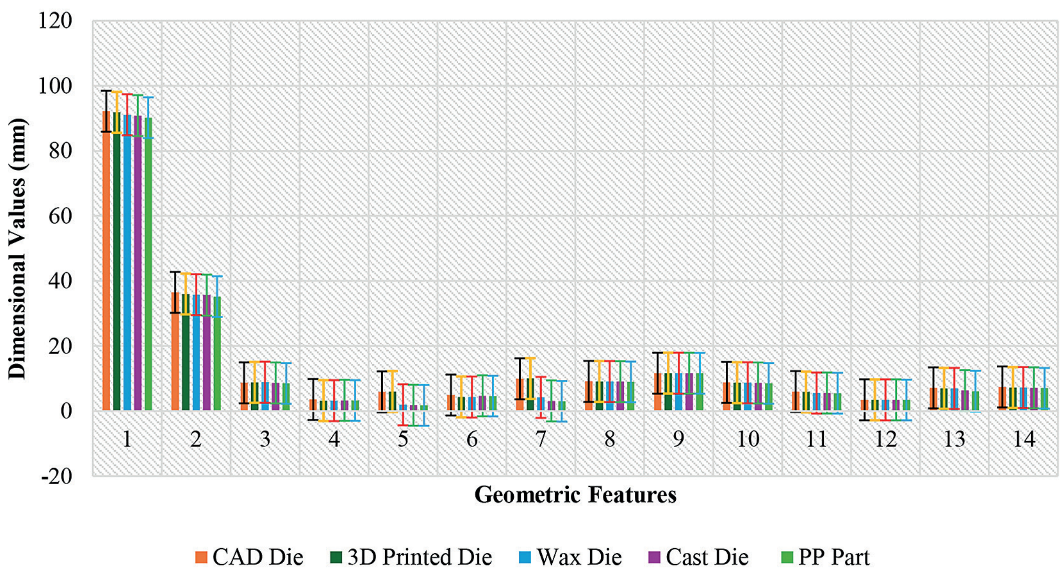

Figure 7. Dimensional value graphically

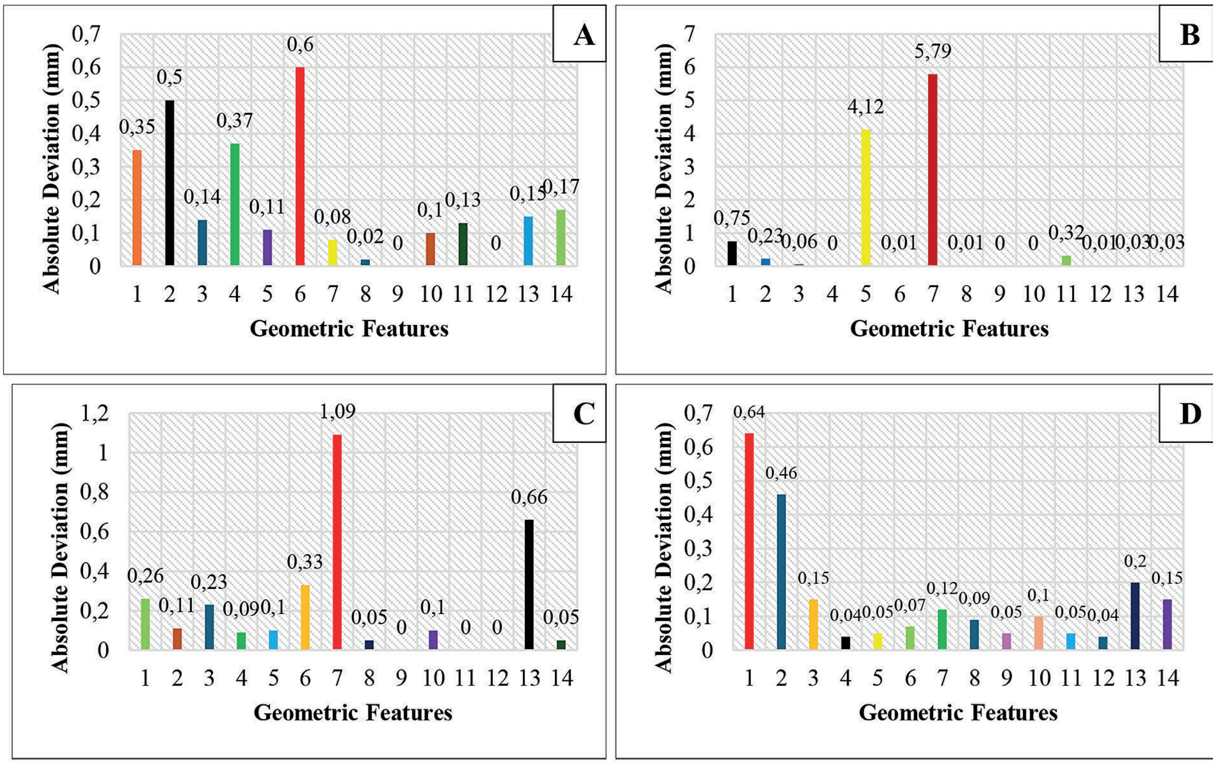

Figure 8. Absolute deviation at each stage (A) CAD -3D Printing die, (B) 3D Printing die- Wax die, (C), Wax die- Casting die, (D) Casting die to PP part

circle diameter along the large pin, front lengths, and upper slope depth maintained good dimensional consistency, with minimal cumulative deviations (within ±0.1 mm to ±0.2 mm). However, sloped features such as small slope length 1 saw a significant decrease, particularly during casting, where a 0.66 mm reduction was recorded – probably caused by angular mold erosion or material pullback. The small and large mounting pin lengths, handle length, and small slope length 1 showed the largest deviations. These areas are more prone to distortion because of their narrow shapes, vertical orientation, and sensitivity to geometric changes during wax cooling, shell burnout, and metal solidification. Careful control of process parameters, shrinkage allowances, and mold design are crucial for improving dimensional accuracy in rapid investment casting.

A one-way ANOVA was conducted to evaluate the dimensional variations across four stages: CAD–3D printed die, 3D printed die–wax die, wax die–casting die, and casting die–PP part. The results ($F = 1.60$, $p = 0.200$) indicated that differences in mean deviations were not statistically significant at the 95% confidence level (see Table 6). The coefficient of determination ($R^2 = 8.46\%$) showed that only a small portion of the variation in deviations was related to the process stage. Nonetheless, the mean deviations revealed that the 3D printed die–wax die stage had the highest average deviation (0.811 ± 1.798 mm), while the cast die–PP part stage had the lowest (0.158 ± 0.177 mm). Although these differences were not statistically significant, the wax stage consistently presented the largest deviations, aligning with practical observations of wax shrinkage and mold distortion.

Table 6. One-way anova statistical results

Factor	N	Mean	StDev	95% CI
CAD- 3D printed die	14	0.1943	0.1876	(-0.2996, 0.6881)
3D printed die-wax die	14	0.811	1.798	(0.318, 1.305)
Wax die-casting die	14	0.2193	0.3070	(-0.2746, 0.7131)
Cast die-PP part	14	0.1579	0.1766	(-0.3360, 0.6517)

Surface roughness

The Mitutoyo SJ-410 surface roughness tester was used to measure the surface roughness of the cast die. This device operates based on stylus profilometry, with a measurement range up to 160 µm and a resolution of 0.01 µm [35]. Before measurements, the device was calibrated using the reference specimen provided by the manufacturer to ensure accuracy. Surface roughness (Ra) was measured at three points on each feature, and the average was calculated. The tolerance limit was set at ±1.0 µm, in accordance with standards for casting surface finish evaluation. The process for measurement consisted of several steps: (i) preparing the surface; (ii) positioning the probe so that it's perpendicular to the surface; (iii) calibrating the device; (iv) configuring the setup; (v) traversing the probe along the feature; (vi) gathering data; and (vii) analyzing the results. Figure 9, and Table 7 outlines a comparison of the surface roughness metrics of the cast aluminum die and the injected PP part against the reference standard value of 3.2 µm [40]. Surface roughness was measured on the casted die without machining and the PP part injected from injection molding.

Most of the measurements from the cast die either within or slightly exceed this standard. Features like the handle width at the end (4.00 µm) and handle depth along the small pin (3.60 µm) exhibited increased roughness due to their intricate geometries and limited flow control during the casting process. In contrast, smoother

Table 7. Surface roughness comparison

Code	Feature	Standard value (µm)	Cast die (µm)	PP part (µm)
1	Handle length	3.2	3.25	2.46
2	Handle width overall	3.2	3.4	2.28
3	Handle width at the end	3.2	4	1.48
4	Mounting pin dia (small)	3.2	3.1	1.44
5	Mounting pin dia (large)	3.2	3.2	1.44
6	Front length along large pin	3.2	3.3	1.6
7	Front length along small pin	3.2	2.9	1.88
8	Handle depth along small pin	3.2	3.6	1.76
9	Depth along upper slope	3.2	3.15	1.58
10	Small slope length 1	3.2	3.45	2
11	Small slope length 2	3.2	3	1.38

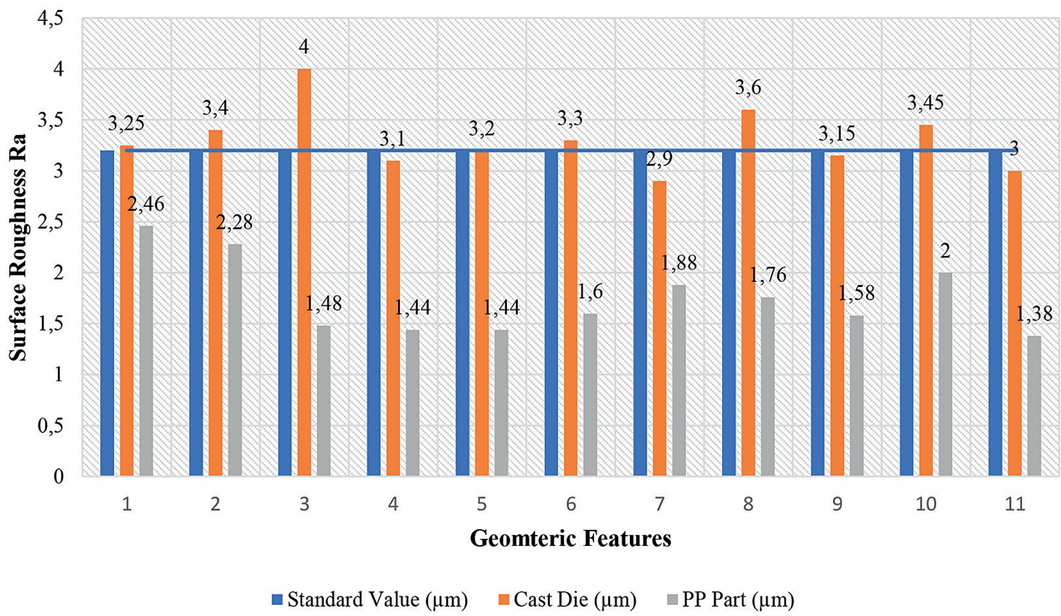

Figure 9. Surface roughness comparison

Table 8. Lead-time and cost comparison of rubber and steel molds for pattern preparation

Silicone rubber mold	Time	Conventional steel mold	Time
CAD design of die	1 week	CAD design of die	1 week
Die development	2 days	Die development	6 weeks
Total time	1.2 week		7 weeks
Silicone rubber mold	Cost	Conventional steel mold	Cost
Cost of master pattern	$18	Mold production	$720
Cost of silicone rubber material	$26	Maximum replicates	>50000
Maximum replicates	40–50		
Total cost	$44		$720

Table 9. Time and cost comparison of mold manufacturing using RIC and machining process

Time analysis			
Rapid investment casting	Time	CNC/EDM	Time
CAD design of die	1 week	CAD design of die	1 week
Die development	2 weeks	Die development	6 weeks
Total time	3 weeks	Total time	7 weeks
Cost analysis			
Rapid investment casting	Cost	CNC/EDM	Cost
Die development	$180	Die development	$720*
Maximum replicates	Up to 5000	Maximum replicates	>50000

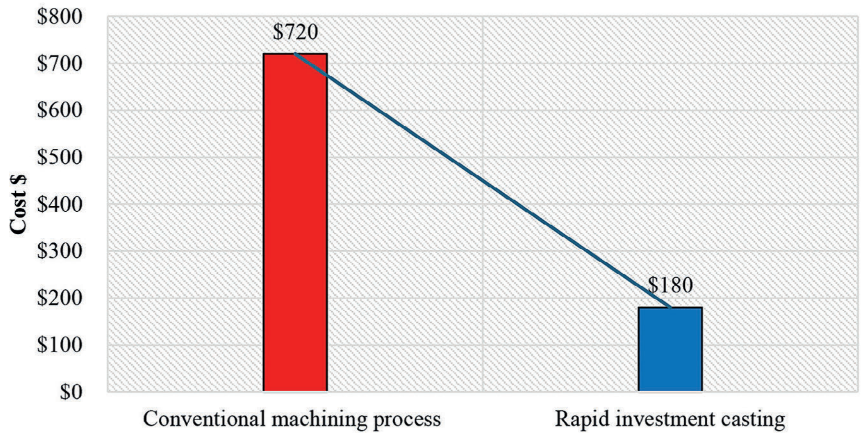

Figure 10. Cost comparison of the die development process

areas such as the front length along the small pin (2.90 µm) and small slope length 2 (3.00 µm) reflect improved replication of the mold surface and consistent shell formation. The injected PP part, created using the aluminum die, demonstrated notably lower surface roughness across all features, ranging from 1.38 µm to 2.46 µm. This enhancement is linked to the high-pressure injection molding technique and the beneficial flow characteristics of polypropylene, which facilitate precise replication of the texture from the die's surface. Cast die produced surface finishes approaching the industry standard, the final PP part revealed a significantly enhanced surface quality, confirming the success of this hybrid manufacturing method for both functional and aesthetic components.

Time and cost analysis

To evaluate the time and production cost savings of pattern fabrication using silicone rubber molds compared to traditional metal molds, lead-time and cost comparison studies were conducted and summarized in Tables 8. The lead-time required to create a sacrificial pattern with silicone rubber molding offers several advantages. Overall lead-time is reduced from 7 weeks (for traditional metal molds) to just 1.2 week using a silicone rubber mold, resulting in a total savings of about 5.8 weeks. In addition to time, silicone rubber molds can also lead to significant cost savings. The production of silicone rubber molds costs only $44, while traditional metal molds cost $720. This indicates a 93% decrease in costs. Although metal molds allow for larger production volumes, silicone rubber molds remain affordable for small-scale production of wax patterns, making them an appealing alternative for prototyping.

To evaluate the effectiveness of die development using rapid investment casting in comparison to CNC and EDM machining processes, a thorough analysis of lead-times and manufacturing costs was performed (Table 9). According to the lead-time comparison, rapid investment casting significantly reduces the time required for die development. This method takes approximately 3 weeks to complete the die, while CNC and EDM machining processes take around 7 weeks. Rapid prototyping and tooling are the primary factors contributing to these substantial time saving of over 4 weeks, as they expedite the mold development process. The cost comparison shows that rapid investment casting leads to significant cost reductions as graphically represented in Figure 10. Rapid investment casting costs only $180, whereas die manufacturing using CNC and EDM machining costs $720. These savings are due to lower expenses for pattern creation, ceramic coating, and the melting and pouring procedures. Additionally, the aluminum dies produced through rapid investment casting allow for customized part dies, unlike traditional steel dies, which are better suited for larger production volumes exceeding 50,000 copies. Since rapid investment casting is approximately 75% less expensive than conventional machining for low- to medium-production volumes, it is a more economical option for smaller-scale production needs, according to the analysis.

CONCLUSIONS

This study presents and validates a structured framework for the development of low-cost aluminum dies using the RIC process, offering a viable alternative to conventional die manufacturing methods for low- to medium-volume and customized applications. Grounded in a comprehensive review of peer-reviewed publications and demonstrated through a real-world case study, the framework emphasizes the advantages of RIC—such as reduced tooling cost, faster production cycles, and the ability to accommodate complex geometries. The developed die, produced from LM30 aluminum and tested with PP for an automotive door handle, achieved a surface roughness close to the industry standard of 3.2 µm. The molded PP parts exhibited an improved surface finish, validating the process's effectiveness in maintaining surface quality. Dimensional analysis revealed that certain features—such as the circle diameter along the large pin, front lengths, and upper slope depth—maintained strong consistency with minimal cumulative deviations (within ±0.1 mm to ±0.2 mm). In contrast, more complex or slender features like the small and large mounting pin lengths, handle length, and particularly small slope length 1 showed notable dimensional deviations. A 0.66 mm reduction in small slope length 1 was observed, most likely due to angular mold erosion or material pullback during casting. These areas are more susceptible to distortion due to their narrow shapes, vertical orientations, and sensitivity to geometric changes during wax cooling, shell burnout, and metal solidification. Statistical analysis using one-way ANOVA validated consistent dimensional accuracy across various features of the die against different process stages. Economic considerations reveal substantial savings, reducing production time from approximately 7 weeks to 3 weeks and cutting costs from $720 to $180. These findings underscore the importance of careful control over process parameters, die design, and shrinkage allowances to enhance dimensional accuracy in RIC. Overall, the validated framework demonstrates that RIC is not only technically feasible but also a cost-effective and flexible approach for producing customized aluminum dies with acceptable precision and quality.

Acknowledgment

All authors acknowledge the support of HEC-NRPU (National Research Program for Universities)-17013 for funding this project. The author further acknowledges the administrative and technical support of the University of Engineering and Technology (UET) Taxila and Department of Industrial Engineering, UET Taxila.

REFERENCES

1. Rozeman S., Adesta E. Y. T., Sophian A., and Tomadi S. H., Improvement activities in stamping die manufacturing: a systematic literature review, International Journal of Engineering Materials and Manufacture, 2023; 8(2): 21–35.
2. Selvarajoo S., Raja Ghazilla R. A., and Mamat A., Industrial practices of collaborative manufacturing involving tool and die development: Malaysian perspective, Journal of Manufacturing Technology Management, 2021; 32(2): 485–505.
3. Altan T., Lilly B., and Yen Y., Manufacturing of dies and molds, CiRP Annals, 2001; 50(2): 404–422.
4. Fallböhmer P., Altan T., Tönshoff H.-K., and Nakagawa T., Survey of the die and mold manufacturing industry-Practices in Germany, Japan, and the United States, Journal of Materials Processing Technology, 1996; 59(1–2): 158–168.
5. Hossain M. S. J. and Ahmad N., A neuro-fuzzy approach to select cutting parameters for commercial die manufacturing, Procedia Engineering, 2014; 90: 753–759.
6. Sarfraz S., Shehab E., Salonitis K., Suder W., and Sajid M., Towards cost modelling for laser drilling process, in Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0: IOS Press, 2018; 611–618.
7. Wang K. B., Dailami F., and Matthews J., Towards collaborative robotic polishing of mould and die sets, Procedia Manufacturing, 2019; 38: 1499–1507.
8. Wu S., Lee K., and Fuh J., Feature-based parametric design of a gating system for a die-casting die, The international journal of advanced manufacturing technology, 2002; 19(11): 821–829.
9. Ukey K., Hiremath S., and Majumder H., Investigation of investment casting pattern using fused deposition modeling, Engineering Science & Technology, 2021; 201–207.
10. Shah M., Patel D., Pande S., Abidi M. H., Alasim F., and Mahajan K. A., Dimensional and Surface Roughness Analysis of 3D Printed Impeller Pattern for Investment Casting, 2025.
11. Rosochowski A. and Matuszak A., Rapid tooling: the state of the art, Journal of Materials Processing Technology, 2000/10/31/ 2000; 106(1): 191–198.
12. Abdu Y. A., Shafii T., Dubey K., and Gupta U., Design and analysis of pressure die casting die for automobile component, Global Journal of Research In Engineering, 2016; 16(1): 1–8.
13. Borikar G., Velankar V., Joshi S., Dandawate P., and Deshmukh S., Rapid tooling technologies based on additive manufacturing: a comprehensive review, in Proceedings of International Conference on Intelligent Manufacturing and Automation, Singapore, 2023; 77–88. Springer Nature Singapore.
14. Rosochowski A. and Matuszak A., Rapid tooling: the state of the art, Journal of materials processing technology, 2000; 106(1–3) 191–198.
15. Vaghela J. R., Valaki J. B., Thanki S. J., and Pandey A. B., Sustainability analysis of rapid tooling-based investment casting: a comprehensive review, Smart and Sustainable Manufacturing Systems, 2023; 7(1): 54–81.
16. Wang J., Sama S. R., Lynch P. C., and Manogharan G., Design and topology optimization of 3D-printed wax patterns for rapid investment casting, Procedia Manufacturing, 2019; 34: 683–694.
17. Badanova N., Perveen A., and Talamona D., Study of SLA printing parameters affecting the dimensional accuracy of the pattern and casting in rapid investment casting, Journal of Manufacturing and Materials Processing, 2022; 6(5): 109.
18. Ripetskiy A., Khotina G., and Arkhipova O., The role of additive manufacturing in the investment casting process, in E3S Web of Conferences, 2023; 413: 04015: EDP Sciences.
19. Richard C. T. and Kwok T.-H., Rapid investment casting: design and manufacturing technologies," in International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2019; 59179: V001T02A022: American Society of Mechanical Engineers.
20. Li X. et al., A rapid prototyping method for crop models using the discrete element method, Computers and Electronics in Agriculture, 2022; 203: 107451.
21. Peko I., Špar I., and Basic A., Rapid Prototyping of Mechanical Measurement Level Device. 2016.
22. Shah M., Patel D. R., and Pande S., Additive manufacturing integrated Casting-A review, Materials Today: Proceedings, 2022; 62: 7199–7203.
23. Cheah C. M., Chua C., Lee C., Feng C., and Totong K., Rapid prototyping and tooling techniques: a review of applications for rapid investment casting, The International Journal of Advanced Manufacturing Technology, 2005; 25: 308–320.
24. Arora P., Design, Manufacturing and Development of Hybrid Manufacturing System for Rapid Investment Casting, 2024.
25. Jiang R.-s., Zhang D.-h., Bu K., Wang W.-h., and Tian J.-w., A deformation compensation method for wax pattern die of turbine blade, The International Journal of Advanced Manufacturing Technology, 2017; 88: 3195–3203.
26. Altinbalik M. T. and Mutlu, A comparative cost analysis between conventional and progressive draw die, 2014.
27. Wang X., Zhang D., Li A., Yi D., and Li T. J. M., A review on traditional processes and laser powder bed fusion of aluminum alloy microstructures, mechanical properties, costs, and applications, 2024; 17(11): 2553.

28. Baser T. A., Umay E., Akıncı V., New trends in aluminum die casting alloys for automotive applications, 2022; 21: 79–87.
29. Kalpakjian S., Manufacturing engineering and technology. Pearson Education India, 2001.
30. Chua C., Feng C., Lee C., and Ang G., Rapid investment casting: direct and indirect approaches via model maker II, The International Journal of Advanced Manufacturing Technology, 2005; 25: 26–32.
31. Gibson I. et al., Additive manufacturing technologies. Springer, 2021.
32. Chua C. K., Leong K. F., and Lim C. S., Rapid prototyping: principles and applications. World scientific, 2010.
33. Groover M. P., Fundamentals of modern manufacturing: materials, processes, and systems. John Wiley & Sons, 2010.
34. Vojdani M., Torabi K., Farjood E., and Khaledi A., Comparison the marginal and internal fit of metal copings cast from wax patterns fabricated by CAD/CAM and conventional wax up techniques, Journal of Dentistry, 2013; 14(3): 118.
35. M. A. Corporation. (2021). Portable Surface Roughness Tester Surftest SJ-410 Series. Available: https://www.mitutoyo.com/webfoo/wp-content/uploads/2110_SJ-410-1.pdf
36. Chua C., Feng C., Lee C., and Ang G., Rapid investment casting: direct and indirect approaches via model maker II, The International Journal of Advanced Manufacturing Technology, 2005; 25(1): 26–32.
37. Yu W., Shi J., Sun L., and Lei W., Effects of printing parameters on properties of FDM 3D printed residue of astragalus/polylactic acid biomass composites, Molecules, 2022; 27(21): 7373.
38. Farashi S. and Vafaee F., Effect of printing parameters on the tensile strength of FDM 3D samples: a meta-analysis focusing on layer thickness and sample orientation, Progress in Additive Manufacturing, 2022; 1–18.
39. Tanveer M. Q., Mishra G., Mishra S., and Sharma R., Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts-a current review, Materials Today: Proceedings, 2022; 62: 100–108.
40. I. P. I. Limited. (5 July 2022, 18 October). IMPRO>Investment Casting Surface Finish. Available: https://www.improprecision.com/investment-casting-surface-finish/