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RAPID INVESTMENT CASTING: DESIGN AND MANUFACTURING TECHNOLOGIES

Christopher T. Richard, Tsz-Ho Kwok[*]
Department of Mechanical, Industrial and Aerospace Engineering
Concordia University
Montreal, QC H3G 1M8, Canada

ABSTRACT

With the emergence of new metal AM (additive manufacturing) methods, rapid IC (investment casting), a variation of conventional investment casting has been a popular topic of research in the fields of: aerospace, dentistry and biomedical engineering. RIC (Rapid investment casting) takes advantage of the additive nature of 3D printing for pattern making which allows for more complex castings than traditional investment casting. RIC is a manufacturing process that combines the casting knowledge accumulated over five thousand years with relatively novel AM knowledge. The result is a process that can compete with newer metal AM methods with the added benefits of excellent surface finish, fatigue strength and the ability to create parts from almost any metal or metal alloy. This article will focus on research advancements in investment casting, AM and all the topics that are closely related to optimizing these two processes. Beyond that, aerospace, dentistry and biomedical engineering advancements using investment casting will be reviewed.

Nomenclature	
AM	Additive Manufacturing
DMLS	Direct Metal Laser Sintering
DMLS	Digital Light Processing
FDM	Fused Deposition Modeling
IC	Investment Casting
MJM	MultiJet Modeling
RIC	Rapid Investment Casting
SLA	Stereolithography Apparatus
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

[*]Email: tszho.kwok@concordia.ca

1 Introduction

Metal AM has been gaining a lot of popularity due to the increase in design freedom it provides. Yan et al. [1] presented a gyroid cellular lattice structure for SLM that eliminates the need for supports. This showed great potential for making lightweight structures. The engineering profession has shifted toward the use of lightweight, heavily optimized designs. Only a couple processes currently in existence can be used for the manufacturing of these complex components, such as a turbine blades with integrated cooling channels. The three processes that can be used for metal AM are DMLS (direct metal laser sintering), SLM (selective laser melting) and RIC (rapid investment casting). SLM and DMLS are processes that use a laser for melting or sintering a metallic powder point by point and layer by layer. By the end of this paper, it will become clear that RIC is the best option for many industrial applications. According to Leuders et al. [2], When we compare IC to SLM, fatigue loadings are still a challenge for SLM, and the same is true for SLS. Li et al. [3] demonstrated the presence of residual stresses in most metal AM processes. The residual stresses are due to high temperature gradient and rapid cooling. Given that RIC is a hybrid AM and solidification process, it is less prone to residual stresses. In addition of the three manufacturing processes, IC is already well established in many industries that would benefit from a shift towards metal AM.

There are many benefits to RIC over other manufacturing processes. RIC can produce parts with complex geometries such as: thin sections, cavities and complex internal lattice structures. Beyond that, RIC requires very little post processing and it can produce parts with great dimensional accuracy and surface fin-

ish. Finally, RIC components do not suffer from poor fatigue strength so it can be used in industries like aerospace, dentistry and biomedical engineering, etc. This paper will present the background information on IC and RIC and then delve deeper into the current open areas of research. Some areas of research show more potential towards improving the manufacturing process as a whole and these will be presented with the intention of identifying the most lucrative research directions in RIC.

1.1 Investment Casting

Investment casting was described by Khirsariya [4] as taking advantage of the ability for a fluid to assume the shape of its container. The research on RIC is still very much in its nascent stages. IC (investment casting) is a process that dates back to the late 19th century. IC uses a sacrificial pattern to form a mold. This is done by encasing the pattern in refractory material. The pattern then undergoes a burnout process leaving a mold cavity in the shape of the pattern. Molten metal can then be poured into the mold cavity creating a metal part with the same geometry as the pattern, see Fig.1. RIC is a type of IC that uses modern AM methods to create a sacrificial pattern for mold making.

IC for engineering applications, is a process developed and refined over two hundred years. Throughout this time the applications of IC have changed the most. If we look at Fig.2, we can see that before the late 19th century, IC was primarily used with precious metals for ornamentation and religious purposes. After 1897, dentists began using the manufacturing processes to make dental inlays. During WWII, IC became the manufacturing process of choice for military aerospace components. Afterwards, the IC process transitioned to many commercial and industrial applications. The applications of IC have evolved from ornamentation to dental and finally aerospace, all these applications are still in use today in addition to biomedical engineering. The main difference with the modern applications is that they test the limits of the process using complex design elements such as small cross sections, integral ceramic molds and high dimensional accuracy.

According to Hunt [5], the main process at its core hasn't changed a huge amount since 1936 when Thoger Gronborg Jungersen introduced the use of flexible rubber moulds for making multiple wax patterns. Much like the process invented in 1936, conventional IC uses wax for pattern making, this is often formed with a reusable silicone mold. Traditionally, ceramic or plaster slurries are used as refractory material and can be made into either a shell or flask mold. Shells are formed by coating the pattern with refractory material. A flask is formed by placing the pattern in a metal cylinder and filling it with refractory material. Although a shell mold saves on molding material, it is more prone to cracking than flask molds. The wax pattern can then be melted and vaporized from the mold to allow molten metal to be poured into the cavity. Like any other solidification process,

IC has several design elements that are required to produce successful castings. IC uses a feeding, gating and venting system in order to supply molten metal to the casting and allow trapped gasses to escape. Risers are reservoirs of molten metal that protrude from the 3D pattern, they help prevent voids from forming due to metal shrinkage caused by cooling. A sprue is a tapered passage that allows molten metal to flow into the mold cavity. These are just a handful of the design features required for IC.

Like any other casting method, IC has design considerations that can be made to produce better quality castings. Marwah [11] stated that rapid prototyping is currently the most popular option to replace the wax used in pattern making. Thanks to RIC, complex patterns can be created from a computer generated 3D model in a relatively short time. The pattern can be made using AM processes such as DLP (digital light processing), SLA (stereolithography apparatus), FDM (fused deposition modeling) and MJM (MultiJet modeling). IC is a process that can create parts with a great surface finish requiring very little post processing. The only post processing IC does require is separating the casting from its gating system. Kuo et al. [12] presented a method for separating investment cast components from their gating systems using vibration induced fatigue failure. This was achieved by incorporating notches into the gating system design. As can be seen, even one of the few post processing operations associated with RIC can be eliminated. RIC can be such a vast topic that branches far into the fields of casting and AM. This leaves a lot of potential research directions some of which are surface level focusing on trial and error and others which show greater potential.

1.2 Structure of Paper

This review paper is broken into three main topics: one is on the RIC and IC processes, the second is on process, material and design optimization and the last one is on current applications of RIC and IC as well as future research directions.

The first two sections talk about surface level advancements in pattern making (Section 2), patternless mold making (Section 3) and the AM processes associated with them. Surface level refers to research focused more towards testing and validation and less towards design and optimization.

The next two sections focus on optimizing the casting or AM process via material or parameter selection (Section 4) and optimizing pattern design with the intent of producing high quality cast parts (Section 5).

The last two sections discuss the advancements in IC and RIC in aerospace, dental and biomedical engineering Section 6.The paper is concluded in Section 7 with the review of promising future research directions.
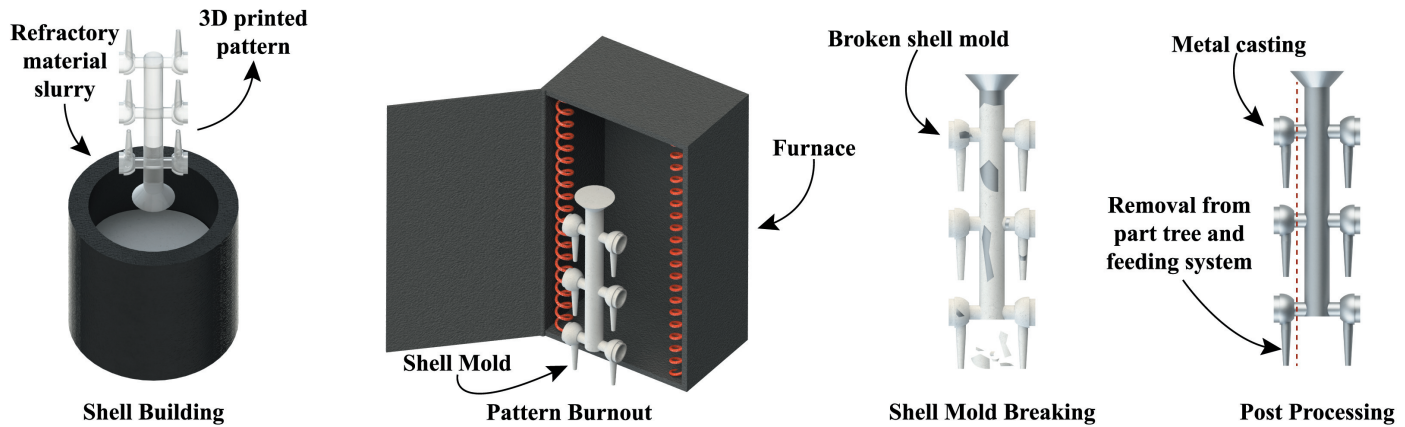
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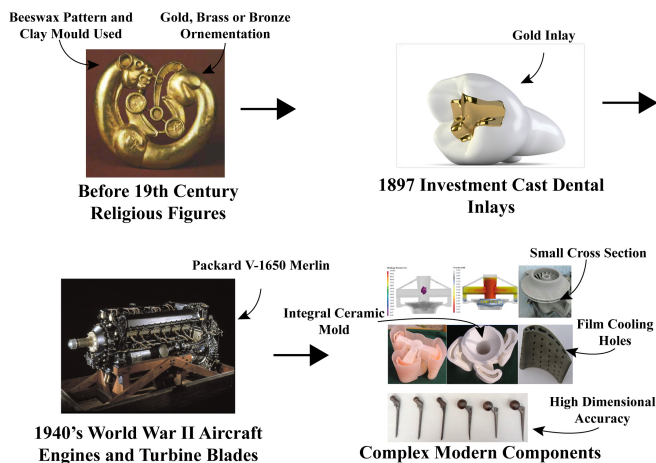**FIGURE 1**. Investment Casting Process

FIGURE 2. History of Investment Casting Applications [5–10]

2 Pattern Making Process

RIC utilizes newer AM methods for pattern making. Conventional processes opted for cruder methods such as casting or carving of patterns. The pattern making process can be broken up into lost wax pattern making and AM for pattern making. RIC depends on AM whereas traditional IC depends on the lost wax process.

2.1 Lost Wax Pattern Making

One of the more conventional materials for pattern making is wax. Although newer additive methods are presently being used for pattern making, wax still has benefits such as: lower cost, lower melting temperature and lower induced burnout stresses. For the reasons previously mentioned, research is still being done to improve the lost wax process. Wax patterns are generally made using a reusable silicone mold; Malomo et al., Alderighi et al.

and Nakashima et al. [13–15] proposed a method for designing these silicone molds. The software they created can generate custom 3D printed containers called meta-molds which define the cuts required to extract a complex cast part from the silicone without damaging the pattern. The main drawback of the lost wax process is that pattern complexity is inhibited by the reusable silicone mold, as the pattern must be removable. The only way to avoid this is by using a wax 3D printing processes such as FDM or MJM for pattern making.

Contrary to RIC where the pattern is burned out from the mold, lost wax relies mostly on melting for pattern removal. Improper dewaxing could cause casting impurities that affect the cast parts strength. Mishra and Ranjana [16] proposed a novel method for dewaxing of ceramic shells in IC. The process relies on a dilation gap at the entrance of the mold which serves as a passageway for molten wax to properly flow out of the mold without applying any pressure to the mold walls. Although there is still research being done to improve the use of wax patterns, there is not nearly as much as newer resin based materials. Given that MJM and FDM printers can print with wax based materials, lost wax based RIC is a possibility.

2.2 Additive Manufacturing for Pattern Making

There are various 3D printing methods that can be used for pattern making. These methods are: FDM, SLA, DLP and MJM. FDM is a 3D printing process in which plastic filament made from PLA (polylactic acid), ABS (acrylonitrile butadiene styrene) etc. is melted through a heated nozzle and deposited following a tool path on a print bed. Tool paths can be generated using a slicer software. The software breaks down 3D models into layers each with its own tool path. SLA and DLP are photo-curable resin based processes, SLA uses a laser to cure a layer point by point and layer by layer. DLP uses a projector or LCD to cure full layers at a time. The benefits of these

3D printing processes are that they can create really high quality patterns with great surface finishes. SLA was used by Huang and Huang [17] to compare RIC and traditional IC by creating a miniature turbine blade. They found that SLA can create high precision casting patterns. MJM can also 3D print using photocurable resins, but has the benefit of printing in wax materials as well, it can also create much larger parts, with resolutions slightly higher than SLA and DLP. The resolution of 3D prints are highly dependent on the machine and materials used. For small scale IC, given the low cost, high speed and resolution of DLP, it is a excellent choice for pattern making. For larger parts MJM seems to be the best process available at the moment.

2.2.1 DLP/SLA Pattern

There has been a lot of research targeted towards improving DLP and SLA AM. Given that RIC utilizes these two 3D printing technologies, it can greatly benefit from their advancements. One of the main issues with resin patterns is that resin has a higher thermal expansion coefficient than the refractory mold material. This difference in coefficients generally results in mold cracking. The cracking is more apparent in certain geometries such as free-form surfaces. Some methods have been proposed to deal with the high expansion coefficient of resin. Norouzi et al. [18] proposed a octagonal internal lattice structure to aid with pattern burnout. This resulted in 62 percent reduction in hoop stresses compared to the traditional hexagonal structure. Alternatively Chen et al. [19] focused on pattern collapse using micro-structures. FEA (finite element analysis) was used to determine the areas of high hoop stress in a turbine blade casting. The shell was then reinforced at those locations using a high temperature polymer that was resistant to the peak stress temperature range. Although these advancements can be used to avoid mold cracking, the validated designs were too simple to conclude the same results could be had for complex parts cast in industry.

Given that SLA and DLP are used for pattern making, any defects caused by the AM process will reflect in the final casting. For this reason, although the following research was not intended for RIC, it can be used to improve pattern quality. Zhou and Chen [20] proposed the use of a digital micro-mirror and a mask video projection process instead of the mask image projection used in DLP. The results show that this process can improve the X and Y resolution of mask projection large-area SLA. Zhou et al. [21] optimized the SLA process by combining vector scanning with mask projection. This hybrid process has the speed of DLP at the center and the surface quality of SLA at the layer boundaries. The limitations of this process include: alignment issues, material bonding and a limited range of materials. This hybrid process benefits from the higher surface finish of SLA combined with the speed of DLP's layer by layer curing. Monzon et al. [22] discovered the presence of anisotropy in patterns made using DLP. The authors found that post curing does remove the anisotropy for certain resins where UV light can pass through the resin and pigment. This could be concerning depending on the application for these 3D printed parts. Anisotropy can often associated with nonuniform strength. Even in RIC, anisotropy could cause unpredictable mold cracking. Finally as with any 3D printing process, if parts gets stuck to the print bed they could break or deform. Jin et al. [23] proposed a vibration assisted glass resin vat to reduce the separation forces required for SLA. There remains a lot of work before large cross sectional areas can be printed. Large parts require a dynamically changing vibration frequencies. As can be seen most of the considerations and scientific advancements that have been applied to 3D printing, can also applied to further develop the RIC process given its dependence on AM. Although improving the quality of 3D printing is an important topic, it is also a heavily researched topic.

2.2.2 FDM Pattern

FDM is one of the cheapest 3D printing methods but also one of the least accurate. Given the aforementioned disadvantages of FDM, it is not always considered to be a good option for pattern making. FDM can be used create much larger parts than its resin based alternatives. Given the low cost and large build volumes, a lot of research has been done to improve its surface finishes and dimensional accuracy. According to Kumar et al [24] in order to use FDM for IC various conflicting parameters need to be optimized such as: raster angle, layer thickness, build time and part orientation. The most critical is having the layer thickness as small as possible to improve the surface finish. Kumar et al. [25] attempted to improve the surface finish of 3D printed patterns by observing the effect of varying process parameters such as: geometric volume to area ratios, wax coated or uncoated patterns, orientation, mold thickness and material grade in order to achieve high dimensional accuracy when casting a hip joint. They concluded, a thin coating of wax increases accuracy of the patterns being made. Higher volume to area ratios and pattern orientations of 90 degrees lead to higher accuracy. They were able to achieve the permissible tolerances grades determined by the ISO standard. Hafsa [26] and Ibrahim et al. [27] compared the use of two AM methods, MJM and FDM for creating RIC patterns. The authors found that utilizing different internal structure for their patterns had an effect on surface roughness. They concluded that the FDM pattern made with PLA had a better surface roughness than the MJM pattern made with acrylic, though it should be noted that the printers are out-dated. Although the FDM part produced a better surface finish the MJM part produced better accuracy if an optimal build orientation was used. The main drawback of using FDM for investment casting is that too much effort is required to improve the quality of the printed parts. Without further research, FDM does not produce high enough quality patterns for RIC to compete with DLP, SLA and MJM.

2.2.3 Smoothing Process In order to improve the surface finish of FDM printed patterns, various different methods have been proposed. For example, Singh et al. [28, 29] evaluated the feasibility of FDM combined with chemical vapor smoothing, vacuum casting and IC for developing custom hip joint implants. The implants created met ISO standard for tolerance grades. Chemical vapor smoothing is a process that uses solvent vapor in order to dissolve the surface layer of a 3D printed part. Singh et al. [30] later investigated the use of this process for FDM ABS 3D printed parts and found negligible changes in the dimensional features for use in IC as sacrificial patterns. Mechanical smoothing processes can also be used for pattern smoothing. Boschetto and Bottini [31] investigated the use of barrel finishing to improve the surface quality of FDM 3D printed parts. Barrel finishing is a process which uses a rotating drum filled with abrasive media in order to smooth the surface of the part. Given the larger build volumes and low cost of FDM 3D printers, improvements in the surface finish of the 3D printed parts is an important research topic for pattern making in IC. Without further research, even with smoothing FDM still can not compete with DLP, SLA and MJM in terms of quality for RIC.

3 Patternless Mold Making

Patternless mold making can improve time efficiency when compared to pattern making. The burnout process can be omited for patternless mold making. The main drawback of the process is that it is dependent on SLS (selective laser sintering) or binder jetting technology. The two powder based process both undergo large amounts of shrinkage during the mold sintering processes.The sintering process is required to fully consolidate the ceramic or plaster refractory powders used. Generally the powder based AM processes can produce surface finishes on par with sand casting. This pales in comparison to the surface finish achievable with a pattern. Chhabra and Singh [32] evaluated the use of ZCast binder jetting technology to create aluminum castings by reducing the mold wall thickness from 12mm to 5mm. The aluminum castings were evaluated on dimensional accuracy and surface roughness and were found to be in the range of sand casting. Walker et al. [33] utilized binder jetting technology in combination with sand casting in order to take advantage of the design freedom provided by AM. Using this technology, a complex mold with internal cavities was created. The 3D printed mold allowed sensors to be embedded in it. The sensors facilitated the collection of casting data from deep within molds. The data collected was temperature and magnetic field data which was generated by the molten metal flow. The data was used to validate complex computer models. According to Patel et al. [34], using binder jetting, sand molds can be made with high compressive strength without the use of a pattern, which in turn can reduce cost and save on lead time. Wei et al. [35]
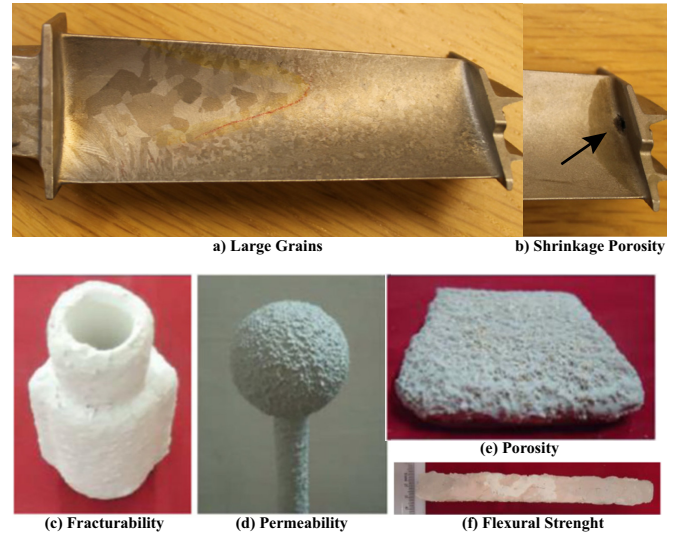

FIGURE 3. Defects in Turbine Blade Castings and Reinforced IC Molds [36, 37]

used SLS for fabricating a mullite ceramic shell mold which was later post processed using a high temperature sintering operation. The authors concluded that SLS combined with sintering presents a quicker process for producing mullite shell molds. These molds possess excellent strength surpassing most traditional shell-making techniques. Though patternless mold making presents a large time savings for RIC, the powder based AM processes it relies on need improvement. The main benefit of the patternless process is the ability to better incorporate metrology into the casting process

4 Process Parameter and Material Optimization

IC is method that is very dependent on process parameters and material selection. The effects of different parameters and materials on the IC process can be consolidated into a library that can improve the reliability of the process as a whole.

4.1 Parameter Optimization

Process parameter selection for IC can greatly impact final casting quality. Gating system design, pattern making, mold making, pattern burnout, preheat and metal pouring are all processes required for IC. In order to create successful castings, all these processes require proper parameter selection and control. If we follow the sequence of casting operations for IC we can get a better understanding of the vast number of parameters that impact casting quality.

The first step in the casting process is gating system design. The gating system is what allows molten metal to enter the mold. Without a proper gating system, castings can be prone to porosity

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and shrinkage defects. Kuo et al. [12] found that thin sections are prone to shrinkage defects due to rapid cooling and insufficient feeding. Beyond that the inclusion of vent holes allows for the release of pressure and results in an extended cooling time which leads to a lower probability of shrinkage defects. Gating system and pattern design and parameter selection plays an important role in reducing voids, defects and porosity. Ragab et al. [38] optimized the design parameters for semi-solid casting, the authors modified their control arm design by removing ribs and relocating feeders in order to reduce porosity. Design parameter selection has a big effect on the fatigue strength of a casting. The research presented above simply scratches the surface of casting design because it narrowly focuses on parameter selection rather than looking at the entire casting design.

For IC, poor pattern quality will lead to a poor quality casting. In order to remedy this problem, Rahmati et al. [39] focused on metal injection temperature, injection pressure and time. Using the Taguchi method along with the utility concept, the authors were successful in determining the best parameters and concluded that a combination of a lower level of injection time and temperature along with higher level of injection pressure, lead to higher quality parts. Akhil et al. [40] evaluated the cooling characteristics of different cross section sizes of A356 aluminum alloy and concluded that smaller section sizes resulted in grain refinement and therefore produced better mechanical properties. There are softwares that can be used to better understand the way metal behaves as it flows through a mold and better predict what effect it will have on the final casting. Khan and Sheikh [41] compared various different software for mold flow analysis to evaluate the following: defects prediction, typical clients/users, and advanced simulation capabilities of each software. The results were that ProCAST, MAGMASoft, Nova-Solid/flow, and Flow-3D CAPCAST were the best software. All the research presented above was focused towards optimizing metal flow through parameter selection in order to create better castings.

Alternatively the mold making parameters can also be optimized. Raza et al. [36] evaluated the effect of mold shell thickness insulation and casting temperature on shrinkage porosity and grain size see Fig. 3 (a) and (b). Given the free-form surfaces present on turbine blades, shrinkage at the thin sections of the turbine blades can be troublesome. In addition, grain structure is important to avoid creep in the high temperature applications of the blades. Pattnaik [42] evaluated the effectiveness of controlling process parameters such as shell preheat temperature, firing temperature, firing time, pouring temperature in order to reduce volumetric, linear shrinkage and brittleness as well as increase tensile strength of investment cast parts.

Parameter selection for pattern design, molding and metal pouring all have an effect on the success of a casting. Ideally, if all these parameters could be consolidated into a cohesive design language or software tailored toward RIC, this would make the process a lot more reliable.

4.2 Material Optimization

For IC, there exist many different pattern and mold making materials. Wang et al. [8] investigated various different materials and processes for pattern making. They compared a 3D printed pattern made of high impact polystyrene that had been infiltrated with wax, to a photosensitive resin pattern. The HIPS pattern was made using a SLS process, whereas the resin pattern was manufactured using SLA. The results were that the resin pattern caused mold cracking. Jiang et al. [43] investigated the process of selective laser sintering a eucalyptus and polyethersulfone plastic blend. This material is ideal for SLS because it is low cost and can create high precision patterns, which combined with wax penetration can be used for IC. The materials used for pattern making need to be burned out of the mold before casting. Zhao et al. [44] performed a thermal decomposition study for EPS foam (expandable polystyrene), PU foam (polyurethane) and epoxy resin (SLA) patterns. The authors concluded that EPS foam fully degrades above 450 degrees Celsius and SLA fully degrades above 600 degrees Celsius. PU foam showed complications resulting in casting defects.

Beyond material selection for pattern making, molding materials need to be correctly chosen as well. Pattnaik [45] investigated the use of natural additives for enhancing ceramic shell molds. The author compared the use of saw dust and coconut fiber modified shell molds. The aluminum castings made using these molds, showed increased tensile strength and reduced porosity. Pattnaik et al. [37, 46] later investigated the possibility of using sawdust to improve mold strenght. They measured ceramic shell fracturability, permeability, porosity, and flexural strength for IC , see Fig. 3 (c), (d), (e) and (f). The authors recommended this process in order to reduce cost and lead time for constructing ceramic shell molds. Shumkov and Muratov [47] found that having monolithic and porous structures within a pattern didn't affect the accuracy of the mold cavity being formed.

Material selection can be used to reduce the likelihood of pattern cracking and the formation of defects due to incomplete thermal decomposition. Beyond that, the addition of infiltrants can fill the porous surfaces associated with some 3D printing methods and materials. This will allow them to be used for making high quality molds. An alternative to solving mold cracking is using natural or synthetic additives for enhancing ceramic shell molds.

5 Design Optimization

Newer AM methods can present a lot of design freedom. Since RIC depends on AM, it also has a lot of design freedom. In the past manufacturability was always a concern. Now with
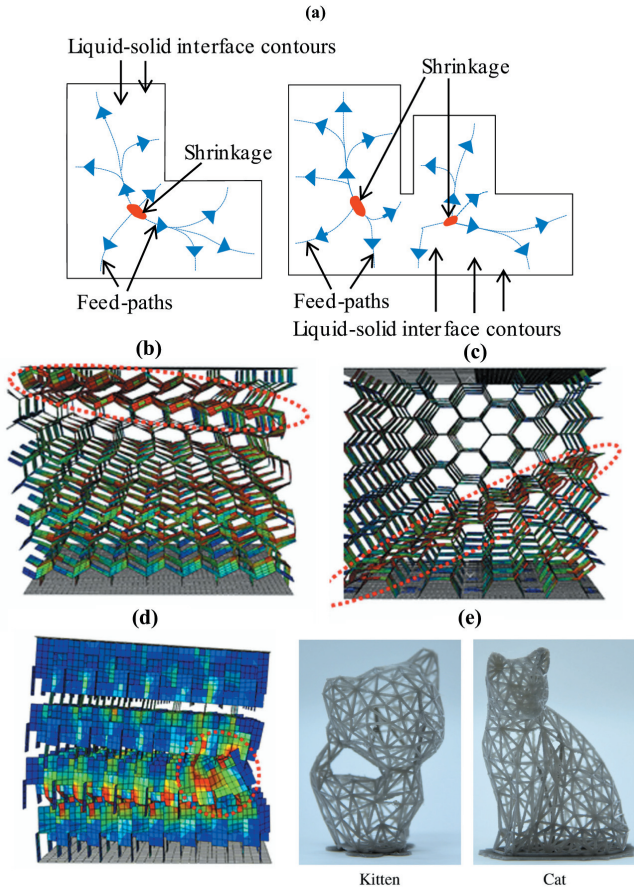
(a)

(b) **(c)**

(d) **(e)**

Kitten Cat

FIGURE 4. Self-supporting struts, Anisotropic internal structures and molten metal feed paths [48–50].

AM, manufacturability has been replaced by design selection and generation concerns. The gating, feeding, venting system and internal pattern support structure are all design features associated with RIC. These design features can be optimized through the use of compensation frameworks or topology optimization.

5.1 Design for Casting

Thanks to RIC and AM, castings can now be made with more complex gating and feeding systems. This could be used to improve casting quality. According to Maidin et al. [51] improper gating system design leads to casting defects. A design where the size of sprue and runner is unbalanced will produce unstable molten metal flow resulting in a rough surface finish and accuracy of the end product. This is only one of the many decisions that affect the effectiveness of a gating system design. In order to better predict the effects of gating system design on final casting, metal feeding needs to be better controlled. Bishop et al. [52] proposed placing feeders within feeding distance of hot spots to avoid shrinkage defects. Later, Sutaria and Ravi [48]

expanded on this idea by proposing the use of feeding paths in order to properly visualize the direction of solidification and locate potential hot-spot locations see Fig. 4(a), this was validated with the successful casting of an industrial rail wheel. Huang and Guo [53] optimized a gating and riser system design in order to aid in the IC of complex impeller pumps. They found that the main source of shrinkage and gas porosity was the complex impeller structure. By changing pouring parameters and optimizing their gating and feeding system with the help of AnyCasting numerical simulations, they were able to lower the cooling rate of the thin sections of impeller. Liu et al. [54] investigated the shrinkage of cast parts with variable cross section, multidimensional, and unconstrained/constrained features. The dimensions of the wax pattern and cast part were compared. Liu et al. established a exponential relationship between dimensions and shrinkage for IC. This allows for castings to be designed for high accuracy with less trial and error. Dong et al. [55] proposed the use of a displacement field to predict the nonuniform shrinkage of thin-walled hollow turbine blades during IC. Based on the deformation characteristics of torsion, bending and shrinkage, the geometrical accuracy was improved. This information could be of great use for newly developed turbine blade models, given that previous data for these models isn't available.

The general consensus from most of the research is that thin or nonuniform cross sections and complex structures causes nonuniform cooling which leads to shrinkage defects. The cooling characteristics can be controlled by implementing a more complex gating and feeding system. Feeding distance and feed paths can also be used to better visualize molten metal flow. This will allow for better feeding and gating system designs.

5.2 Internal Structure

The design and structure of patterns can be optimized in various ways, one of which is using internal lattice structures to aid in mold burnout. Hague and Dickens [56] focused on improving the pattern burnout procedure by designing a new style of internal lattice structure based on a hexagon with collapsibility in mind. According to Cheah et al. [57] when IC using wax patterns, autoclaving is used to melt the pattern. Any remaining wax gets vaporized in a separate firing stage. This leaves a hollow mold cavity for casting. For patterns created from other materials, a mismatch in thermal coefficients can result in pattern expansion during burnout causing mold cracking. This mismatch of thermal coefficients is common in resin based patterns. Tang et al. [58] used functional volumes and functional surfaces combined with a bidirectional evolutionary structural optimization design method to optimize lattice strut thickness and distribution. This was done to create a engine bracket design tailored to its specific loading case. Li et al. [49] took an alternate approach by focusing on the anisotropy caused by the internal honeycomb structure orientation for SLA patterns. The results found that facesheet thickness,

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and orientation of the honeycomb structure were the key factors of shell stress during pattern firing, see Fig. 4 (b), (c) and (d) for x, y and z stress distributions. Finally, Marwah et al. [59] presented an internal polygonal lattice structure for resin patterns which had better collapsibility when compared to square internal supports during burnout.

Internal lattice structures can be used for RIC to to create patterns with no internal supports which in turn saves on materials, cost and lead time. Alternatively lattice strut thickness and distribution can be optimized to selectively weaken patterns in locations of high hoop stress to avoid shell cracking. Current research uses mostly uniform internal structures to avoid mold cracking. A possible research direction would be to integrate topology optimization into the process in order to reduce the patterns expansion coefficient in locations of high thermal stress. The ideal result would be a nonuniform lattice structure that is strong enough to endure the stress of the molding process without inducing shell stress during pattern firing.

5.3 Compensation

Given that deformation can occur during casting and AM. Geometrically accurate castings can be achieved using reverse compensation.

Pan and Chen [60] proposed a method to apply the meniscus approach and controlled cure depth planning to SLA 3D printing in order to improve surface finish and remove the stair-stepping effect. The authors propose a greyscale image planning method to precisely control the energy going into each pixel. The presented method proved to be effective with a lot of room for improvement. Given the heat released throughout the process of resin curing, resin based 3D printing methods are prone to shape deformation such as warping. Xu et al. [61] later proposed a compensation framework for shape deformation in AM. The main principle was to cover the surface of a DLP printed part in feature points which aid in comparing the deformed freeform surfaces to undeformed ones. The results showed promise in generating a compensated STL (standard tessellation language) model which greatly reduced shape deformation. Xu and Chen [62] proposed using mask image planning in order to control deformation for any projection based SLA process. They proposed various different exposure masks to break down the internal curing of the printed part and found that isolated cube pattern lead to a much lower shape deformation caused by less temperature increase during the curing process. Xu et al. [63] later proposed optimizing the photocuring temperature of projection based SLA to control curl distortion of 3D printed part. Given that projection based SLA is used for creating patterns for RIC it becomes important to control deformation in order to manufacture accurate final parts. The authors concluded that photocuring temperature is predominantly based off of layer thickness. Using this knowledge they developed two exposure strategies based off

of greyscale and mask pattern exposures and demonstrated using physical experiments that the strategies can effectively reduce curl distortion at the expense of build time. Generally the main cause of deformation is heat. The resin based 3D printing processes are often exothermic and it is the release of heat that causes deformation.

RIC is a hybrid process of AM and solidification. The solidification process like the AM process is also prone to deformation. Jiang et al. [64] utilized a compensation method based on Taylor expansion in order to control and reduce the amount of deformation in wax IC of a turbine blade. Due to the complex inner and outer geometries as well as stringent material requirements such as anti-oxidation and creep strength, turbine blades must be precisely manufactured using IC. Zhang et al. [65] proposed a reverse deformation method in order to optimize the mold cavity of a turbine blade, therefore, reducing the design time and cost. The authors compensated for shrinkage of the wax and alloy solidification in their pattern design.

The RIC process as a whole can be prone to deformation. Both the AM and solidification portions of the process can be responsible for final casting deformation. Given the high accuracy applications of RIC, the process can greatly benefit from the application of deformation compensation.

5.4 Topological Optimization

In RIC the presence of supports could compromise a parts surface finish, Guo et al. [66] proposed an explicit topological optimization for the design of self-supporting 3D printed parts. Hornus and Lefebvre [67] later focused on optimizing 3D prints to create unsupported cavities. The authors employ a technique called iterative geometric carving which leads to quality printed hollow parts which have been scaled up and down and requires minimal extra computation from the slicer. Wang et al. [50] proposed a method to generate support-free frames with no redundant struts for a 3D model using a sparsity optimization see Fig. 4 (e). Some of the main limitations of this algorithm were that the external frame structure is not optimized for external forces as well as this method is primarily suited for FDM. Wang et al. [68] later elaborated on this idea of support free 3D printing with a method for support-free hollowing. Their method uses multiple consecutive shape optimization steps to the interior mesh of a hollowed part in order to reduce volume while maintaining a self-supporting angle. This results in the potential for lightweight design and static stability of hollowed 3D printed parts.

Alternatively topology optimization can be used to strengthen 3D printed parts, Wu et al. [69] utilized infill in order to create strong and lightweight porous structures like those found in bones. The authors presented internal structures that were numerically optimized for stiffness in order to be robust when it comes to material deficiency, damage tolerance and di-

rection of applied load which is ideal for 3D printing infill. Dbouk [70] reviewed all the different topology optimization methods for optimal heat transfer. The results were that each method has its pros and cons but there is still much work that needs to be done in order to improve computational time, 3D mesh handling techniques, optimization algorithms and experimental validations.

The majority of topology optimization research is focused towards either strengthening AM parts for a specific load case or support free printing. RIC can be improved through the use of topology optimization. Support free printing for patterns could improve the final casting surface finish, and lead time. Topology optimization can be used to improve pattern strength or selectively reduce thermomechanical stresses during burnout. This could improve the reliability of the RIC process.

6 Applications

According to Pattnaik et al. [71], IC has been used to manufacture: jewellery, art and weapons in ancient civilization. Given that IC can create parts with complex geometries, accurate dimensions and excellent surface finishes, it is no surprise that fields such as: dental, biomedical and aerospace utilize this technology. Pattnaik et al. [72] stated that IC is superior to other casting practices and for this reason it can be applied to many applications such as: making automobile components, aircraft engines, jewelry, statues, prosthetics, computer hardware, electronics hardware, radar and machine tool components. With the new design freedom provided by RIC and the isotropic nature of IC it can be used for many manufacturing applications requiring high accuracy. The following section will illustrate recent RIC advancements in the fields of biomedical engineering, dentistry and aerospace engineering.

6.1 Biomedical

IC as of late has showed a lot of promise for the manufacturing of implants in the biomedical field, given that components are generally individualized. Beyond that RIC is known for its ability to create complex 3D parts with excellent surface finishes which lends itself well to create lightweight components that don't lack in strength and interface well with the human body. Singh et al. [73] proposed the use of FDM for printing biomedical implants for use in IC. The study was focused on controlling surface roughness using three factors of the IC process such as slurry layers, slurry viscosity and dry time of primary layer. The research found that all three properties affected the surface quality of the cast hip joint and the research optimized the finish to micro-level resulting in a reduction of post processing operations. Singh et al. [74] later reviewed all the current research focused on improving the surface finish of FDM 3D printed patterns through parameter selection of IC and AM for biomedical implants. FDM is the AM method of choice for pattern making in the biomedical field due to its ability to create larger parts. One of the issues that remains to be resolved is the poor surface finish associated with FDM. MJM would serve to make better quality patterns for biomedical applications while still being able to create large parts.

6.2 Dental

Dentistry has been using IC since 1897, Pattnaik et al. [71] stated that many dental laboratories employ the lost wax casting process. Given that every dentistry partial denture is unique to the anatomy of the patient, IC is perfect for this application. The conventional IC process has been replaced with RIC and instead of having crowns fit using molds, the process has been replaced by a combination of 3D scanning, CAD/CAM and RIC. A prime example of the use of IC in dentistry is Revilla-León and Özcan [75] who reviewed the different AM methods for processing the alloys used in dentistry. The authors compared SLM and DMLS with casting. The results were that there are issues regarding accuracy and reproducibility with SLM and DMLS and for that reason there remains room for improvement in 3D printing metals. Alternatively Dahl et al. [76] investigated if single dental crowns designed using CAD and CAM would have as good a fit as those made with lost wax IC. Given the limited number of crowns tested, the authors were forced to reject the hypothesis that crowns made using CAD and CAM were similar to those produced using the conventional casting method. Given the unique geometry, high accuracy and surface finish requirements associated with dentistry, RIC is the manufacturing method of choice. The main struggle with the implementation of RIC in dentistry is the scanning and design aspect of the process rather than the casting process itself.

6.3 Aerospace

RIC can create parts with very little porosity, excellent surface finish and RIC parts can be used for applications where fatigue strength is critical. For this reason it is the obvious choice for manufacturing aerospace components. Wu et al [77] presented a new rapid casting process based on gelcasting and SLA. The process relies on the addition of an aqueous colloidal silica to the mold material slurry in order to rapidly cast hollow turbine blades. Given the need for accurate castings that aren't prone to creep, RIC is an ideal manufacturing method for turbine blades that have complex freeform surfaces and complex internal cooling channels, which can't be made using many other manufacturing processes. Wu et al. [10] later presented the use of the aforementioned gel casting technology for manufacturing turbine blades with film cooling holes. Compared to cylindrical cooling holes, abnormal cooling holes are more efficient. The new process was less time consuming and costly which in turn resulted in a higher production yield. Aguilar et al. [78] evaluated the use of

TABLE 1. POTENTIAL RESEARCH DIRECTIONS

Research Direction	Complexity	Industry Impact	Research Impact	Total
Topology Optimized Internal Lattice Structures to Reduce Thermomechanical Stresses During Pattern Burnout	7	10	10	9
Generative Gating Feeding and Venting System Design	10	6	8	8
Deformation Compensation for Complex Inner and Outer Geometries in RIC	9	10	9	9.33
Using Other Pattern Making AM Methods than FDM for Biomedical RIC	6	8	6	6.66
Design Methodology for Pattern and Material Selection and Optimization	6	10	7	7.66

IC to produce low pressure turbine blades made from intermetallic titanium aluminide alloys. Given these blades are 50 percent lighter than the nickel-based alternative. The authors were able to qualify this production technology. In aerospace how much a component weighs is of great importance, being able to create components with more complex internal geometries instead of using assemblies can lead to significant weight savings and better performance. It seems that complex internal structures in aerospace have mostly been made using gelcasting, it would be interesting to further investigate the use of RIC for this process.

7 Conclusion and Future Works

Conventional manufacturing methods impose geometric restrictions. In order to manufacture complex parts, the need for fixtures and custom tooling is common and there exist many geometries that aren't manufacturable using conventional processes. RIC is a hybrid AM and consolidation process that shares many of its pros and cons with IC and AM. According to Liu et al. [79], AM can take almost full advantage of the freeform nature of topological optimization. This means complex, lightweight and application specific components that take full advantage of newer generative design styles such as topology optimization and deformation compensation methods can be manufactured out of engineering materials using RIC.

Some of the potential research directions of RIC are; using topology optimized internal lattice structures to reduce thermomechanical stresses during pattern burnout, generative gating feeding and venting system design, deformation compensation for complex inner and outer geometries in RIC, using other pattern making AM methods than FDM for biomedical RIC and design methodology for pattern and material selection and optimization to reduce the likelihood of defect formation. The different topics have been evaluated based on the impact they will have on the industries that use RIC, IC and metal AM, their impact on the research community and their complexity. The results have been tabulate as can be seen in Table 1. The results show that the generative design is the best research direction, but given its complexity, the internal lattice structure for pattern burnout seems to be a very promising direction as well.

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