Overview on Rapid Investment Casting of Pattern making process

Chiradip Pal
Mechanical Engineering Department
Dr. B. C. Roy polytechnic
Durgapur, India
chiradip.pal@bcrec.ac.in

Amlan Datta
Mechanical Engineering Department
Dr. B. C. Roy polytechnic
Durgapur, India
amlan.datta@bcrec.ac.in

Rohit Ghosh
Mechanical Engineering Department
Dr. B. C. Roy polytechnic
Durgapur, India
rohitghosh7678@gmail.com

***Abstract*— RIC i.e. Rapid investment casting is a manufacturing process that uses Additive Manufacturing (AM) technologies to create master patterns. Common techniques for producing wax and non-wax patterns contain FDM (Fused Deposition Modeling), ink-jet rapid prototyping, and Stereolithography (SLA). The characteristic of RIC products is influenced by the abilities and inabilities of each AM technology and the materials used. In addition to pattern materials like wax, thermoplastic, ice, and photopolymer, this paper evaluates the benefits and drawbacks of FDM, MMII (Model Maker II), SLA, and RFP (Rapid Freeze Prototyping). The evaluation indicates that SLA yields the highest quality patterns, while FDM (Fused Deposition Modeling) is the most economical option. Additionally, new challenges in materials, including how ice patterns develop, have been identified and require further research. Additionally, the paper reviews recent models for the investment casting process's numerical simulations, noting that most studies focus on estimating the time needed for solidification, hot spots, areas of hot tearing, and macro and micro porosities**

Keywords*— RIC (Rapid investment casting); solidification simulation; stereolithography (SLA); additive manufacturing (AM); fused deposition modeling(FDM)

I. INTRODUCTION

IC (Investment casting) is a widely recognized manufacturing method for producing intricate metal components that are high quality and close to net shape. It is employed in the mass production of complex geometrical products. IC has a broad range of applications across various industries, including aerospace, automotive, firearms, power generation, energy, military, oil and gas, food, and custom commercial needs.(1,2).

IC is commonly referred to as lost-wax casting because wax patterns are eliminated from the ceramic shell at the time of heating process (de-waxing). Traditionally, the patterns of wax are made by pouring molten wax into metal molds created with hard tooling, which is time-consuming as well as costly for small-scale production. Moreover, the design flexibility for gating systems and sprues are restricted for the challenges of the tooling process. However, this problem has been addressed by the AM-assisted IC process.

AM technologies enable the creation of parts layer by layer using various materials, including plastic, metal, ceramics, and biomaterials, through different methods. AM offers advantages over traditional manufacturing processes, such as greater design flexibility, minimized material waste, and lower tooling costs. (3,4). Therefore, AM enhances traditional manufacturing methods like sand casting and IC (investment casting). The AM-assisted IC process is referred to as RIC (rapid investment casting) because it allows for rapid casting pattern prototyping. In the conventional IC process, producing wax patterns can cost between $1,415 and $70,752, and creating metal instruments for injecting wax can take anywhere from 2 to 16 weeks, significantly extending the overall lead time of the IC process.(5) RIC can decrease production costs and lead time by 60% and 89%, respectively, in comparison to the traditional IC process. (5,6). A comparison of Rapid Injection Casting (RIC) and traditional Injection Casting (IC) for aluminum showed that using AM technology significantly reduces the need for expensive tools, energy, and time. It also drastically cuts production costs. It reduce the energy consumption, , production time carbon emissions and processing cost by 70%, 19% 71%, and 93%, respectively by eliminating necessity of lead and hard tooling. (7).

These improvements stem not only from efficient printing of pattern geometry but also from the ability to optimize the casting system. Reducing material waste can be achieved by improving casting systems and the overall cast geometry (8,9). These benefits of RIC expand its use in areas such as medical implants (particularly in dentistry), jewelry manufacturing, the automotive & aerospace sectors (1).

There are two methods for applying AM (additive manufacturing) in RIC (Rapid investment casting): indirect and direct. In the direct approach, the pattern is printed in 3D itself, while in the indirect method, printing in 3D is used to create a wax pattern for casting (10). For producing complex geometries when internal cavities are there, over the indirect method, the direct AM approach is preferred, as the latter carries a risk of mold damage during pattern production (11). An experimental study was performed to make comparison the direct and indirect uses of AM (additive manufacturing) in RIC with conventional IC, focusing on lead time and cost. The study utilized MM-II (Model Maker II) for printing and aluminum as the casting material (12). Conclusions of their outcomes is in Table 1

	RIC (Direct)	*RIC (Indirect)*	*IC (Conventional)*
Method of producing patterns	The Pattern is printed	Printed molds are used to fabricate the pattern.	Molds created by hard tooling are used to create the pattern.
Lead time	4–5 days	12–13 days	9 weeks
Total cost	$300	$500	$4000

TABLE 1. COMPARISON OF CONVENTIONAL IC WITH INDIRECT AND DIRECT AM APPROACHES IN RIC.

The material requirements vary based regarding the printing techniques, making RIC a complex process that depends on additional factors than conventional IC parts. It reviews studies to assess the benefits and drawbacks of Different 3D printing methods and materials are employed in the direct pattern production process for RIC.

II. AM TECHNOLOGIES USED IN RIC

Additive manufacturing process employed in RIC use powdered or sometimes liquid raw materials for printing. These include FDM (Fused Deposition Modeling), MM II (Model Maker II), SLA (Stereolithography), 3DP (Three-Dimensional Printing), SLS (Selective Laser Sintering), and ThermoJet (12).

A. SLA

The use of 3D printing technologies in the IC process began in 1989. SLA (Stereolithography) was the first AM technique used in IC, developed in 1986. Since then, numerous research studies have focused on the application of SLA-produced patterns in RIC(13-14). SLA-fabricated patterns exhibit a good surface finish, but their designs are only suitable for certain geometries. Nonreactive volatile diluents can be added to the resin to solve the problem of considerable thermal expansion, which can cause shell cracks. (14). The suggested method shows significant improvements in the shell and a substantial reduction in both material usage and printing time in SLA. A paper examined the application of Stereolithography in RIC. It isfound that three factors contribute to ceramic shell cracking: the glass transition temperature of the resins, the inner lattice geometry, and the shell thickness (15). A new technique for constructing the geometry of the inner lattice of SLA patterns permits the structure of the epoxy resin to crumble during the autoclaving process, prior to dewaxing. This approach helps prevent the formation of fractures in the ceramic shell (16). All the studies referenced utilized epoxy resin instead of wax-like materials for pattern printing and suggested methods to prevent shell cracking. However, it's important to note that SLA can also print using waxes and paraffins. To maximize the advantages of Stereolithography pattern production for RIC (resin investment casting), it's essential to develop a QuickCast trade-off model that considers the casting objectives, ceramic slurry components, and geometry.

B. FDM

Technology for FDM printing involves the extrusion of heated using plastic filament to produce an object. Various materials are utilized in the FDM process, including polycarbonates, ABS (acrylonitrile butadiene styrene), PLA (polylactic acid), PVC (polyvinyl chloride), and wax (17). A research on the use of Patterns printed using FDM indicates that acrylonitrile butadiene styrene is particularly acceptable for direct RIC (resin investment casting) because of its excellent surface quality, elimination of the requirement for hard tooling, and reduced cost and time in the process. While it's recognized that FDM has lower dimensional accuracy In contrast to alternative 3D printing techniques, because of the thicker layer resulting from the nozzle of the extruder diameter, it remains a more affordable and accessible option in the market. As a result, numerous studies focus on enhancing the surface finish and accuracy of FDM pattern dimensions (11). To achieve a good surface finish, it is essential to carefully select the post-processing methods and process parameters based on geometry of the part and the material (18).

Researchers have reported acceptable dimensional accuracy and surface roughness for castings, with deviations of 1.260 mm and 1.906 μm (Ra), respectively. Singh (19) also examined similar properties of medical implants manufactured through CVS (chemical vapor smoothing) of FDM (Fused Deposition Modeling) patterns. The case study results indicated that the application of chemical vapor smoothing (CVS) greatly enhances surface roughness. Additionally, Singh et al.(20) examined how vapor smoothing (VS) affects the accuracy of the casting's dimensions. They discovered that vapor smoothing (VS) enhances the pattern's surface quality in two cycles without compromising casting's dimensional accuracy. A comprehensive study of FDM-printed part optimization highlighted current trends in research, including vacuum-assisted FDM printing. The printing chamber's vacuum facilitates slow cooling of the component, which improves bonding between layers and overall surface quality (21).

Dimensional accuracy in the 3D printing process is primarily influenced by the thickness of the layer. Many FDM 3D printers that are sold commercially offer layer thicknesses ranging from 0.127 to 0.254 mm. While reducing layer thickness can lead to smoother surfaces, it may also result in reduction in both length and width of the printed part. Harun et al.(22) studied the accuracy of the dimensions, distortion and surface roughness of both solid and hollow ABS (P400) patterns produced by FDM. It was determined that the building technique (solid versus hollow structures) doesn't impact surface roughness; however, the accuracy of the dimensions is superior in hollow structures. An analysis of patterns made of wax with the similar geometry revealed that patterns made of wax undergo greater distortion compared to those printed with ABS (23). A case study examining the manufacturing of functionally graded dental crowns through investment casting, as a master pattern for silicon molding, an ABS pattern was used.. The FDM-printed ABS patterns exhibited excellent attributes of the surface and were selected for their affordability and sufficient accuracy for replicating the silicon molds (24).

Moreover, FDM printers can print items using wax filaments. Pranjal (25) utilized MOLDLAY filament that resembles wax to produce topology-optimized engine bracket patterns via FDM. Their study compared these results with those obtained using conventional investment casting (IC) technology. The production cost for the RIC bracket was $100, with duration of two weeks, while traditional IC required forty to fifty weeks and cost near about $40,000 for the similar bracket. The study identified several limitations associated with RIC technology. The gradual solidification time of wax-like filaments extends the duration in FDM printing. As a result, RIC (Rapid investment casting), using printed wax-like patterns is only cost- and time-effective within a limited production volume range. Furthermore, FDM-printed wax patterns do not match the accuracy of the dimensions, uniformity of geometry, and surface roughness of traditionally injection-molded wax patterns. So, enhancing the properties of wax pattern that is extruded and creating cutting-edge wax filaments with enhanced solidification times remains a key area for future research. Same findings were proposed by Chua et al. (12).

C. RFP

A comparatively recent technological advancements developed in the early 2000s, called (rapid freeze prototyping) RFP, utilizes ice to create prototypes. The RFP technology can be enhanced through the use of selective water deposition method, along with methods for drop-on-demand and continuous water deposition (26, 27). The the environment for printing is maintained at a temperature below the freezing point of water. Water is deposited onto a previously solidified layer of ice to generate the object. Liu (26) investigated the use of RFP (rapid freeze prototyping) in RIC (rapid investment casting) and discovered that the freeze cast method outperformed the lost-wax process regarding surface quality, the accuracy of the dimensions, and defects in the cast parts. Castings created with ice patterns achieved a tolerance of 0.69 mm, 2.07 µm (Ra) of average surface roughness, and had 2 defects. In contrast, castings produced with wax patterns exhibited a tolerance of 1.96 mm, 2.89 µm (Ra) of surface roughness, and 6 defects. The superior performance of the freeze cast process, which utilizes RFP for pattern production, makes it well-suited for manufacturing dental crowns, where high dimensional accuracy is essential (28). While this technology has demonstrated its practicality, there is a gap in research regarding how slurry content interacts using the pattern of ice, which could significantly impact quality of casting. The main drawback of this method is the expense associated with the freezing environment, so further studies should focus on assessing the cost and time efficiency of this process in comparison to traditional lost-wax methods.

D. Technology for ink-jet printing

Another AM technology that uses the ink-jet printing method is called MMII (Model Maker II) (12). The object is constructed in MMII (Model Maker II) by wax (the support material) and ink-jetting thermoplastic (the built material). Chua et al. (12) compared MMII-assisted RIC with traditional IC for aluminum castings and found that the MMII-assisted RIC method produced castings in just 4–5 days at a cost of $300, whereas the conventional method took nine weeks & cost $10,000 for the similar product. MMII (Model Maker II) patterns had an average surface roughness of 0.59 µm Ra, while the castings made from these patterns had 5.7 µm Ra surface roughnesses, which is under the acceptable range for conventional IC, in between 3 and 6 µm Ra. The research also examined the indirect RIC (rapid investment casting) using MMII and observed that for production purposes involving 1 to 5 parts, utilizing MMII (Model Maker II) in direct RIC (rapid investment casting) is economically beneficial. However, for larger production runs, the indirect method with MMII-assisted RIC is more cost-effective.

Table 2 compares the benefits and drawbacks of the AM technologies utilized in RIC.

AM technology	*Benefits*	*Drawbacks*	*Reference*
SLA	+ accurate dimensions and a smooth surface + Infills can be made with QuickCast ™ to enhance the behavior of thermoplastic patterns.	- Epoxy resins cause the shell to crack while the waxing process is underway. - Before dipping into the ceramic slurry, patterns may require an extra coating.	[15–16]
FDM	+ appropriate surface quality when process parameters are appropriately adjusted, etc. + able to utilize wax filaments + Patterns made of thermoplastic are useful for guaranteeing the postprocessing + faster and cheaper production	- Surface quality is not as precise. - inadequate dimensional accuracy (caused by shrinkage of thermoplastic) - Shell cracks are also caused by thermoplastics.	[11-25, 27]
RFP	+ improved surface quality + Heat treatment is not necessary for pattern loss. + less expensive in terms of material + improved pattern dimensional accuracy	- might not be cost-effective because printing requires a constant low temperature.	[26, 27]
MMII	+ produces denser layers than FDM and SLA, so patterns might not require the extra coating.	- Shell cracks during dewaxing are caused by thermoplastics.	[12, 26]

TABLE 2. BENEFITS AND DRAWBACKS OF THE AM TECHNOLOGIES UTILIZED IN RIC.

Regarding the methods employed in RIC (rapid investment casting), the following research possibilities and gaps in knowledge were noted:

- The impact of process variables on part quality has been explored less for SLA than for FDM technology.

- There is limited information available on the feasibility and financial viability of printing MMII.

- The RFP (Rapid Freeze Prototyping) method requires further research to assess its price and duration efficiency.

III. MATERIALS FOR THE PRODUCTION OF PATTERNS

Materials that resemble wax are typically used for creating patterns in IC due to their Low thermal expansion characteristics and effective burnout. These patterns made of wax are primarily removed during the autoclaving phase before the shell is burned. Any issues related to any leftover wax following autoclaving can be eliminated by utilizing microwave techniques (29). The proposed technology involves using a microwave oven to dewax, which facilitates the recycling of wax waste since the wax structure remains intact after microwave heating. Additionally, Wax filaments based FDM printing takes longer than with thermoplastics because the filaments, made of wax, solidify at a slower rate (30). While wax patterns offer a good surface finish, they are unsuitable for printing thin-walled parts due to their weakness, brittleness, and poor mechanical properties (11). The commercial alternative to filaments (made of wax) is non-wax materials, which are commonly utilized in various additive manufacturing (AM) technologies.

In SLA, the Materials that are not wax consist of photoresins or photopolymers. In the course of the curing process, chain-reaction polymerization takes place, where the monomers react with one another to form solid polymer chains (31, 32). Photopolymers are derived from cationic and/or systems of radical monomers. Commercially accessible cationic photopolymers exhibit excellent characteristics of a thermo-mechanical, high resilience, minimal viscosity, and a high modulus of elasticity (33). They may produce precise dimensional results when printing intricate parts (34). Parts made from radical monomers exhibit good hardness, thermal properties, and flexibility (35). Parts created from resins through photopolymerization generally achieve good dimensional accuracy, typically within ±50 µm (32). A recent experimental study noted that shell cracking occurred during heating at temperatures as low as 200–250°C (30, 36). The high price of photopolymers is another barrier to the use of SLA in RIC(rapid investment casting) (37).

In FDM (Fused Deposition Modeling) and MMII, the material that is not wax, utilized is thermoplastics, with ABS being the most commonly used in RIC studies. Thermoplastics offer substantial mechanical strength, toughness, durability, and rigidity, enabling the printing of thin-walled patterns, which is not possible with wax. Furthermore, the non-wax patterns' stiffness facilitates post-processing techniques to enhance surface quality, unlike wax patterns (24). However, like photopolymers, materials made of thermoplastic have a higher thermal expansion compared to wax, leading to cracking of the shell during autoclaving. This problem is mitigated by the introduction of fresh filaments for Polycast designed in order to produce investment patterns, in addition to the utilization of a hatched structure design for the patterns (38).

Another method for producing non-wax patterns includes applying ice. Patterns made of ice offer a better surface quality and can accommodate various geometries. However, they are fragile and weak, requiring low operating temperatures, which can lead to cost inefficiencies. low temperature of operation necessitates careful selection of ceramic slurry to ensure excellent fluidity of the binder. Additionally, RFP faces unresolved issues related to the relationship between The designed substance and the slurry substance.

The results regarding the wax and nonwax materials used in the RIC are summarized in table 3.

Material	*3D technology*	*Benefits*	*Drawbacks*	*Reference*
Wax	FDM & SLA	+ high surface quality and dimensional tolerances + minimal expansion of heat + total capacity for burnout (at temperatures lower) + reduced amount of leftover ash + lower price	- fragile and brittle - difficulties in producing thin-walled structures	[11, 29, 30]
Photopolymers	SLA	+ high strength and toughness + favorable thermomechanical characteristics + high dimensional precision + superior surface quality compared to thermoplastics + having the capacity to create walls that are thinner than thermoplastics	- higher heat expansion, which results in the ceramic shell cracking - minimal temperature for glass transitions - costly	[31, 33-37]
Thermoplastics	MMII & FDM	+ high strength to resist loss from cleaning as well as transportation + The capacity to print thin walls + Fast printing is ensured by a short solidification time. + less expensive than photopolymers	- less precise measurements as a result of shrinking plastic - inadequate surface quality as a result of the staircasing effect - elevated melting point - Shell cracks caused by high temperature increases	[17-25, 38]
Ice	RFP	+ high precision in dimensions + superior surface quality of pattern + lower melting point, so the pattern can be removed without a furnace.	- The price of cooling area could be high. - delicate and brittle	[26, 27, 37]

TABLE 3. INVESTMENT PATTERN MATERIALS COMPARISON

The study of materials highlights several research prospects and obstacles:

- The time that it takes to solidify for wax filaments used in FDM requires improvement.

- The toxicity of photopolymers and new materials for thermoplastics during burnout in the RIC procedure requires assessment..

- There has been limited research on how low temperature environments affect the components of ceramic slurry during RFP-assisted RIC.

- Despite the widespread use of Polycast filament, there is insufficient information regarding its mechanical and thermal characteristics.

IV. Conclusion

The excellence of patterns utilized in RIC is influenced by the AM method, parameters for printing, & the materials employed in their Manufacturing. This study has highlighted the benefits and drawbacks of various AM technologies and The materials utilized in the production of patterns. The analysis of AM method revealed that:

- SLA-printed patterns provide surface precision and exceptional dimensional but are costly regarding both the materials and printer.

- FDM is a cost-effective option, however it has a number of drawbacks with regard to surface finish performance and dimensional tolerances.

- RFP produces superior quality patterns, yet the financial feasibility of this technology requires further evaluation.

The reviewed materials for the making of patterns include photopolymers, thermoplastics, wax, and ice. The findings indicate that the primary distinctions between non-wax and wax materials lie at the temperatures at which they melt and characteristics of thermal expansion..

References

[1] Lynch PC, Beniwal C, Iv Jh W, editors. Integration of binder jet additive manufacturing technology into the metal casting industry. IIE Annual Conference. Proceedings; 2017: Pittsburgh, USA: Institute of Industrial and Systems Engineers (IISE).

[2] Shay B. Investment castings | what are investment castings used for? Ferralloy Inc.2017 [cited 2021]. https://www.ferralloy.com/investment-castings-applications/.

[3] Technologies ACFoAM, Terminology ACFoAMTSFo. Standard terminology for additive manufacturing technologies. Astm International; 2012.

[4] Wohlers TT. Wohlers report 2010: additive manufacturing state of the industry: annual worldwide progress report. Belgium: Wohlers Associates, Inc; 2010.

[5] Pattnaik S, Jha PK, Karunakar DB. A review of rapid prototyping integrated investment casting processes. Proc Inst Mech Eng L J Mat Des Appl. 2014;228(4):249–277.

[6] Cheah CM, Chua C, Lee C, et al. Rapid prototyping and tooling techniques: a review of applications for rapid investment casting. Int J Adv Manuf Technol. 2005;25(3–4):308–320.

[7] Prakash C, Singh S, Kopperi H, et al. Comparative job production based life cycle assessment of conventional and additive manufacturing assisted investment casting of aluminium: a case study. J Cleaner Prod. 2021;289:125164.

[8] Sama SR, Badamo T, Lynch P, et al. Novel sprue designs in metal casting via 3D sand-printing. Additive Manuf. 2019;25:563–578

[9] Sama SR, Wang J, Manogharan G. Non-conventional mold design for metal casting using 3D sand-printing. J Manuf Proc. 2018;34: 765–775

[10] Lee C, Chua C, Cheah C, et al. Rapid investment casting: direct and indirect approaches via fused deposition modelling. Int J Adv Manuf Technol. 2004;23(1–2):93–101.

[11] Kumar P, Ahuja I, Singh R. Application of fusion deposition modelling for rapid investment casting - a review. Int J Mater Eng Innov. 2012;3(3/4):204–227

[12] Chua C, Feng C, Lee C, et al. Rapid investment casting: direct and indirect approaches via model maker II. Int J Adv Manuf Technol. 2005;25(1–2):26–32

[13] Jacobs P, et al. Stereolithography 1993: epoxy resins, improved accuracy, and investment casting. coupling technology to national need. Inter Soc Optics Photonics. 1994.

[14] Sundaram R Investment casting using stereolithography case of complex objects. 1996

[15] Mukhtarkhanov M, Perveen A, Talamona D. Application of stereolithography based 3D printing technology in investment casting. Micromachines. 2020;1110:946. PubMed PMID

[16] Hague R, Dickens P. Improvements in investment casting with stereolithography patterns. Proc Inst Mech Eng Part B. 2001;215(1):1–11

[17] Kumar P, Singh R, Ahuja I, editors. Investigations for mechanical properties of hybrid investment casting: a case study. Mater Sci Forum. 2015. Trans Tech Pub1.

[18] Thrimurthulu K, Pandey PM, Reddy NV. Optimum part deposition orientation in fused deposition modeling. Int J Mach Tools Manuf. 2004;44(6):585–594.

[19] Singh J, Singh R, Singh H. Investigations and mathematical modelling using dimensionless analysis for hardness of SS-316L implants fabricated for batch production through rapid investment casting. Adv Mater Process Technol. 2020; 1–18.

[20] Singh D, Singh R, Boparai K. Investigations for surface roughness and dimensional accuracy of biomedical implants prepared by combining fused deposition modelling, vapour smoothing and investment casting. Adv Mater Process Technol. 2020; 1–20

[21] Syrlybayev D, Zharylkassyn B, Seisekulova A, et al. Optimisation of strength properties of FDM printed parts—a critical review. Polymers 2021;13(10):1587.

[22] Harun W, Safian S, Idris M. Evaluation of ABS patterns produced from FDM for investment casting process. Comput Method Exp Mater Character IV. 2009;1:319–328

[23] Yarlagadda PKDV, Hock TS. Statistical analysis on accuracy of wax patterns used in investment casting process. J Mater Process Technol. 2003;138(1–3):75–81.

[24] Kumar S, Singh R, Hashmi M. Metal matrix composite: a methodological review. Adv Mater Process Technol. 2019;6: 13–24.

[25] Pranjal J, Kuthe A. Feasibility study of manufacturing using rapid prototyping: FDM approach. Procedia Eng. 2013;63: 4–11.

[26] Liu Q, Sui G, Leu MC. Experimental study on the ice pattern fabrication for the investment casting by rapid freeze prototyping (RFP). Comput Ind. 2002;48(3):181–197

[27] Liu Q, Leu MC, Richards VL, et al. Dimensional accuracy and surface roughness of rapid freeze prototyping ice patterns and investment casting metal parts. Int J Adv Manuf Technol. 2004;24(7–8):485–495

[28] Mueller T. Rapid prototyping patterns create new opportunities for investment casting. AFS Trans. 2005; 1–9.

[29] Brum FJB, Amico SC, Vedana I, et al. Microwave dewaxing applied to the investment casting process. J Mater Process Technol. 2009;209(7):3166–3171

[30] Donghong W, Dong A, Guoliang Z, et al. Rapid casting of complex impeller based on 3D printing wax pattern and simulation optimization. Int J Adv Manuf Technol. 2019;100(9– 12):2629–2635

[31]] Fei W, Fuke W. Liquid resins-based additive manufacturing. J Mol Eng Mater. 2017;5 (02):1740004

[32] Bagheri A, Jin J. Photopolymerization in 3D printing. ACS Appl Polym Mater. 2019;1 (4):593–611

[33] Green WA. Industrial photoinitiators: a technical guide. CRC Press; 2010.

[34] Inc. C A new photoinitiator for cationic curing from Ciba specialty chemicals basel, Switzerland. chemeurope.com; 2002 [cited 2021]. https://www.chemeurope.com/en/news/ 10417/a-new-photoinitiator-for-cationic-curing-from-ciba-specialty-chemicals.html

[35] Kaczmarek H, Gałka P. Effect of irgacure 651 initiator on poly(methyl methacrylate)photostability studied by UV-Vis spectroscopy#. Open Process Chem J. 2008;1(1):1

[36] Wang D, Dong A, Zhu G, et al. Rapid casting of complex impeller based on 3D printing wax pattern and simulation optimization. Int J Adv Manuf Technol. 2019;100(9–12):2629–2635

[37] Weng Z, Zhou Y, Lin W, et al. Structure-property relationship of nano enhanced stereolithography resin for desktop SLA 3D printer Part A Applied science and manufacturing. 2016.

[38] Körber S, Völkl R, Glatzel U. 3D printed polymer positive models for the investment casting of extremely thin-walled single crystals. J Mater Process Technol. 2021;293: 117095