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# Enhancing Dimensional Accuracy in Budget-Friendly 3D Printing through Solid Model Geometry Tuning and Its Use in Rapid Casting

**Barun Haldar**

Mechanical Engineering Department, College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11432, Saudi Arabia; bhaldar@imamu.edu.sa

**Abstract:** Achieving precise dimensional accuracy and improving surface quality are the primary research and development objectives in the engineering and industrial applications of 3D printing (3DP) technologies. This experimental study investigates the pivotal role of solid model geometry tuning in enhancing the dimensional accuracy of affordable 3D printing technologies, with a specific focus on economical engineering applications. This experiment utilises low-cost Material Extrusion/Fused Filament Fabrication (FFF) and Stereolithography (SLA)/Digital Light Processing (DLP) 3D-printed patterns for the meticulous measurement of errors in the $X$, $Y$, and $Z$ directions. These errors are then used to refine subsequent solid models, resulting in a marked improvement in dimensional accuracy (i.e., 0.15%, 0.33%, and 2.16% in the $X$, $Y$, and $Z$ directions, respectively) in the final DLP 3D-printed parts. The study also derives and experimentally validates a novel and simple mathematical model for tuning the solid model based on the calculated linear directional errors ($e_i$, $e_j$, and $e_k$). The developed mathematical model offers a versatile approach for achieving superior dimensional accuracy in other 3D printing processes. Medium-sized (4 to 10 cm) wax-made DLP- and PLA-made patterns are used to test the ceramic mould-building capacity for rapid casting (RC), where the FFF-based 3D-printed (hollow inside) pattern favours successful RC. This work comprehensively addresses the critical challenges encountered in low-cost DLP and FFF processes and their scopes in engineering applications. It provides novel suggestions and answers to improve the effectiveness, quality, and accuracy of the FFF 3D printing process for future applications in RC.

**Keywords:** low-cost 3D printing; additive manufacturing; dimensional accuracy enhancing; rapid casting; Industry 4.0



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## 1. Introduction

### 1.1. The 3D Printing Technology and Its Industrial Significance

Basic 3D printing (3DP), a layer-by-layer generative manufacturing process, also known as rapid prototyping (RP), began in the 1980s with the innovation of 3D Systems Inc. CA [1]. Due to its accessibility, 3DP was initially utilised for prototyping by architects and designers. Its usage has now extended to schools, homes, offices, libraries, and labs [2], primarily due to its affordability. The technological and material evaluation tends to the direct manufacturing (DM) [2] of lightweight, strong, and safe products just-in-time with cost benefits. To meet the demands of the ongoing industrial revolution, additive manufacturing (AM)/3DP technologies are booming areas of research and enabling the production of exotic industrial products and even artificial human organs directly from the designed 3D model. The ability to manufacture integrated and complex geometries (which are impossible to produce using conventional manufacturing processes) [3], with high precision, material savings, and design flexibility [4], represents the key features of this cutting-edge technology [5], making it a fundamental component of Industry 4.0 [6]. It offers the potential for mass customisation and personalisation, thereby providing an opportunity to eliminate high custom-tailored production costs [4]. Moreover, it enhances response time, shortens supply chains, cuts storage and delivery costs, and reduces lead times for crucial replacement parts in on-demand manufacturing [3] according to historical global survey statistics and forecasts on yearly spending for final 3DP component manufacturing provided by Hubs, Wohler's Associates, and SmarTech [7–11] are depicted in Figure 1.

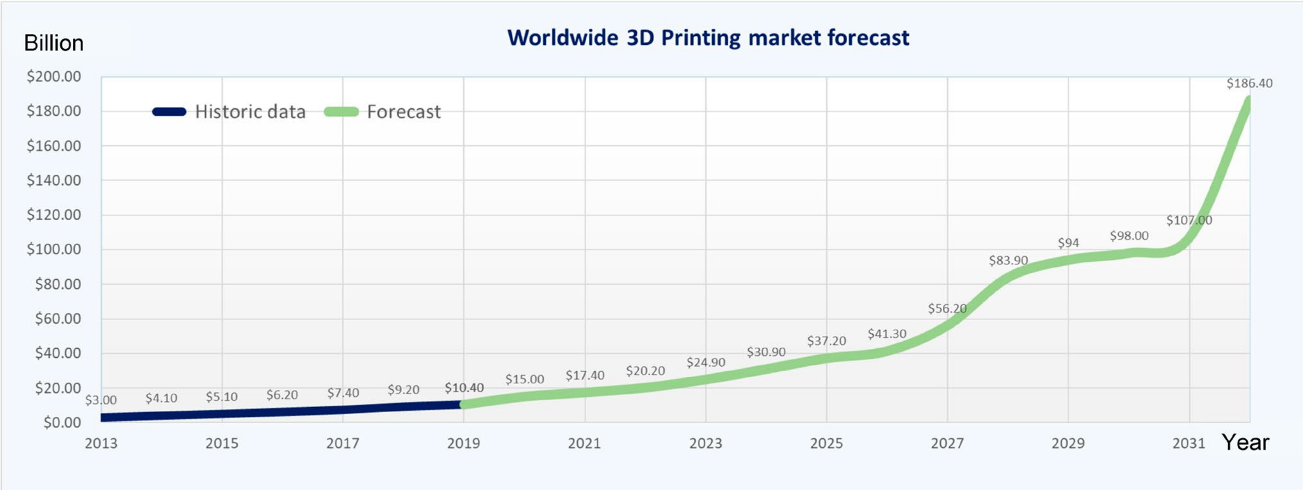


**Figure 1.** Projection of additive manufacturing (AM) worldwide market values [7–11].

AM is rapidly expanding in today's industrial sectors, and the demands of AM have increased almost fourfold in the last five years. Out of the total parts manufactured by 3DP worldwide in 2020 (as plotted in Figure 2), 47% were prototypes, 21% were jigs and fixtures, 29% were aesthetic and functional parts, and 3% were others (data source: Additive manufacturing trend report 2021, Hubs) [8].

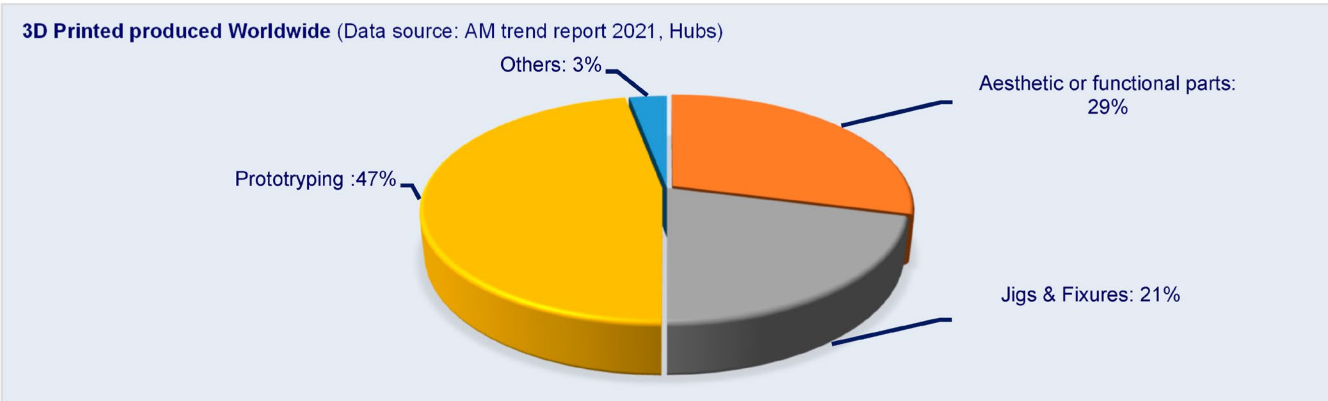


**Figure 2.** Worldwide applications of AM products [8].

The various AM methods' in-built rate vs. machine cost are presented in Figure 3.

Among the various 3DP technologies available, four main additive manufacturing methods stand out: fused deposition modelling (FDM)/material extrusion, binder jetting, stereolithography(SLA), and selective laser sintering (SLS) [4]. In direct metal 3DP/AM processes, the price of the laser and the cost of the raw ingredients (metal powders) make the abovementioned methods expensive to invest in. Industrial-grade metal 3D printers can range in price from several hundred thousand to a few million USD [12], while FDM or SLA printers typically range from a few hundred to a few thousand USD. Figure 4 displays the global share of metal-based AM technologies sold in 2020.

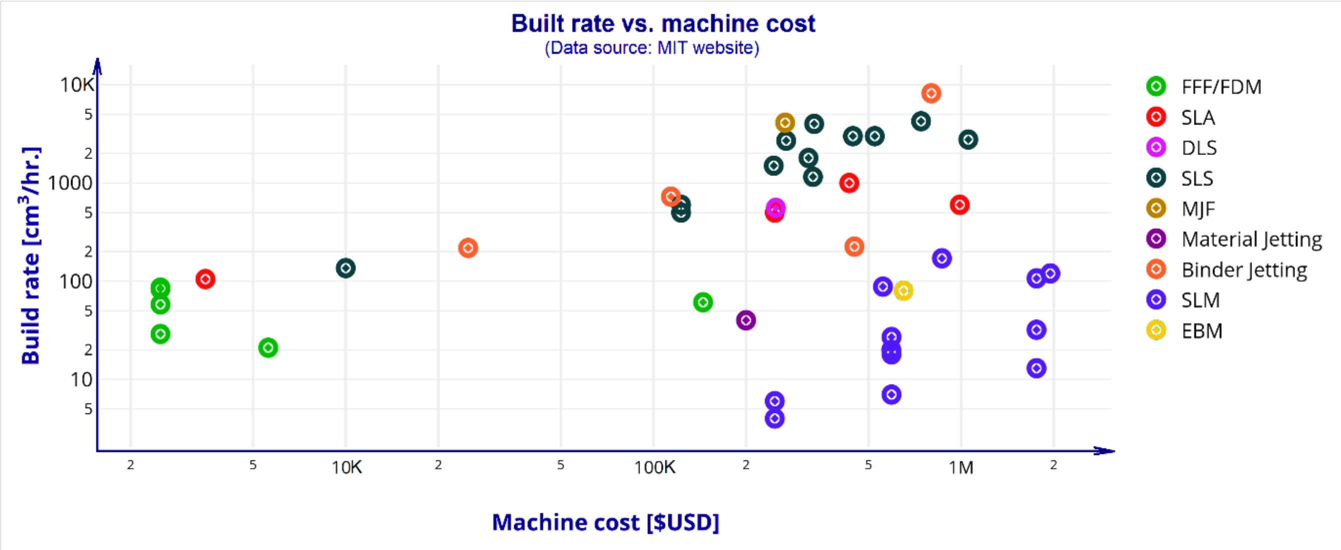


**Figure 3.** Comparing AM processes in-built rate vs. machine cost [12].

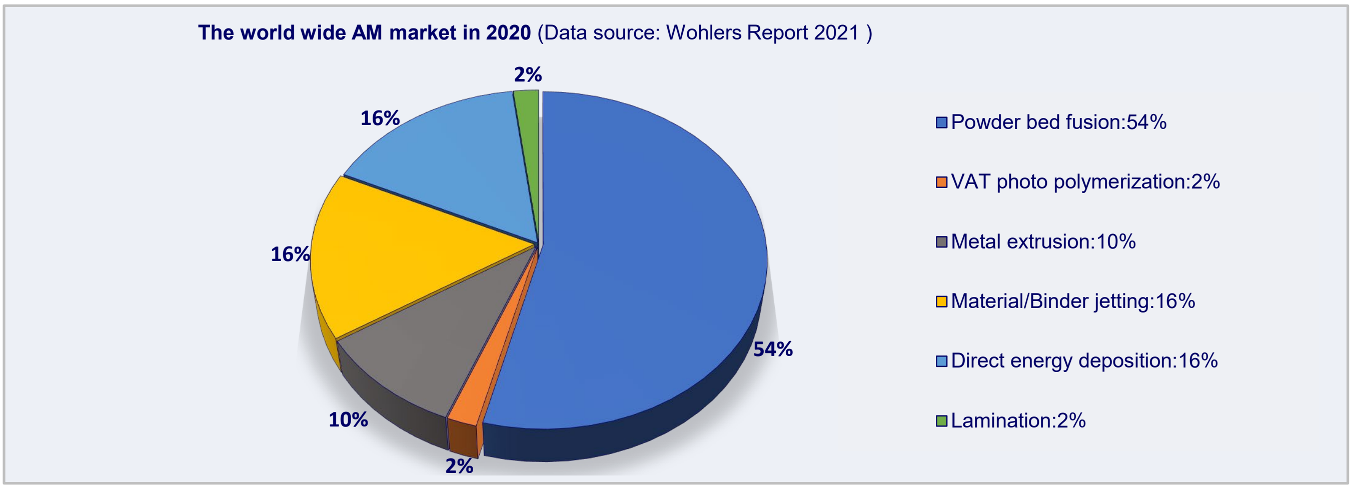


**Figure 4.** The worldwide metal additive manufacturing market in 2020 [3].

On the verge of the growing popularity of low-cost 3DP technologies, FDM/FFF and SLA are the two leading technologies in consideration. In addition, these two technologies are promising for utilisation in the pattern making of RC to produce metallic industrial products in an indirect route. The comparative characteristics of direct metal 3DP vs. polymer and photo-polymer-based low cost (FFF/SLA) are tabulated in Table 1.

**Table 1.** Some comparative critical characteristics of direct 3DP and FFF or SLA cum ceramic casting.

| Characteristics | Metallic Product Manufacturing Through: | |
|---|---|---|
| | **FDM/FFF or SLA Patterns** | **Direct 3DP** |
| Advantages: | ▪ Low cost (polymer) of products, prototypes, and patterns 3DP<br>▪ Low- to medium-complexity metal products can be manufactured by casting using 3D-printed patterns<br>▪ Customised product manufacturing<br>▪ Flexible in metal, alloys, super alloys, product making, etc. | ▪ Direct metal product 3DP<br>▪ High-complexity product-building capacity<br>▪ Customised product manufacturing<br>▪ Wide range of metals and alloys using scopes<br>▪ Scope for product weight reduction (by producing internal mesh structure) for efficient exotic applications like aerospace and medical implants. . . |

**Table 1.** *Cont.*

| Characteristics | Metallic Product Manufacturing Through: | |
|---|---|---|
| | **FDM/FFF or SLA Patterns** | **Direct 3DP** |
| Limitations: | ▪ Costly setup, peripherals, and raw materials<br>▪ High running and maintenance cost<br>▪ Limited manufacturer of metal 3DP machines | ▪ Need skilled staffing<br>▪ Higher production time (due to 3D printing and ceramic/investment casting)<br>▪ A metallic internal mesh structure is not possible |
| Research scope: | ▪ Dimensional accuracy and surface topography [13]<br>▪ Microstructure structure control and defects<br>▪ Artificial intelligence (AI) integration for process control and quality improvement<br>▪ Atomic self-assembly [14] or area-selective atomic layer deposition [15] for faster and quality production<br>▪ Use of difficult-to-machine exotic materials like MMCs, super alloys and nano-materials<br>▪ Quality improvement and cost minimisation [1] | ▪ Dimensional accuracy and surface topography [1]<br>▪ Printing speed and size [1] improvement<br>▪ Widening range of 3DP materials<br>▪ Use of difficult-to-machine exotic materials like MMCs, super alloys, etc.<br>▪ Quality improvement and cost minimisation [1] |

Note: Material extrusion/FFF technology is also under development for direct metal product manufacturing [16].

Advanced metal 3DP (Selective Laser Melting (SLM)) technologies, namely Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Direct Metal Printing (DMP), Laser Powder Bed Fusion (LPBF), and Selective Laser Melting (SLM) [17], use expensive energy sources like laser, electron beam, and costly metal powder for obtaining an exotic metal product through 3DP. This technology allows for free-form design with higher complexity and enables the manufacture of items that no other manufacturing process can produce. Shapes with lower to moderate complexity can be cost-effective through indirect or alternative methods, such as RC. Continuous research and development in FMD/FFF and SLA 3DP technologies are necessary for such benefits to be obtained in industrial contexts. The global demand trends of using polymer and photopolymer in AM were reported (2022) by Wohlers Association [18] and are plotted here in Figure 5.

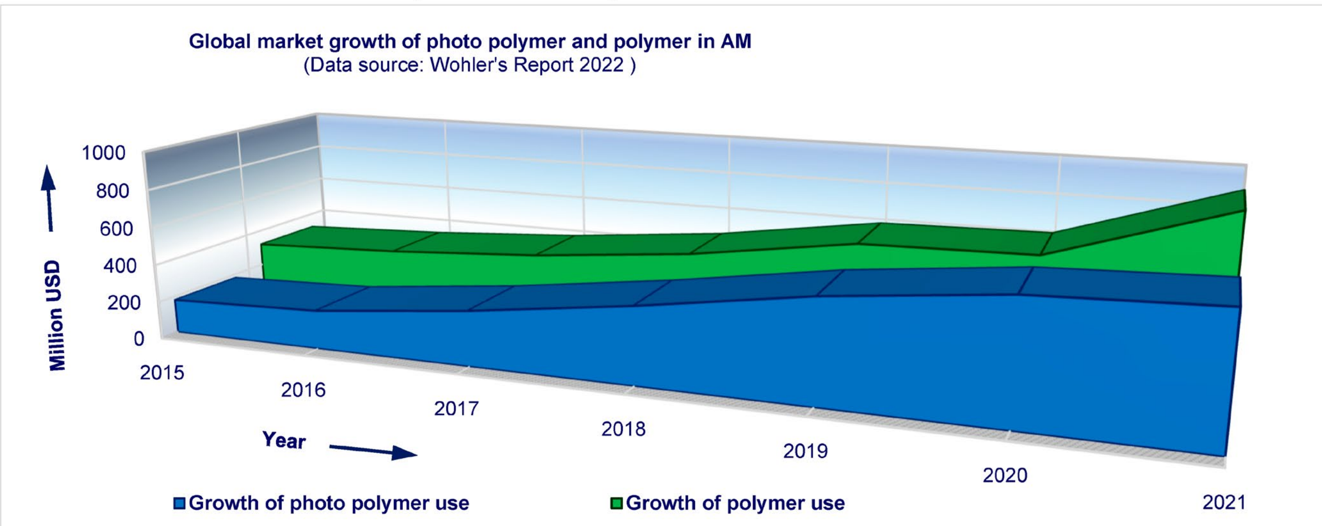


**Figure 5.** Growth of the polymer and photopolymer market worldwide [18].

With the improved dimensional accuracy of low-cost FFF and SLA 3D printing processes, these technologies could gain more popularity in the investment casting of exotic materials and alloys, potentially facilitating cellular manufacturing and encouraging entrepreneurship. To assist in selecting an affordable Fused Filament Fabrication (FFF) or Stereolithography (SLA) process, the comparative characteristics of these processes are provided in Table 2.

**Table 2.** The characteristics of FFF and SLA (DLP) 3DP.

| Characteristics | FDM/FFF process | DLP 3DP |
|---|---|---|
| Cost: | ▪ Mostly available low-cost printer | ▪ Available low-cost printer |
| Consumable: | ▪ Filament | ▪ Vat resin, fluorinated ethylene propylene (FEP) film |
| Running skills: | ▪ User friendly | ▪ The skilled operator is essential in changing FEP film and VAT resin. |
| Health issue: | ▪ Safe in handling<br>▪ No smell | ▪ VAT resin is toxic and detrimental to respiratory and cardiovascular [19] organs |
| Maintenance: | ▪ Easier | ▪ Relatively difficult |
| Running cost: | ▪ Low | ▪ Relatively high |
| Accuracy: | ▪ Poor | ▪ Poor |
| Surface quality: | ▪ Poor due to wavy surface and stair-casing effects [Figure 6a] | ▪ Sooth horizontal and vertical surfaces but sharp stair-casing results in slanting characters [Figure 6b]. |
| Complexity: | ▪ Highly complex geometry builds possible | ▪ Suitable for low- to medium-complexity geometry |
| Material savings: | ▪ Inside mesh/honeycomb structure [Figure 6a] can save material, and it is favourable to accommodate thermal stress in RC ceramic shell burning | ▪ Inert [Figure 6b] and material saving is not possible |

The layer-by-layer material build mechanisms of FFF and DLP 3DP processes are shown in Figure 6a,b, respectively.

The mesh/honeycomb building capacity of FFF 3DP under the surfaces of the workpiece is adequate for material savings, while using it as a pattern in RC, it can also easily accommodate thermal expansion due to burning of the ceramic mould for cavity making. On the other hand, the SLA process is well established for minimal non-engineering product RC, like, making of jewellery, dentistry [20–23], items where dimensional tolerance is not mandatory.

The improvement in the dimensional accuracy of such low-cost FFF and SLA processes and experimental investigations to use such patterns in RC may beget effective outcomes for the successful engineering implementation of such technology. This may significantly reduce the initial investment cost for manufacturing metallic products in the rapid casting (RC) route, which is favourable for fostering entrepreneurship development and industrial applications.

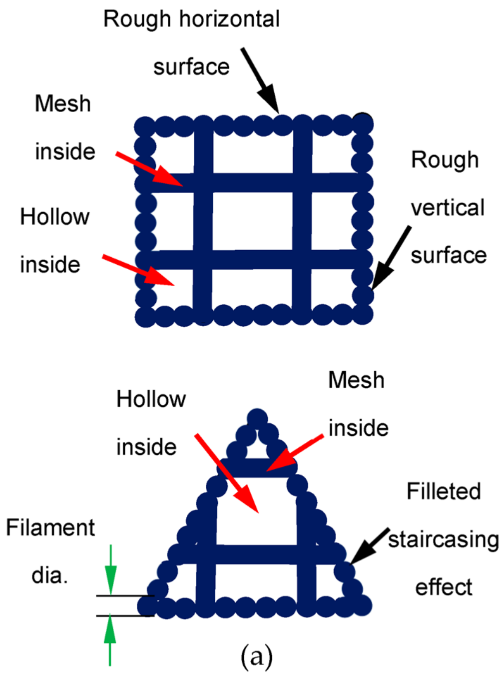


**Figure 6.** The layer-by-layer material build mechanisms of (**a**) FFF and (**b**) DLP 3D printing processes.

### *1.2. Integration of 3DP in Rapid Casting in Industrial Contexts*

The World Casting Census 2019, published by the American Foundry Society in 2021, reported the existence of more than 45,377 [24] well-functioning metal casting plants worldwide. Approximately 10% of these plants produce high-quality steel products through the ceramic shell and/or investment casting processes. These processes are near-net-shaped manufacturing methods that enable the production of complex metal shapes with a high dimensional accuracy and excellent surface finish [25], often without the need for post-processing. The main advantages of conventional IC are [26]:

- Shape complexity: almost any degree of external complexity and a wide range of internal complexity can be achieved;
- Freedom of alloy selection: super alloys, MMC, advanced materials, etc.;
- Close dimensional tolerances: consistent and repetitive close tolerances [27] and accuracy grade between CT4 and CT8 [28];
- The availability of prototype and temporary tooling;
- Reliability: demanding industries, including gas turbine engines, petroleum, chemicals, military, and medicine, have long relied on investment casting [27];
- Wide range of applications: few grams to more than 300 kg.

The ceramic shell mould can withstand high pouring temperatures (1500 °C to 1600 °C) [29], which makes the process compatible with casting high-temperature melting point metals, such as $Y_2O_3$, $CaZrO_3$, etc. Ceramic shells [30,31] enable the casting of metals like titanium (with a melting point above 1600 °C) and superalloys.

The hybridisation of investment casting using a low-cost 3DP (FFF, SLA) pattern can overcome the use of the high investment cost (varies from 100K to 2M USD) [12] of metal 3DP.

Additionally, the hybridisation of cost-effective 3D printing (FFF, SLA) with investment casting has the potential to eliminate mutual limitations and yield combined advantages from both processes. The key characteristics of low-cost 3D printing (FFF, SLA), investment casting (IC), and RC (hybrid) are summarised in Table 3.

**Table 3.** The characteristics of low-cost 3D printing (FFF, SLA), investment casting (IC), and RC [1].

| Characteristics | Low-Cost (FFF, SLA) 3DP (AM) Technologies | Investment Casting | Rapid Investment Casting/Rapid Casting |
|---|---|---|---|
| Cost: | Low | Metallic die price is affordable in mass production only. | Profitable for job production to batch production, reverse engineering, just-in-time, and cellular manufacturing |
| Material: | Low melting points like PLA, PVA, WAX, etc. | Metals, alloys, super alloys | Metals, alloys, super alloys |
| Production time: | 1 to 7 days for a batch of product | Significant time consumed initially for making metallic dies | 2-8 days for a batch of product |
| Geometry complexity: | FDM/FFF can make any complex internal geometry, and any externally connected internal geometry can be made using SLA 3DP | Any externally connected internal geometry can be made using SLA 3DP | Any externally linked internal geometry can be made using SLA 3DP |
| Just-in-time: | Possible | Not viable for small amounts and quick delivery | Possible |
| Cellular manufacturing: | Possible | NA | Possible |
| Reverse engineering: | Possible | NA | Possible |

Finally, the augmentation of cost-effective metal products using RIC/RC (hybrid) will reduce the initial investment cost and production cost in some production ranges. Additionally, a wide variety of raw materials, including metals, alloys, superalloys, and metal matrix composites, can be used, thereby opening up further research opportunities. The expansion of metallic product manufacturing through rapid casting (RC) using Fused Filament Fabrication (FFF) or Stereolithography (SLA) patterns may present the following research and application opportunities, as depicted in the schematic gear diagram in Figure 7.

Aircraft engines, robot parts, airframes, aerospace, missiles, fuel systems, automotive, bicycles and motorcycles, materials handling equipment, ground support systems, agricultural equipment, textile equipment, baling and strapping equipment, dentistry and dental tools electrical equipment, cameras, electronics, radar, guns and small armaments, hand tools jewellery, machine tools, metalworking equipment, pneumatic and hydraulic systems, oil well drilling and auxiliary equipment, prosthetic appliances, high-pressure pumps, sports items, turbines, and wire processing equipment/parts [26] could all be effectively manufactured using the RC/RIC process.

The present state-of-the-art research status of hybrid 3DP and casting, i.e., RC, is presented in Table 4.

**Table 4.** The research status of RC (hybrid) and IC.

| Researcher/s Details | Research Objectives | Materials | Results/Conclusion |
|---|---|---|---|
| (2021), F. Li et al. [32] | ▪ SS impeller RC through 3DP of ceramic shell | ▪ $Al_2O_3.2SiO_2$ (calcined kaolin) suspension and UV-curable resin binder, sintered at 1200 °C | ▪ Shell work surface roughness 4.51~4.82 µm<br>▪ Post-treatment of the ceramic shell with a fine clay ceramic layer improved the surface quality of the parts |

**Table 4.** *Cont.*

| Researcher/s Details | Research Objectives | Materials | Results/Conclusion |
|---|---|---|---|
| (2020), M. Mukhtarkhanov et al. [33] | ▪ RC through FEM and SLA 3DP | ▪ Patterns: ABS, PLA, WAX | ▪ Surface finish 83% enhanced due to the post-treatment of ABS and PLA patterns.<br>▪ Wax pattern tolerance limit up to 500 µm |
| (2019), UE Klotz et al. [31] | ▪ IC of titanium alloys with | ▪ Silica and calcium zirconate ($CaZrO_3$) shell, yttria face coat on alumina-based crucibles, $CaZrO_3$ crucibles | ▪ $CaZrO_3$ showed stability as a shell and crucible in Ti casting |
| (2019), V. K. Tiwary et al. [34] | ▪ FDM-based pattern for improving the surface quality of medical implants | ▪ Pre- and post-processing of acrylonitrile butadiene styrene FDM pattern for IC of low alloy carbon steel | ▪ Surface roughness decreased from 23.37 to 0.68 µm, dimensional divergence from 1 to 3%, and lead time reduced from one week to one day<br>▪ Polystyrene/wax/ PLA as FDM pattern materials could be used for comparative study |
| (2018), D. Wang et al. [35] | ▪ Shorten the production cycle time of the IC impeller through simulation and optimisation of the gating system | ▪ Wax patterns: high-impact polystyrene (HIPS) and photosensitive resin by SLS and SL processes. Mould shell: Silica and zircon clay | ▪ Rapid IC reduces production lead time and costs and improves product quality<br>▪ The photosensitive resin is not suitable for IC |
| (2013), Y. Chen et al. [30] | ▪ Thin-walled high-temperature Ti alloy IC | ▪ Wax patterns made using an aluminium mould<br>▪ $Y_2O_3$, $ZrO_2$, and $Al_2O_3$ shell pre-heating at 300, 600, and 900 °C and filled, mesh pattern used for filling capacity evaluation | ▪ High pre-heating temperature increases interfacial reaction, $Y_2O_3$ shell performs better at 300 °C pre-heating<br>▪ Using a 3D-printed pattern for making a $Y_2O_3$ shell and a comparative study could be performed in IC |
| (2012), M. Macků and M. Horáček [36] | ▪ Dimensional changes study in FDM to IC of AlSi7Mg0.6 | ▪ FDM ABS pattern was used in the silicon die of the wax pattern making | ▪ Dimensional variation in the final product is about 1 to 2%<br>▪ The use of direct wax pattern 3DP may further improve dimensional accuracy |

**Table 4.** *Cont.*

| Researcher/s Details | Research Objectives | Materials | Results/Conclusion |
|---|---|---|---|
| (2010), S. Wang et al. [37] | ▪ Expandable plastic patterns used in IC | ▪ The plastic pattern is burnt at 1120 °C to obtain a cavity in the ceramic shell | ▪ Successful metal IC<br>▪ Plastic patterns burning may cause environment-related issues |
| (2011), M. Vaezi et al., 2011 [38] | ▪ Reverse engineering using RC of turbine blades | ▪ Wax patterns made by MultiJet Modelling (MJM) and CNC machined aluminium die | ▪ MJM technology is cheaper and has a shorter lead time for job-shop production<br>▪ CNC-machined aluminium dies may be beneficial in mass production |
| (2007), E. Bassoli and A. Gatto [39] | ▪ Dimensional accuracy in the cavity of light-alloys IC | ▪ Starch patterns and ZCast process | ▪ ZCast shows satisfactory results<br>▪ The ZCast process leaves parting line marks on the product surface |

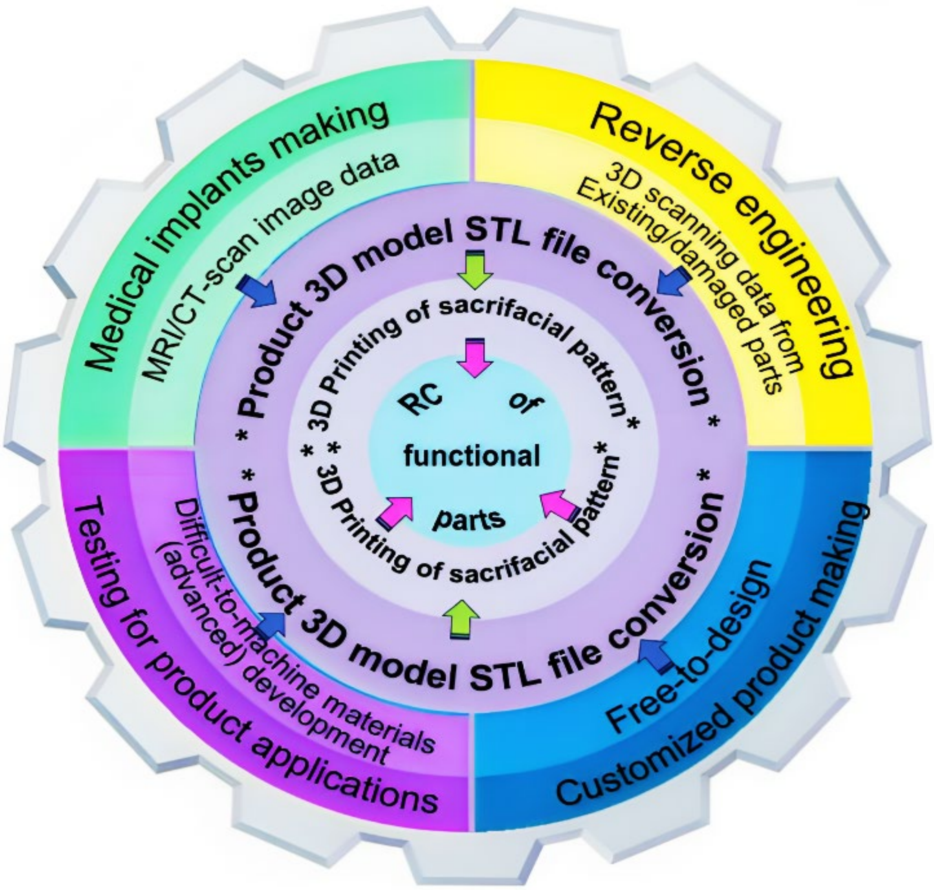


**Figure 7.** Research and the application scopes of RC/RIC through 3DP.

Searches and reviews indicate that there has been limited research conducted on the RC/hybridizing of 3DP and the precision casting process. The process has considerable potential to reduce the production cost from job shop to batch production levels. Unless the direct metal 3D printing process becomes cost-effective (which is challenging), the RC process may serve as an alternative, to some extent, for cost-effective production. Therefore, the use of affordable 3D printers has the potential to significantly reduce overall production costs if the dimensional accuracy of such 3D printing can be enhanced for engineering and industrial applications. The author of this work employed solid model geometry adjustments to enhance the dimensional accuracy of affordable FFF and SLA/DLP printing patterns. These adjustments were experimentally applied in ceramic casting to explore the potential for further development in this field. A schematic overview of the present work is given in Figure 8.

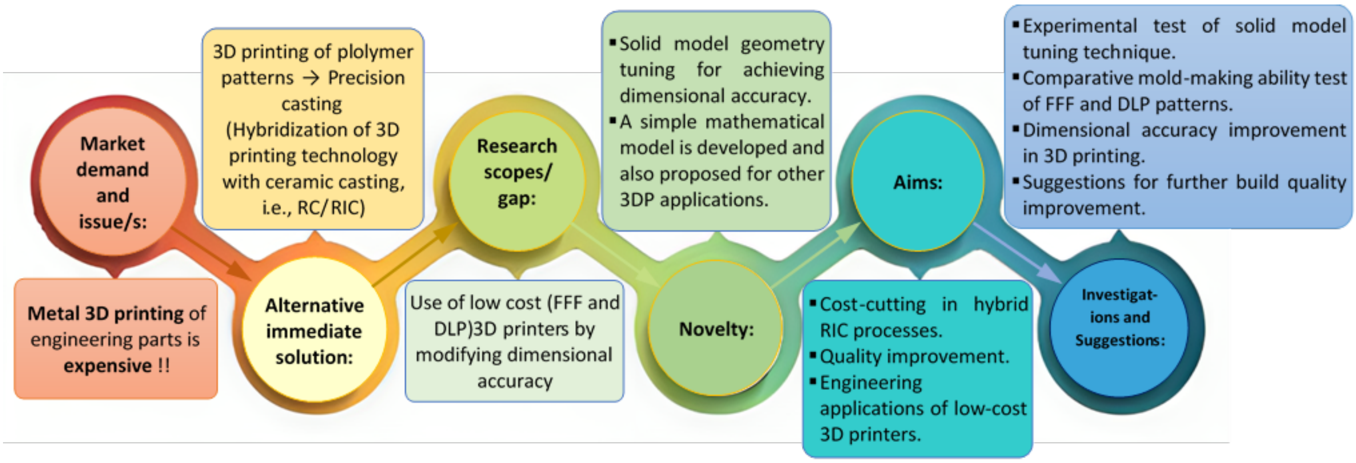


**Figure 8.** The inherent target of the present investigation of solid model tuning.

*1.3. Statement of the Research Objectives*

This work aims to explore the potential application of affordable prototype-making 3D printers in engineering product manufacturing through a novel solid model tuning technique and its implementation in rapid casting (RC). To achieve these aims, the following objectives are set in this experimental investigation to improve the dimensional accuracy and quality of the final product.

- To develop a solid model (1st phase) and 3DP by FFF and SLA (DLP) technology and measure the dimensional variations in $X$, $Y$, and $Z$ directions.
- Tuning/modifying first solid mode by adjusting dimensional variations (allowances) in $X$, $Y$, and $Z$ directions and developing a modified solid model (second) and 3DP for dimensional accuracy improvement verification.
- A modified solid model is used for pattern printing in the FFF and SLA (DLP) process and tested to make the same metallic parts in rapid casting.
- Exploring the technical issues and remedial measure findings as the future scope of this work.

## 2. Materials and Methods

*2.1. Three-Dimensional Printing Machine and Material Details*

A budget-friendly DLP and an FFF 3DP machine are used in this investigation. The machine and material details are as follows:

SLA 3D printer: JX215 (China make) DLP (light curing LCD) 3D printer with volume-built rate (215 × 135 × 15) mm$^3$ per hour, LCD screen spot size 0.0067 mm$^2$, 405 nm light wavelengths based wax photopolymer resin, layer thickness 0.025 mm. Slicer 2.4.0 software supplied with the machine makes STL files from Auto CAD 3D models.

FFF 3D printer: Ultimaker S3(USA made) FFF 3D printer with built size (230 × 190 × 200) mm$^3$, speed ~24 mm$^3$/s, nozzle size 0.25 mm, PLA filament, nozzle temperature 220 °C.

### 2.2. RC Mould Making and Material Details

Silica sand (180 to 300 microns) and gypsum, mixed in a 50:50 wt.% ratio with water, are stirred to create clay. A small amount of acetone (1 to 2%) is added to reduce bubbles in the clay. The patterns, which are fixed inside the mould box, are submerged in the ceramic slurry and left for an hour. After solidification, the moulds are baked in a muffle furnace at temperatures of 650 °C, 450 °C, and 350 °C for 2 h, 4 h, and 8 h, respectively. Brass is used as the working material for casting tests.

### 2.3. Techniques for Solid Model Geometry Tuning

The technique and experimental procedure for the tuning of the solid model dimensions are described with the process flow cycle in Figure 9. All the measured dimensions are the average of three consecutive measurements.

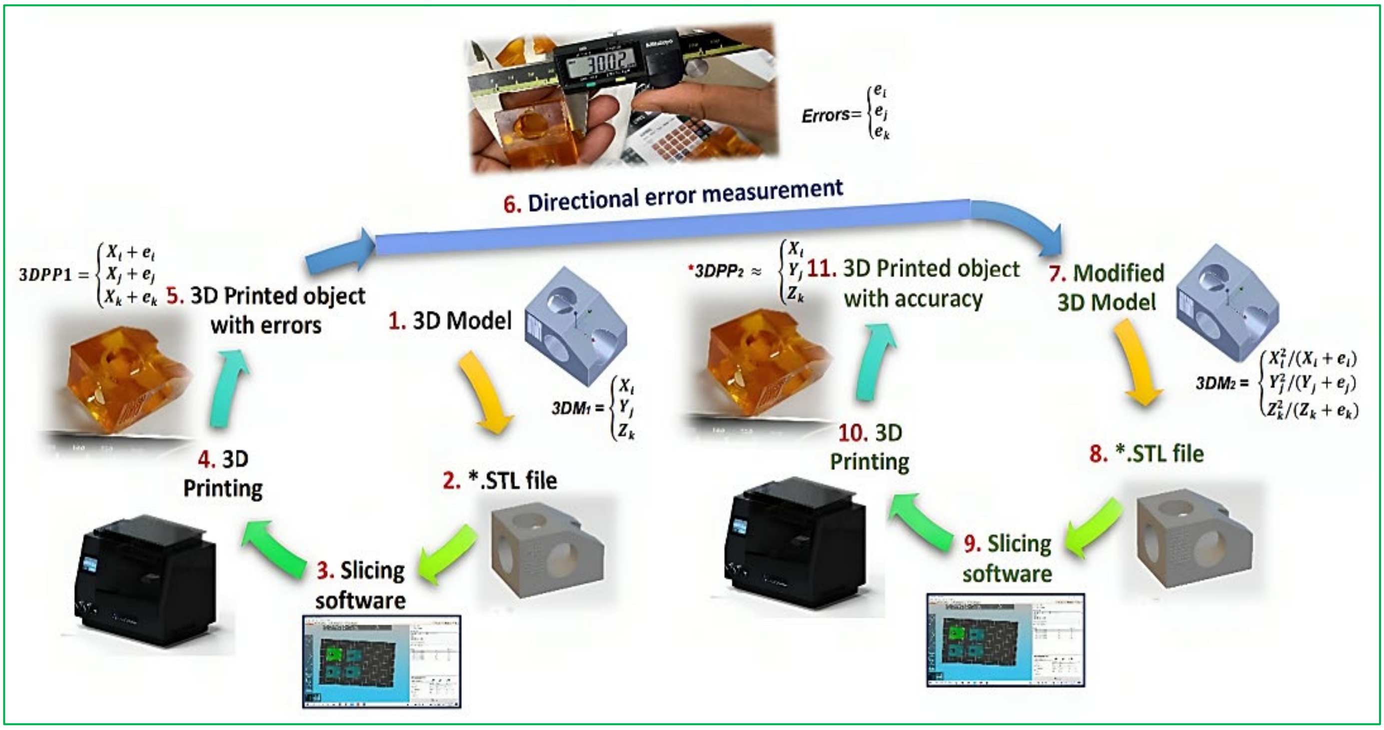


**Figure 9.** The process cycle of solid model tuning for error compensation in dimensional accuracy improvement.

#### The Error-Tuning Model

The model for calculating the dimensions for the tuning of the 3D model, aiming to obtain the targeted dimensions, is as follows:

Assume that the 3D model 1 dimension, $3DM_1 = \begin{cases} X_i \\ Y_j \\ Z_k \end{cases};$

which is used to make the 3D-printed parts. But, after 3DP, the measured 3D-printed pattern1 dimensions are

$$3DPP_1 = \begin{cases} X_i + e_i \\ Y_j + e_j \\ Z_k + e_k \end{cases};$$

and now the tuning of the 3D model dimensions is

$$3DM_2 = \begin{cases} X_i^2/(X_i + e_i) \\ Y_j^2/(Y_j + e_j) \\ Z_k^2/(Z_k + e_k) \end{cases};$$

i.e., $3DM_2$ will expectedly produce $3DPP_2$ with the dimensions of $3DM_1$

$$3DPP_2 \approx \begin{cases} X_i \\ Y_j ; \\ Z_k \end{cases}$$

so,

$$\underbrace{\begin{cases} X_i \\ Y_j \\ Z_k \end{cases}}_{\textit{Final product dimensions}} \rightarrow \underbrace{\begin{cases} X_i^2/(X_i + e_i) \\ Y_j^2/\left(Y_j + e_j\right) \\ Z_k^2/(Z_k + e_k) \end{cases}}_{\textit{Tuned 3D model dimensions}}$$

where, $X_i$, $Y_j$, and $Z_k$ are the actual 3D model dimensions in the $X$, $Y$, and $Z$ directions, respectively, and $e_i$, $e_j$, and $e_k$ are the measured errors on 3D-printed parts in the $X$, $Y$, and $Z$ directions, respectively, using the same 3D model.

### *2.4. Rapid Casting Test*

The tuned 3D model is employed in 3D printing to generate an enhanced pattern. This pattern is then attached to a wax gating system and placed beneath a layer of ceramic clay, resulting in the solidification of a green ceramic mould, as depicted in Figure 10a. The green ceramic mould is then subjected to baking inside a muffle furnace to sacrifice the wax pattern assembly and form a mould cavity. The worked metal (brass) is melted and heated up to 1100 °C and then poured into the ceramic mould cavity, as shown in Figure 10b.

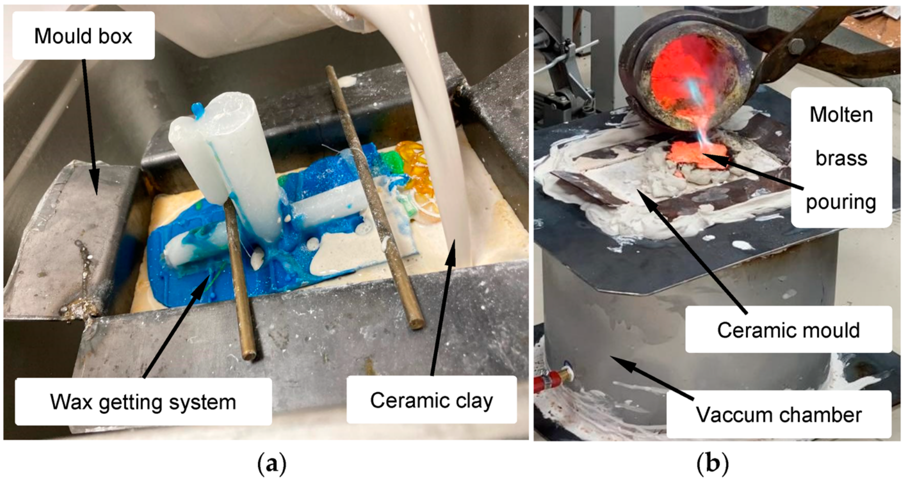


**Figure 10.** Rapid casting (**a**) green mould making and (**b**) pouring of molten material in a ceramic mould.

After the workpiece solidifies and cools down, the ceramic mould is broken, and the excess impressions (gating system: sprue, runner, risers, etc.) are removed, and the surface is cleaned with a metallic brush and shop water.

## 3. Results and Discussions

Material extrusion/FFF and SLA/DLP 3D printing technologies are among the recent low-cost 3D printing machines available on the market. The improvement in the dimensional accuracy of these 3D printing processes within engineering tolerances can be effective for engineering applications, potentially reducing the overall investment cost of final products. Such an improvement can encourage the growth of small-scale and micro-industries, as illustrated in Figure 11 below.

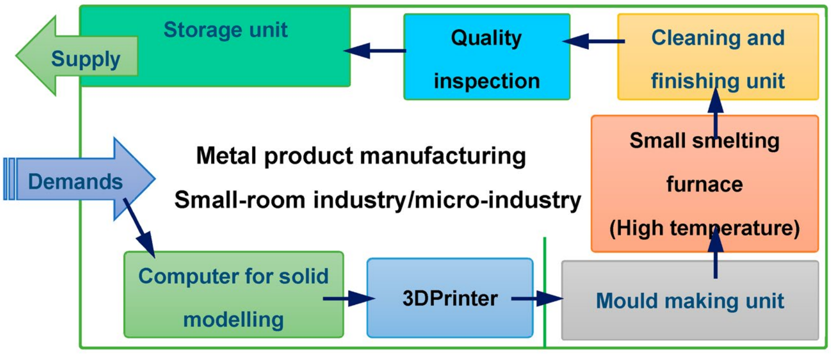


**Figure 11.** A job shop floor plan for a future RIC micro-industry.

The future RIC industry described above would have the capability to manufacture a wide variety of advanced materials and products for testing and job production.

### 3.1. Presentation of Empirical Data Showcasing Dimensional Accuracy before and after Geometry Tuning

A simple 3D model is made for the ease of validating the error tuning model, and the measured (as in Figure 12) and calculated data are given in Table 5.


**Figure 12.** Three-dimensional-printed specimen made from tuned model and error measurement (**a**) in *X*, (**b**) in *Y*, and (**c**) in *Z* directions.

**Table 5.** Three-dimensional-printed parts dimensions before and after 3D model tuning.

| 3D Object Directions | 1st Model Dimension (Actual Target) | 1st Printed Object Dimensions (mm) | Tuned 2nd Model Dimensions (mm) | 3DP Specimen after Solid Model Tuning (mm) | Actual Error (%) (Before Validation) | Error (%) in 3D-Printed Specimen after Validation | Reduction in Error (%) after First Validation |
|---|---|---|---|---|---|---|---|
| X | 40 | 40.48 | 39.52 | 40.42 | 1.2% | 1.05% | 0.15% |
| Y | 30 | 30.12 | 29.88 | 30.02 | 0.4% | 0.07% | 0.33% |
| Z | 25 | 24.51 | 25.51 | 25.03 | −2.04% | 0.12% | 2.16% |

For validating the tuned model, the dimensions of the 3D-printed parts are measured before and after 3D model tuning, and the improvement in the dimensional accuracy is given in Table 5.

By applying the developed mathematical model here, the dimensional accuracy of rapid casting could be significantly improved, as observed in Table 5.

### 3.2. Observations in Rapid Casting

The trial experiment was performed to realize the rapid casting (as in Figure 13) ability using the FFF and SLA(DLP) wax patterns. The observations and results of the rapid casting test are provided in Table 6.

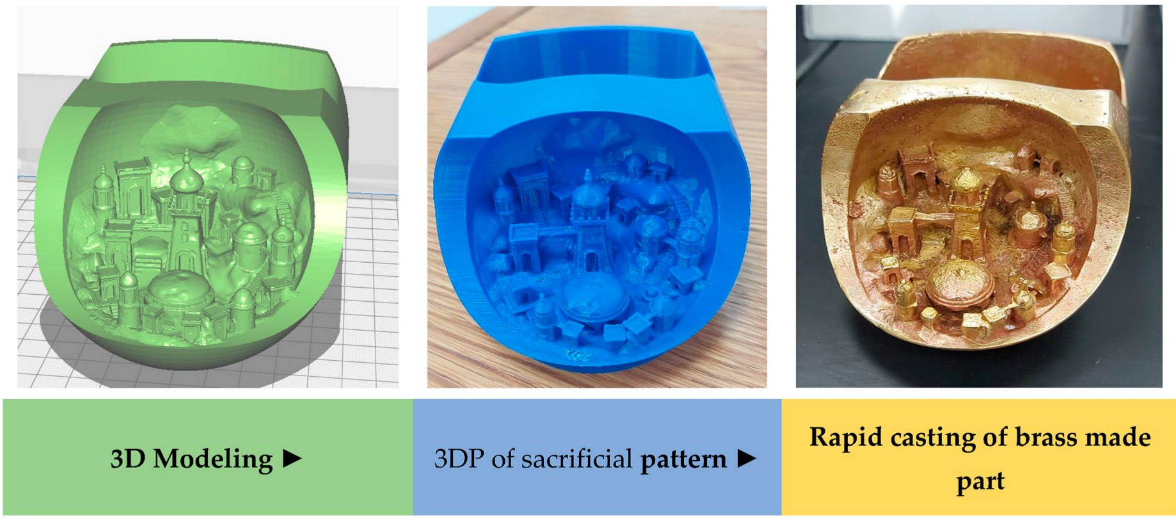


**Figure 13.** Rapid ceramic casting process sequence in reality in this investigation.

**Table 6.** Observations on applications of low-cost FFF and DLP 3DP in rapid casting.

| Pattern-Making Process and Material | Observations | | | |
|---|---|---|---|---|
| | Pattern Surface Quality | Pattern Burning Effects | Mould Quality | Rapid Casting Status |
| **FFF/PLA:** | ▪ Rough surface (Ra ≈ 20 µm);<br>▪ Staircasing in slanting surfaces | ▪ Smell in PLA burnin<br>▪ Small ash formed in the mould cavity | ▪ Mould formed successfully<br>▪ Some ash stacked mould on the inner side | ▪ Casting completed successfully<br>▪ Minute surface defects made due to ash<br>▪ Stair casting impression observed |
| **SLA(DLP)/ Wax:** | ▪ Smooth surface (Ra ≈ 5 µm);<br>▪ Staircasing in slanting surfaces | ▪ No smell<br>▪ No ash formed | ▪ A large crack formed in the mould due to the thermal expansion of the wax pattern | ▪ Failed (due to mould damage) |

From the above observation, RC was not successful using the SLA wax pattern, which was generated using the UV photopolymer. The researcher D. Wang et al., in 2018 [35], also reported that photosensitive resin is not suitable for IC. On the other hand, it could be said that the FFF pattern is more effective in making medium-sized ceramic moulds. This might be due to the honeycomb/net structure/vacant space inside the pattern body surfaces that may easily accommodate thermal stress [34], as schematically shown in Figure 14. R. V. Baier et al. [40] demonstrated that low-cost, in-house FFF printers can efficiently produce porous structures comparable to those made by commercial, higher-cost FFF 3D printers.

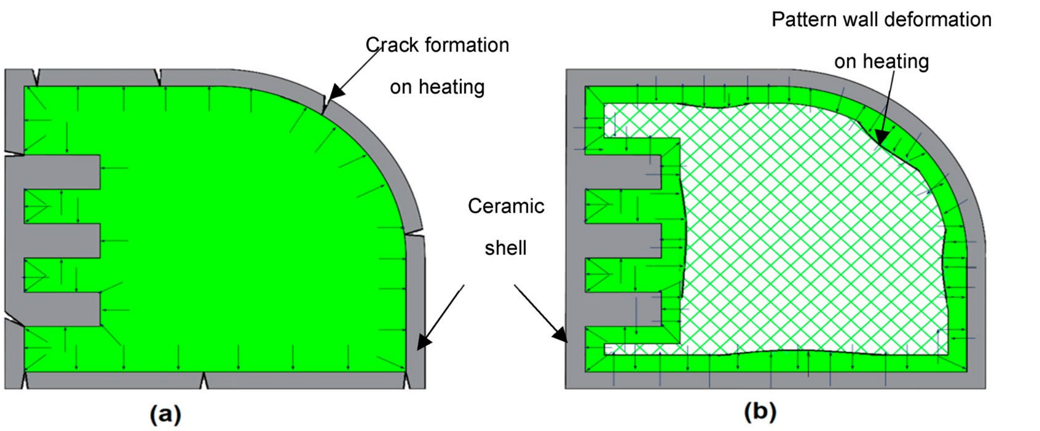


**Figure 14.** Nature of thermal stress compensation in (**a**) solid/inert pattern by SLA and (**b**) honeycomb/net structured pattern by FFF method and their effect on ceramic shell.

However, the rough surface of the FFF pattern and ash PLA content hinder the RC product's quality. So, FFF wax filament (non-ash content and no smell in burning) may be selected for pattern 3DP with a surface modification for RC. The FFF pattern can save pattern material and it is easier to modify the surface to improve the surface quality.

A circular nozzle is used to extrude the filament for layer deposition, which is a common practice. Surface roughness, height loss, gap between the layers, etc., hinder the quality of FFF 3DP. To improve surface quality in FFF 3DP parts/patterns, chemical treatment, vapour treatment, polishing [34], laser polishing [41], and micro-grit/sand blasting [42] techniques are practised by some researchers. Laser polishing shows promise in enhancing strength and sustainability. Additionally, the printing quality of low-cost 3D printers can be improved by increasing machine stiffness and reducing chatter [43].

The present author proposes using a rectangular FFF nozzle with rounded corners to extrude a filleted square cross-section filament for layer deposition, as illustrated in Figure 15a. This approach is expected to mitigate internal gaps and reduce height loss compared to circular filament deposition, as shown in Figure 15b.

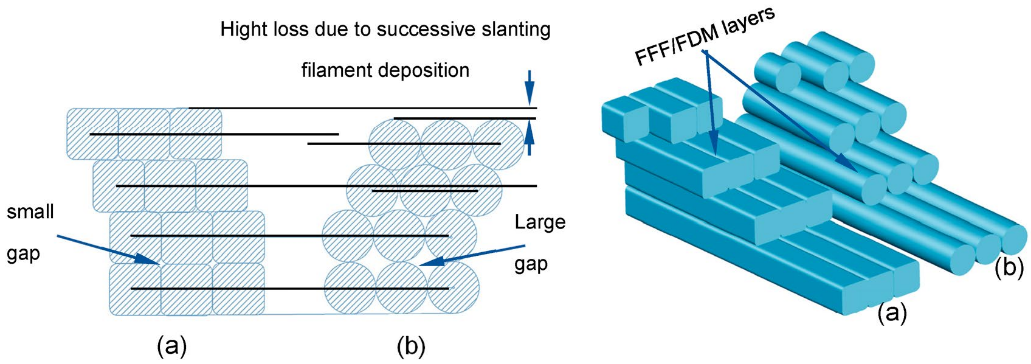


**Figure 15.** Geometrically proven improvement in deposition quality in FFF 3DP using (**a**) filleted square cross-section compared to (**b**) round cross-section filament.

It is clear from the above figure that the filleted square cross-section extrusion nozzle may have an effect on reducing the internal gaps in FFF-made parts, which could be a future area of investigation.

## 4. Conclusions

The research survey and experimental investigation conducted in this study aim to develop and establish solid model tuning for improving dimensional accuracy and implementing it in engineering and industrial applications. This work leads to the following observations being made:

- Highly complex parts that cannot be manufactured using other manufacturing processes can be effectively produced through direct metal 3D printing. For low- to medium-complexity metal parts, cost-effective production can be achieved through the RC/RIC process.
- A substantial amount of research and investigation is crucial for the commercialisation of the RC/RIC process.
- Affordable 3D printing (3DP) technologies, such as FFF or DLP processes, can potentially be leveraged for cost-effective engineering applications and the manufacturing of metal products using the RC/RIC route in job shop production houses through solid model tuning.
- The proposed and experimentally tested mathematical model for solid model geometry tuning can be applied to other 3D printing methods to enhance the dimensional accuracy of 3D-printed products, making them compliant with engineering tolerances and suitable for various applications.
- This study examines the ceramic mould-building capacity for rapid casting (RC) using medium-sized (4 to 10 cm) wax-made DLP patterns and PLA-made FFF patterns. The hollow interior of the FFF-based 3D-printed patterns facilitates successful RC.
- The suggested filleted square shape extruder nozzle may deposit better build quality products than the commonly used circular extruder in FFF 3DP.
- Such low-cost process development could enable the establishment of a room-based or micro-scale RC/RIC industry with a low initial investment cost.

Immense research scopes exist in this domain to improve product quality and minimize production costs. Hence, rapid casting is a solution to produce low- to medium-complexity metallic products in job-to-batch production.

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## Nomenclature

| | |
|---|---|
| 3DP | 3D Printing |
| AI | Artificial Intelligence |
| AM | Additive Manufacturing |
| DLP | Digital Light Processing |
| DLS | Digital Light Synthesis |
| DM | Direct Manufacturing |
| DMLS | Direct Metal Laser Sintering |
| DMP | Direct Metal Printing |
| EBM | Electron Beam Melting |
| FDM | Fused Deposition Modelling |
| FEP | Fluorinated Ethylene Propylene |
| FFF | Fused Filament Fabrication |
| IC | Investment Casting |
| LPBF | Laser Powder Bed Fusion |
| MJF | Multi Jet Fusion |
| MMC | Metal Matrix Composite |
| PLA | Polylactic Acid |
| RC | Rapid Casting |
| RP | Rapid Prototyping |
| SLA | Stereolithography |
| SLM | Selective Laser Melting |
| SLS | Selective Laser Sintering |

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