DE GRUYTER Rev Chem Eng 2019; 35(3): 335–349

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Formulations, development and characterization techniques of investment casting patterns

https://doi.org/10.1515/revce-2017-0068
Received August 1, 2017; accepted February 25, 2018; previously published online April 14, 2018

Abstract: Conventionally, unfilled wax has been used as a universal pattern material for the investment casting process. With increase in demand for accurate dimensions and complex shapes, various materials have been blended with wax to develop more suitable patterns for investment casting in order to overcome performance limitations exhibited by unfilled wax. The present article initially reviews various investigations on the development of investment casting patterns by exploring pattern materials, type of waxes and their limitations, the effect of filler materials and various additives on unfilled wax, wax blends for pattern materials, plastics and polymers for pattern materials and 3D-printed patterns. The superiority of filled and polymer patterns in terms of dimensional accuracy, pattern strength, surface and flow properties over unfilled wax is also discussed. The present use of 3D patterns following their versatility in the manufacturing sector to revolutionize the investment casting process is also emphasized. Various studies on wax characterization such as physical (surface and dimensions), thermal (thermogravimetric analysis and differential scanning calorimetry), mechanical (thermomechanical analysis, tensile stress testing, dynamic mechanical analysis) and rheological (viscosity and shearing properties) are also discussed.

Keywords: filled pattern; investment casting pattern; semi-filled pattern; unfilled wax pattern.

1 Introduction

Metal parts produced by investment casting currently play an important role in enhancing our daily lives through the manufacture of medical implants, components for power generation, aircraft spare parts and other diverse components (Upadhya et al. 1995, Jones and Yuan 2003). It is vital to have an investment casting pattern with good strength properties, dimensional stability and ease of handling and assembly to achieve the best-quality investment casting products (Pattnaik et al. 2012a,b,c).

Investment casting, often referred to as the “lost wax process”, is an ancient process where ferrous and nonferrous metal components are produced from an alloy (Shivappa et al. 2014). The process enables production of metallic objects with excellent surface finishes, complex shapes and dimensional accuracy. Investment casting involves injecting wax or other material with wax properties into a metallic mold to form a disposable pattern (Karwiński et al. 2011, Pattnaik et al. 2012b, Yadav et al. 2013). A series of shell coatings, composed of ceramic material such as zirconium oxide, a binder that can be either water-based such as colloidal silica, methyl cellulose, or alcohol-based binders such as ethyl silicate or alumina silicates, is applied to the pattern which is finally dried adiabatically in a temperature- and humidity-controlled environment followed by firing at a temperature of 900°C–1200°C (Jones and Yuan 2003). The ceramic shell mold is dewaxed and the alloy is cast into the shell to produce a metallic part. Cheah et al. (2005) have illustrated the eight steps of investment casting process, which include (1) pattern production, (2) pattern assembly, (3) investment, (4) firing/baking, (5) dewaxing, (6) casting, (7) shell removal, (8) cut-off and (9) finishing and inspection, as shown in Figure 1.

Unfilled wax or straight chain waxes as pattern materials for the investment casting process has been widely used for centuries when the investment casting process was used to make, e.g. primitive tools, jewelry and idols (Dadhaniya 2015). The types of waxes that have been used conventionally include beeswax, vegetable waxes such as carnauba and candelilla, mineral waxes such as paraffin wax, microcrystalline wax and montan wax. Synthetic waxes such as amide waxes, ester waxes and castor oil-derived waxes have also been employed (Horáček 2005).

Conventionally, during the investment casting process, wax must be injected at temperatures above room temperature, i.e. >40°C. When wax is gradually heated, it does not melt immediately like a homogeneous

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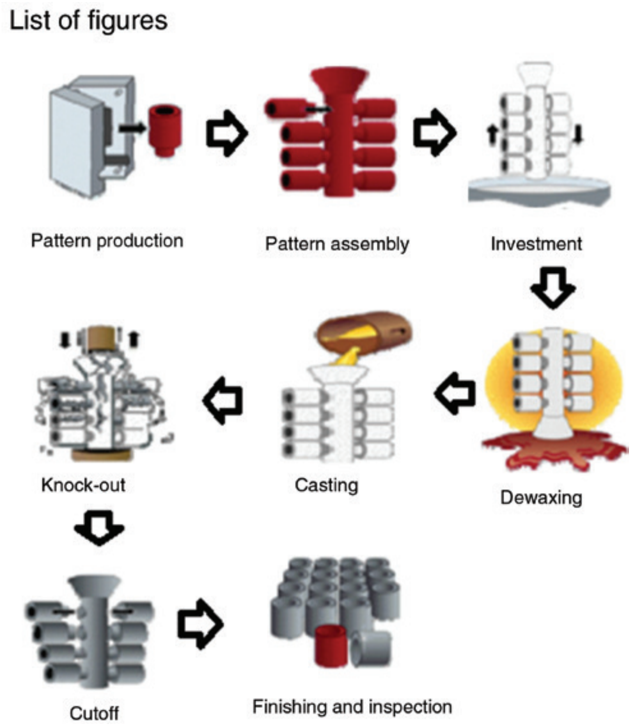

Figure 1: Investment casting process (adapted from Kalpakjian and Schmid 2008).

chemical compound. Initially, it softens, then turns plastic and finally semi-plastic (Ukrainczyk et al. 2010). The short-chain fraction of hydrocarbon wax melts first, while longer chains remain solid. When the wax is heated further, a semi-liquid consistency is acquired and it finally becomes a non-Newtonian fluid (Gebelin and Jolly 2003). This behavior leads waxes to be classified as non-Newtonian fluids. Non-Newtonian fluids exhibit elastoviscoplastic characteristics and are subjected to shearing forces upon melting. Hence, non-Newtonian compounds become more of a fluid when injected into an extrusion molding machine under pressure (Li and Zhang 2003).

Currently, emerging advanced manufacturing technologies coupled with investment casting technology has gained immense application in various industrial sectors; hence, it is critical to explore ways to improve the technology by analyzing the process at all stages of development in order to reach a stage where products are less costly and resource efficient.

The present paper begins by giving an outline of the investment casting process, which covers an introduction, development of patterns, limitations associated with the use of unfilled wax and a summary of the industrial application of the investment casting process. An investigation of previous studies on the modification of unfilled wax by incorporating additives in the wax matrix to improve wax physical, thermal, mechanical and rheological properties is also featured with previous studies on pattern formulation and recent developments being underscored. With the advancement in technology, the advances in the investment casting industry in terms of reduction in manufacturing costs and improvements in pattern properties are important. The findings highlighted in this paper are fundamental to the investment casting industry. Characterization techniques which are vital to define the important properties of investment patterns, which include thermal, mechanical and rheological techniques, are emphasized. Finally, a detailed discussion of all these topics is made, which also seeks to shed light on the gap areas.

2 Pattern materials

2.1 Pattern production

The exact geometry of the final cast is required when making an investment casting pattern, but sometimes, to compensate for any solidification shrinkage as well as volumetric shrinkage, a dimensional allowance is added at the pattern development stage. An injection molding machine has typically been used to produce an investment casting pattern by injecting the pattern material into a metallic die. Currently, other exploratory pattern making techniques include 3D printing. In injection molding, pattern injection is usually done at a temperature between 42°C and 77°C and a pressure of 2.72–102 kPa (Roschochowski and Matuszak 2000). Some of the materials which have been used for making investment casting patterns include wax, polystyrene, frozen mercury, etc. (Pattnaik et al. 2012a,b,c). Craig et al. (1967), after extensive research on the use of wax for making a pattern material for the investment casting process, highlighted the following characteristics: lowest thermal expansion for highest dimensional accuracy; resistance to breakage; low viscosity when melted; wettable and smooth surface for a smoother surface to be obtained; melting point slightly higher than the ambient temperature; environmentally safe and minimal or zero ash content; wax is easily released from the mold after pattern formation.

Pattern performance is assessed by checking the consistency of its physical parameters such as congealing point, volumetric expansion, softening point, viscosity, and penetration. Harsha (2011) concluded that polymeric materials are suitable fillers used to improve wax pattern thermal and mechanical characteristics for the investment casting process. He found that polymeric materials have the following properties that aid in the improvement of the investment casting pattern. Polymeric compounds that are resistant to corrosion have low density and low coefficients of friction as glazing materials and high transparency properties with high toughness. With the ever-increasing trend in demand for investment casting parts, it is pivotal to develop a pattern capable of satisfying the functional requirements of the investment casting process. In previous studies on the development of more suitable pattern material, the challenges posed by the production of thin-section metallic parts by investment casting have been solved to a large extend by the use of filled, plastic and rapid prototyping (RP)-produced parts. Future developments in pattern production should be on reducing lead time, and coming up with new polymer-blend mixtures that are less prone to temperature-induced warpage and curing as well as looking into the development of non-polymeric materials and hence expanding greatly on the application of the investment casting process as well as RP techniques.

2.2 Types of waxes used for investment casting and wax limitations

The typical waxes that have been used for investment casting materials are petroleum waxes, natural waxes and synthetic waxes or mixtures of the three. Paraffin and microcrystalline wax, by-products from the crude oil cracking, have been the most used petroleum waxes for investment casting (Bemblage and Karunakar 2011). Generally, most waxes are saturated alkane hydrocarbons with a general chemical formula – C_nH_{2n+2} (Ukrainczyk et al. 2010, Rani and Karunakar 2013). The use of paraffin wax for investment casting patterns is supported by the following desirable properties: low viscosity and surface tension, low melting point and high heat of fusion, cost, the ability of enhancing rheological properties which influence the fluidity and injection temperatures, good thermal and chemical stability and lack of phase separation and self-nucleating behavior (Rao and Zhang 2011). The use of microcrystalline wax is supported by its easy control of flow and its strength when linked to the hardness of the investment casting pattern. Studies by Patel (2016) have shown that a blend of paraffin and crystalline waxes yields an investment pattern material that lacks uniformity. Natural waxes are long-chain, linear and aliphatic mono-esters derived from plants and animals. Examples of natural waxes include carnauba wax (41% diesters of 4-hydroxycinnamic acid, 21% fatty acid, 12% alcohol C_{26}–C_{30} and 13% ω-hydroxycarboxylic acids), candellila wax, montan wax (non-glyceride carboxylic acid esters (62%–68% w/w; long-chain free acids 22%–26% w/w) and beeswax (esters of fatty acids and long-chain alcohols with palmitate, hydroxy palmitate and oleate alcohol chain esters of C_{30}–C_{32}) (Peleikis 2011). Synthetic waxes are produced by oxidation of polyolefins and addition of co-monomers to hydrocarbons through olefin polymerization or Fischer-Tropsch synthesis. Examples of synthetic waxes that have been utilized for investment casting pattern production include polyethylene wax (Peleikis 2011, Pattnaik et al. 2012a,b,c).

Despite both natural and synthetic waxes having been widely used over time, several researchers have identified shortcomings which hinder their application in making complex metal parts. Harshit and Ajay (2013) investigated the use of unfilled wax for investment casting patterns. These authors discovered two major limitations: dimensional control due to hot deformation and thermal expansion and insufficient rigidity and strength for a very fragile pattern. However, Mishra et al. (2011) found that the properties of waxes that limit their use as investment casting pattern materials can be improved by additives such as filler materials, i.e. oils, plasticizers, and resins. In addition, melted waxes have some detrimental effects on the environment due to the emission of carbon dioxide and volatile organic compounds (VOCs); hence, ventilation and regulative conformity may become a significant concern. Huang et al. (2007) associated wax derived patterns with mold cracks due to wax expanding when stress is exerted on the mold. This is mainly caused by shrinkage due to differential cooling rates between the thick and thin sections of the wax pattern. When a wax pattern is detached from the metal die, there is always a high chance of distortion to mitigate the strain caused (Mohd Nor et al. 2015). In addition, the use of wax patterns for a small number of investment casting pieces as well as for products with thin geometry that readily break or deform when handled is not economically viable due to their limitations in precision casting applications (Zhang and Gilchrist 2012).

The performance limitations exhibited by unfilled wax has led to the development of several more suitable and complex pattern materials for investment casting. Wax properties have been modified by the use of several additives to improve most of the functional shortcomings. Recent advances in the field of polymer composites for investment casting looks into the reduction of molding time. Researchers are now looking into developing ultra-high-speed-curing resins and high-speed injection technology. The realization and application of the technology will greatly improve the development of hybrid patterns and hence represent advancements in the investment casting process.

2.3 Additives and fillers for pattern materials

Additives are compounds are used in small amounts to improve the properties of a material and hence improve its performance, appearance, and its use in a process. In the investment casting process, additives incorporated into pattern waxes also act as stabilizers and polymerizing agents (Pattnaik et al. 2012a,b,c). The use of wax as a pattern material lacks dimensional accuracy, strength and rigidity (Sabau and Viswanathan 2003). The use of additives in investment casting pattern waxes helps to improve their thermal and thermochemical behavior (Pattnaik et al. 2012a,b,c). Wang et al. (2006) concluded that the two most common shortcomings associated with the use of wax only as an investment casting pattern material can be reduced by the inclusion of additives such as fillers, resins, plasticizers and oils in the parent wax material. In the case of filler material incorporation, its selection criteria include higher melting point, non-reactivity with the base wax and the ceramic materials, fine particle size distribution, specific gravity close to that of the base wax and low ash content. Extensive research findings by Borcherding and Luck (1998) alluded to and affirmed that the use of pulverized soybeans as a filler material improves wax properties by reducing shrinkage, improving surface roughness and tensile strength. Soybean powder is combustible and has an appropriate low ash content (≤0.05%). Further investigation by Taşcıoğlu and Akar (2003) revealed that pattern properties such as coefficient of thermal expansion, tensile strength, surface roughness and viscosity can be improved by using additives such as activated charcoal, palmitic acid, cross-linked polyvinylpolypyrrolidone, and some surface-active agents. The addition of rigid fillers increases the modulus, while the addition of soft, microscopic particles lowers the modulus and increases its toughness. The use of fillers in powder form decreases the polymer rate of elongation and its ultimate strength, whereas the use of long fibers causes both the modulus and the ultimate strength to increase.

Studies by Pattnaik et al. (2013) revealed that the use of starch powder as a filler material was compatible with wax. The developed pattern material from the optimum wax-starch blend had improved shrinkage (linear shrinkage of 2.8%) and surface roughness (58.6 nm). The addition of plasticizers into wax brings changes the same as changes witnessed upon an increase in temperature (Larsson 2010). A summary of filler material incorporation significance in investment pattern material is described in Table 1.

The use of resins in investment casting pattern material aids in increasing the strength and body of the pattern (Sabau and Viswanathan 2003). Solidification shrinkage which causes surface cavitation of pattern material is lessened by the addition of a small amount of resin material into the parent pattern material. The most preferred resins added to investment casting pattern materials include acrylate functional oligomers such as acrylate resins of bisphenol (Queiroz et al. 2011).

Resins such as coal-tar resins, terpene resins, and rosin derivatives have fluctuating viscosities and expanded softening points at different temperatures which need to be factored in during their addition to wax materials (Khalaji et al. 2013). Examples of resins which improve the pattern mechanical strength, hardness and its softening point and have been incorporated into pattern materials in practice include acrylic resins such as ethyl- and butyl-methacrylate, thermoplastic resins such as polyvinyl alcohol and polyvinyl acetate and thermosetting resins, such as phenol formaldehyde (Straioto et al. 2010). Further studies done by Pattnaik et al. (2012b) have investigated the use of teraphenolic resin (TR) on the tensile, flexural and compressive strength properties of polyethylene wax. The authors concluded that TR improved the tensile and flexibility strength especially for cylindrical patterns. The choice of resin used as an additive to investment casting pattern material primarily depends on its interaction with the filler and the primary pattern material. The use of

Table 1: Effects of filler material on pattern material (Yadav et al. 2013).

Properties	Characteristic properties enhanced
Thermal stability	Fillers increase material bulk but reduce its weight; hence, they improve the mechanical strength. This is due to filler material having a higher thermal conductivity than polymeric material to a greater extent
Specific gravity	Dimensional stability is improved due to filler materials remaining in its state due to its high melting point compared to thermoplastics
Surface properties	Stiffness and hardness characteristics improved by agglomeration and fillers geometry and particles aggregation

plasticizers such as diethyl phthalate, dibenzyl phthalate, glycerol, polyalkylene glycols, hydroxy ethylated alkyl phenol and polyester plasticizers in investment casting pattern materials aids in improving the static nature of the pattern material and also acts as a lubricating agent (Quinn et al. 1993, Larsson 2010).

Many researchers have established conclusively that wax properties enhanced by incorporation of organic fillers and other additives have shown impressive performance resulting in accurate dimensions, complex part configurations, intricate designs, improved shrinkage characteristics, and good thermal and mechanical properties important in the vestment casting industry. It is a prerequisite for wax-fillers and wax-additives to pattern waxes to always work synergistically in order to produce a pattern that is always user friendly in all refractories used for all alloys. The long lead time has, however, been a great concern for most researchers, but the invention and development of the RP technique, utilized in the development of patterns for investment casting, will greatly improve on the lead time for the process.

2.4 Wax blends for pattern materials

Unfilled or straight pattern waxes were used in early the days for investment casting to produce metal parts of desired shapes. However, with the recent demand for more complex and accurate dimensional casting of metal parts, unfilled waxes exhibited performance limitations which led to the development of filled pattern materials with improved physical, thermal, chemical and mechanical properties (Sabau and Viswanathan 2003, Biernacki et al. 2015). Filled investment casting pattern materials consist of filler materials incorporated either into the wax or any other material used for producing a pattern (Bemblage and Karunakar 2011). The filler materials comprise of solid or liquid compounds. The solid particles are discrete particles that do not melt during the investment casting process. The physical and mechanical properties of polymeric compounds are improved by the addition of particulate fillers (Pattnaik et al. 2012a). Polymeric materials are the ideal filler materials due to their low coefficient of friction as glazing compounds, corrosion resistance, low density and high transparency (Zhang and Gilchrist 2012). Binders used in pattern materials aid in attaining the required hardness, viscosity and melting point characteristics of the pattern. In the case of refractory binders, the binders bond refractory material for mold formation, whereas catalysts added to the slurry reduces the gelling time of the pattern.

Vihtelic et al. (1986) investigated the effect spherical filler material has on the surface quality of the produced metallic part. The authors also found that the injection pressure to fill the die cavity was reduced using spherical filler materials hence, there is a reduction in ceramic breakage. This was attributed to the fact that with spherical filler materials, there is reduced surface depression in the pattern. Vihtelic et al. (1986) further stated that 35%–40%, by mass, filler materials is the preferred amount. The authors further elaborated that the particle size of the solid filler material should be between 25 and 35 μm and preferably 27 and 33 μm to give a particle size distribution that is relatively narrow and hence reduce the surface depression of the investment casting pattern. This would improve the surface texture and uniformity of the investment casting wax. Muschio (1996) further added that the use of solid particles as filler materials should produce no carcinogenic materials during combustion, thereby becoming an important ingredient in improving the properties of investment casting patterns. Sabau and Viswanathan (2003) classified filler materials into several categories which include resins such as polyterpene resin, Ciba-Geigy XB5131 acrylate ester blend, plastics/polymers such as polystyrene beads, polyethylene carbonate, polypropylenecarbonate, polymethylmethacrylate (PMMA), oils such as castor oil, organic acids such as adipic, isophthalic, stearic and terephthalic acids.

Merges et al. (1964) developed an investment casting pattern wax composed of petroleum wax as the major component with an incorporation of other materials. These authors investigated the use of solid, chlorinated polyphenyl acids, montan wax and stearic acid as additives. The resulting investment casting pattern produced from the combination of the four materials gave a pattern material with low penetration and low shrinkage properties. The use of petroleum wax in investment casting pattern making is limited by volume change and its gradual softening characteristics also referred as “slow setup” during melting. Slow setup requires a significant time before the wax hardens enough to be handled. Rani and Karunakar (2013) did some studies on the change of petroleum wax volume during heating. They concluded that when petroleum wax is heated from a temperature of 15°C–43°C, it undergoes a volumetric expansion of 14%. They summarized that a composition (mass percent) consisting of 35%–65% paraffin wax, 25%–55% solid chlorinated polyphenyl, 5%–15% montan wax (acid type) and 0.1%–5% stearic acid produced an improved investment casting pattern material.

Studies done by Merges et al. (1964) further investigated the use of combustible polyhydric alcohol as a filler for investment casting pattern material. From their initial findings, the melting point of polyhydric alcohol was higher than the melting point of most wax types; hence, the combustible polyhydric alcohol will remain in its particulate existence during the injection molding process. They used a petroleum wax mass composition of at least 40%; pentaerythritol as a polyhydric alcohol (5%–50%, by mass) and a fatty acid, preferably stearic acid (5%–15%, by mass). The significance of a particulate filler is that it will tend to resist contraction of the pattern as well as most are non-corrosive to ceramic molds. The use of a fatty acid, such as stearic acid, acts as a suspending agent for the polyhydric alcohol. Ionic suspension rather than a particulate filled melt is usually obtained with the use of polyhydric alcohol as a filler material. Speyer (1974) did some studies on how polymers of α-alkylstyrenes, or polystyrene copolymers with vinyl alkylbenzene or α-alkyl styrenes or the two copolymers, substituted as polystyrene fillers, can be used to produce an innovative pattern material for investment casting. A combination of the copolymers of styrene, a fatty acid and a petroleum wax gives a material that can be injected at a temperature of 50°C–80°C and a pressure of 0–34 atm. Pattern stiffness and shrinkage can also be controlled with the use of styrene. The pattern will have an increased shrinkage characteristic. In general, the use of polystyrene material has homogenous sufficient flow tendencies, the pattern material can be removed freely from the metal without damaging the metal part and the material has a good stability during heating and it cannot be oxidized in the presence of air.

An investigation by Hayes (1979) further affirmed that the introduction of hexamethylenetetramine (HMTA), i.e. methenamine into wax material produced a pattern material with enhanced properties such as low shrinkage properties and low ash content of <0.02%, by mass. HTMA remains in suspension due to its low specific gravity; hence, AN injected non-clogging uniform material is produced. The author concluded that 5%–50% HTMA and 55%–80%, by mass, petroleum wax gives an improved investment casting pattern compared to the conventional unfilled wax pattern. Muschio (1996) demonstrated a new approach where thermoplastic resin and 80%, by mass, or more powders of cellulosic acetate are incorporated, as a filler for investment casting pattern material. Cellulosic resin thermoplastic powders are environmentally safe since no carcinogenic substances are produced on combustion. Cellulose acetate is preferred containing 45% acetyl and up to 52%, by mass, propionyl having a specific gravity of between 1.31 and 1.32. A composition of 15%–25%, by mass, thermoplastic acetate powder and 75%–75%, by mass, base wax gives the best combination for producing a suitable investment casting pattern. A fast setting pattern material is produced with low shrinkage capacity, a low ash content of <0.02%, by mass, and having dimensional stability.

Sturgis et al. (2001) have proposed an improved process whereby polymeric organic carbonate was used as a filler material for investment casting. The polymeric organic carbonates used included polyethylene carbonate, poly(cyclohexane carbonate), polypropylene carbonate and poly(cyclohexane propylene carbonate). From their findings, it was noted that polymeric organic carbonates decompose completely to give carbon dioxide and water. This results in no residual ash and almost no surface flaws on the investment casting produced metallic part. Uygunoglu et al. (2015) carried out further investigations into the physical and mechanical properties of polymeric organic carbonates and confirmed the findings of Sturgis et al. (2001). The authors further added that polymeric organic carbonates increase the thermal stability as well as the comprehensive strength of the pattern formed.

Guinn (2002) showed that the use polyethylene terephthalate was suitable as a filler material for producing investment casting pattern. The use of polyethylene terephthalate as a filler material is efficient for controlling the contraction and expansion characteristics of wax patterns. The author concluded that the advantages associated with the use of polyethylene terephthalate include, polyethylene terephthalate being inexpensive, it provides a pattern material with a high dimensional precision, it is non-reactive and does not chemically attack the refractory mold, its high thermal conductivity properties allows quick cooling of the pattern material, and it produces no substantial ash residue on ignition due to it flowing easily during dewaxing, and it has reduced shell cracking tendencies. A composition of 5%–50%, by mass, polyethylene terephthalate and 50%–95% wax gives a pattern material with the improved properties as discussed. Karwiński et al. (2011) developed an improved pattern wax using paraffin wax, stearin and polyethylene wax. Their studies focused on a typical by mass composition of paraffin wax (70%), stearin (20%) and 10% polyethylene wax. Initially, the authors examined the physicochemical parameters of paraffin wax. The parameters investigated include the dropping point, solidification point and the kinematic viscosity at various temperatures. Polyethylene wax and stearin addition reduced the shrinkage capacity of the pattern material and also preserved the plastic properties of the pattern as well as increased its hardness. The authors summarized the physicochemical properties of the pattern produced as described in Table 2.

Table 2: Physicochemical properties of PET-, paraffin- and stearin-produced pattern (Karwiński et al. 2011).

Parameter	Experiment number		
	1	2	3
Solidification temperature (°C)	71.4	68.6	71.6
Dropping point (°C)	76.0	68.0	74.0
Penetration at 25°C (–)	9	9	8
Kinematic viscosity at 100°C (mm^2/s)	9.11	6.42	8.52
Carbon residue (wt%)	0.0025	0.0028	0.0018

Recently, Patel (2016) described work on how to develop an enhanced investment casting pattern with superior mechanical and physical properties basing on volumetric shrinkage, surface finish and tensile properties of the pattern. He explored the use of commercial wax mixtures (paraffin wax, Irani wax, rosin wax, montan wax and microchip wax) and innovative additives, e.g. charcoal powder, for producing investment casting patterns. The results confirmed that the combination of distinctive commercial waxes and charcoal powder presented improved volumetric, surface roughness and linear shrinkage materials. He further found out that temperature influenced the surface roughness of the pattern. Many researchers have been concerned with the emission of CO_2 and volatile organic matter which leads to issues of ventilation and environmental regulatory compliance. There is also the issue of wax expansion due to stresses from the mold which causes cracking (Taşcıoğlu and Akar 2003).

From their studies, Rani and Karunakar (2013) reported that the use of beeswax and paraffin wax for investment casting gives a better surface finish to the investment cast produced metal part. The authors further highlighted the properties of five wax types as summarized in Table 3.

Sabau and Viswanathan (2003) have done further studies on the use of an industrial wax referred to as Cerita™ 29–51 for investment casting pattern formation. The authors observed that the dimensional differences between the die and the cast metal part were due to thermal expansion and hot deformation phenomena during the pattern making process and solidification of the alloy. As per their conclusion on the use of computer models for dimensional analysis of Cerita™ 29–51, their studies on rheological and thermophysical aspects indicated that Cerita™ 29–51 pattern material has low thermal diffusivity and therefore the wax cools slowly leading to the formation of a small thickness on the pattern surface. Bemblage and Karunakar (2011) developed a wax blend using five different wax mass ratios, as described in Table 4, to produce an improved pattern material for investment casting. From the authors' findings, Blend 2 (Table 4) consisting of paraffin/beeswax/montan/carnauba of 50:30:20:0) produced a pattern material with the best properties such as better surface finish and minimum shrinkage. Bemblage and Karunakar (2011) further used the Taguchi Experimental Analysis technique to design the experiments and develop suitable experimental conditions by optimizing all the process parameters varied in their experiments. From the Taguchi method, the most suitable component ratios gave a linear shrinkage of 0.75%; volumetric shrinkage of 2.25% and surface roughness of 0.7 μm compared to the paraffin. Shivappa et al. (2014) used the factorial method to blend carnauba, montan, paraffin and bee waxes to produce a pattern material for investment casting. The authors' emphasis was to develop an improved and recyclable investment casting pattern material. From the authors' perspective, paraffin wax was required in bulk amounts and was used as the primary wax component. The factorial, statistical technique was used to vary the other three wax components in different mass percentages. The melting points of the four wax types varied from 64°C to 87°C. Shivappa et al. (2014) blended the different waxes to obtain a formulation that gave optimal melting point and congealing point values of 40°C–45°C for pattern formulation. The three wax variables (beeswax, carnauba wax, and montan wax) were coded with letters B, C and D and taken at two-level factorials which formed 2^3 factorial

Table 3: Properties of different types of waxes (Rani and Karunakar 2013).

Type of wax	Density (g/cm^3)	Melting point (°C)	Volumetric shrinkage (%)	Flash point (°C)
Paraffin wax	0.78	52–74	6.20	275
Bee wax	0.958–0.97	62–64	7.25	204.4
Carnauba wax	0.97	82–86	5.45	300
China wax	0.82	62–75	6.28	318
Montan wax	1.02	82–95	2.45	300.26

Table 4: Wax blends proportions (wt%) (Bemblage and Karunakar 2011).

Blend	Paraffin wax (%)	Beeswax (%)	Montan wax (%)	Carnauba wax (%)
1	50	30	0	20
2	50	30	20	0
3	50	30	10	10
4	60	20	10	10
5	70	10	10	10

experiments. Using ANOVA software to interpret the factorial experimental data, the authors concluded that the independent effects of the waxes were significant at 99% and 95% confidence levels. Shivappa et al. (2014) concluded that the best formulation that gave an improved investment casting pattern and a high degree of recyclability was composed of 80% paraffin wax, 8% beeswax B, 8% carnauba wax and 4%, by mass, montan wax. The melting and the congealing points of the optimal mass composition were lowered to 42.6°C and 40.3°C, respectively, and its ash content was 0.16%.

Blended patterns have a great significance in the development of patterns for investment casting. From the review, it was clear that extensive research work had been done by several authors on the pattern materials for investment casting. From the studies on the use of ice as pattern material, ice has good dimensional accuracy and there are less chances of shell cracking. In the case of mercury being used as pattern material, toxicity is a great concern as well as the temperature should be kept extremely low which is very difficult and another disadvantage is its high cost.

Wax blends have been conclusively shown to be good pattern materials, available at a lower cost, and which can yield balanced properties. According to various researchers, blending of a parent wax with other wax types and other materials imparts vital characteristics to the parent wax, resulting in a pattern wax that best suits the needs of all investment casting foundries for the development aspects of investment casting of alloys. Recent positive developments have been made in formulating polymer composites for the development of fast curing resin, to be utilized in the polymer industry blended with other polymers to improve their properties and most importantly to shorten the molding time (Kocsis 2016).

2.5 Ice for pattern materials

In spite of the use of wax as a pattern material having several advantages, the problems remain owing to the expanding wax creating internal pressure within the ceramic shells, which has a great impact on the metallic part being produced. Heating causes a fracture which, in turn, results in shell breakage during the casting process (Yodice 1991). The freeze cast process technique is a freeform fabrication procedure that is environmentally friendly and novel and has been used to produce 3D ice patterns (Liu et al. 2002). Huang et al. (2007) studied the use of ice patterns instead of wax patterns for investment casting. The authors further specified three benefits of ice patterns as environmentally benign; ready availability of ice compared to wax brings the economic aspect of the process to the fore and ice shrinks during melting hence, averting the chance of mold cracks. This follows some further studies done earlier by Pham et al. (2008). Huang et al. (2007) further studied how catalysts and binders are vital constituents used to improve the dimensional accuracy of patterns. Further work needs to be carried out on the use of ice as a pattern material in order to develop improved ice pattern accuracy and duplication of ice pattern surfaces leading to the eventual commercialization of the technology.

2.6 Polymers for pattern materials

Advancement in technology over recent years has led to the improvement of the investment casting process through the formulation of suitable and ready to use pattern materials (Rutto and Focke 2009). Formulation refers to the combination of compounds which have wax-like properties or blends of wax with other components that yield an improved pattern material for investment casting. The inclusion of other components into investment casting waxes results in changes in its properties such as its viscosity, degrees of contraction and expansion, melting-point, hardness etc. (Bemblage and Karunakar 2011). The incorporation of filler materials into wax leads to lower volumetric expansion and lower viscosity values as compared to unfilled wax patterns, as described in Figure 2. A reduction in volumetric expansion reduces the chances of casting breakages whereas lower viscosity values ensure easy injection of pattern material (Larsson 2010).

Rutto and Focke (2009) studied the use of urea with poly (vinyl alcohol) (PVOH), plasticized with glycerol or ethylene vinyl acetate (EVA), together with the wax to produce an investment casting pattern which can result in near net shape metal castings. The authors explained that urea being a material with good mechanical and thermal properties, in addition to its very low toxicity level and low melting point, is attractive for investment casting. Jang and Lee (2003) further revealed that PVOH interacts strongly with urea due to its hydrophilic nature. Since the melting point of PVOH exceeds the thermal degradation onset temperature, plasticizing it with compatible and high boiling point glycerol, lowers its melting point. In conclusion, the differences in the interaction and affinities between polymer phases, urea, and wax, PVOH formulated investment casting pattern materials exhibited elevated, advantageous, mechanical properties such as

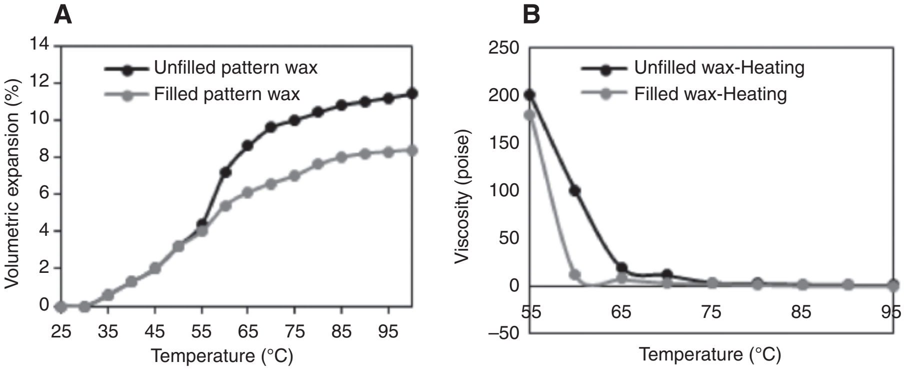

Figure 2: (A) and (B) shows that the incorporation of fillers on pattern waxes helps control and reduce volumetric cavitation as well its viscosity by creating internal resistance.
Effect of filler and temperature on (A) volumetric expansion and (B) viscosity (Stanco 1998).

improved impact resistance, strength, and stiffness as compared to ethylene vinyl acetate formulated investment casting pattern material. The authors, in conclusion, discussed the degradation of urea to ammonia and carbon dioxide at a temperature above its melting point as the greatest impediment to its use in investment casting pattern formulation.

Wang et al. (2010a,b) discussed the current trend of the use of plastic as a pattern material for the investment casting process. The authors studied the use of acrylonitrile butadiene, styrene acrylonitrile and polycarbonate plastics with their investigations focusing on thermal stress on the ceramic shell as a result of thermal expansion during heating. The criteria used by the authors were helpful in recommending the thermal and mechanical properties to achieve a better application of plastics as a pattern material for investment casting (Idris et al. 2009). Plastic patterns may be a solution to the characteristic breakage or deformation experienced by using wax in producing metal parts with thin geometries (Wang et al. 2010a,b). Yadav et al. (2013) studied the effects of using expandable polystyrene as the bulk material for investment casting patterns and the effect this has on the mechanical properties of A713 alloy cast metallic material. The studies used the Orthogonal Array of the Taguchi method with four factors and three levels, to investigate the wax hardness, impact strength and tensile strength. The studies concluded that the tensile strength, hardness and impact strength showed decreasing tendencies with an increase in grain fineness as well as with an increase in pouring temperature. This was attributed to the effects of the mentioned three parameters on the mechanical properties of the pattern.

Despite immense gains in the use of plastic material in pattern making, the authors identified numerous problems associated with the use of non-wax, pattern plastic including features such as incomplete collapsibility of patterns during burnout, excessive thermal expansion leading to ceramic shell cracking, poor surface finish and high residual ash. In order to elucidate the shell cracking problem, the authors proposed the applicability of inner webs known as lattice structures for the application of plastic material in investment casting patterns (Hague 1995). Wang et al. (2010a,b) concluded that the glass transition temperature has a great effect on shell thermal stresses. Ceramic shells will experience more thermal stress with a small increase in glass transition temperature and thus additives may be used to modify the properties of plastic materials thus making their application for use as pattern material feasible.

2.7 RP 3D-printed polymer patterns

Recently, the RP technique has become fundamental in product design and development in the manufacturing sector. The challenges due to lengthy lead time and high tooling costs experienced with the conventional and traditional wax pattern making process can be greatly minimized by RP (Hilton and Jacobs 2000, Chua et al. 2005). RP application in the making of investment casting patterns is developed through RP soft tooling (RPST) and is categorized into two approaches, namely, indirect and direct RP methods. The RP techniques which have been utilized over time to produce patterns for investment casting include fused deposition modeling, laminated object modeling, selective laser sintering, 3D printing, stereolithography and direct shell production casting. The direct RP method, also known as the direct shell production method, is whereby wax, plastic or paper investment casting patterns are produced for ceramic molds intended for direct metal casting (Jain and Kuthe 2013). In the case of indirect RP techniques, a substitute mold is made using silicone rubber. This mold is used with the RP-fabricated master pattern and employed in investment casting (Macků and Horáček 2012). Lee et al. (2004) developed a benchmark investment casting pattern using fused deposition modeling (FDM). 3D printing was utilized using acrylonitrile butadiene styrene. The authors appraised the performance of acrylonitrile butadiene styrene in terms of dimensional stability, surface finish, cost involved and time taken to produce a pattern. Further, Chua et al. (2005) studied direct and indirect RP fabrication of investment casting patterns using Model Maker II software (MMII). The authors concluded that the model patterns produced using MMII possessed thermal properties such as their melting points closely similar to those of wax and also with no residual ash content. They identified some of the drawbacks associated with RP patterns which included ceramic shell damage causing unevenness resulting from the effects of thermal expansion on the ceramic materials by the RP produced patterns (Yao and Leu 1999) and Lee et al. (2004) Chua et al. (2005) summarized this by highlighting the vast superiority when RP patterns are used as sacrificial or master patterns for investment casting. Among the shortcomings of the MMII technique, the authors mentioned long build-up times and the inability of the technique to be used to produce large quantities of investment casting metal parts, as the greatest weakness. The advantages of RP, via FDM, over conventional wax patterns include time and cost saving, better surface quality and dimensional accuracy. One of the major shortcomings of FDM is that the technique cannot be used for mass production of investment cast metal parts.

3 Pattern characterization techniques

3.1 Physical characterization techniques

The two most important physical properties that have an immense impact on the quality of investment casting patterns are surface smoothness and its porosity (Patel 2016). Physical characterization techniques of investment casting patterns involve investigations of their physical properties such as dimensions, particle size, conductivity and surface appearance. In the development of investment casting patterns, differences in material porosity and surface roughness can greatly affect pattern performance characteristics (Zych et al. 2012, Bihari et al. 2015). Poor surface appearance in pattern making for investment casting is caused by several factors, including filler separation, wax/pattern temperature, improper wax/pattern meltdown, overheating of pattern material and low injection pressure (Wolff 1999).

3.2 Thermal characterization techniques

Thermal analysis of investment casting pattern material aids in the establishment of its physical and thermal properties. It plays an important role in relation to the melting and crystallization of the materials used in the wax injector as well as its removal from the mold (Larsson 2010, Steinmann et al. 2013). The techniques which are vital in the investigation of the thermal characteristics of investment casting pattern materials are differential thermal analysis (DTA), thermo-gravimetric analysis (TGA), differential thermo-gravimetric analysis (DTG) and differential scanning calorimetry (DSC) (Kumar 2014). DSC is one of the thermo-analytical techniques widely used to investigate numerous developments in pattern materials occurring during thermal treatment. The properties investigated include identification of the material's melting, crystallization, curing, glass transition temperature and any chemical activity occurring in the material (Kumar 2014). In most polymeric materials and their composites used for investment casting patterns, the determination of α-transition relates to the Brownian motion of the main chains during their transition from the glassy to the rubbery state (Corcione and Frigione 2012). During thermal degradation of pattern wax, heat is absorbed from the free acids and the hydrocarbons during melting and solidification (Thirugnanam and Marimuthu 2013). Grzeskowiak et al. (2015) investigated the thermal properties of three wax blends, namely, blue wax, red wax and aqua wax, to understand their reusability as pattern materials for investment casting. The DSC peaks showed that remelting of a wax composite did not significantly affect the melting points of the three wax blends. The structure of the DSC pattern remained the same for each wax blend after the material was reused 15 times. Krupa and Luyt (2001) investigated the thermal and mechanical properties of extruded wax/LLDPE blends. From their DSC peaks, the authors determined the phase transition temperatures such as melting and solidification points of the wax blends as well as their heat enthalpies. The authors concluded that there were behavioral differences in terms of endothermic peak in the case of heat enthalpy, with higher amounts of wax in a blend. For wax compositions up to 10%, wax and LLDPE are miscible in the

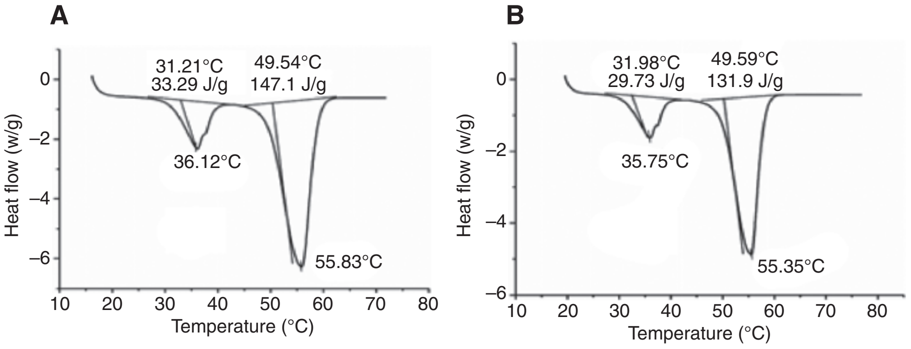

Figure 3: (A) and (B) shows the effect of a filler material on the specific enthalpy during cooling.
There is a shift with the addition of filler material on paraffin wax due to macroscopic homogeneity between the blend. DSC analysis: (A) pure paraffin wax and (B) pure paraffin wax with a filler material (Menard 1999).

crystalline phase. For 30% and more wax amounts, wax and LLDPE distinct peaks were observed. They concluded that LLDPE/wax blends stress at break largely depends on the amount of wax present in a blend.

DSC analysis, shown in Figure 3, obtained from Pu et al. (2007), showed the effect of filler material incorporation into pure paraffin wax. The melting point and heat flow were affected by the addition of fillers to the paraffin wax. A characteristic temperature change can be attributed exothermic and endothermic phase transitions (Xu 2015). DTA analysis is responsible for the establishment of heat differences in the sample and its correlation with the reference temperature throughout the entire experimental temperature increase period (Cao et al. 1991). The thermal stability and composition of the blend are obtained from the TGA analysis. TGA studies by Krupa et al. (2007) on wax/filler blends showed that the thermal stability of the wax-EVA blend decreases with an increase in the amount of wax. This can be attributed to the lower thermal stability of wax.

3.3 Mechanical characterization techniques

Mechanical characterization of investment casting pattern materials is a crucial component for the development of suitable pattern materials with sustainable properties (Wang et al. 2010a). The two most preferred mechanical characterization techniques are dynamic mechanical analysis and the three-point testing technique, as described in Table 5 (Rutto and Focke 2009). The study of the mechanical properties of investment casting pattern materials gives mainly an estimation of the shrinkage factors and pattern deformation tendencies and hence affords a better understanding of the pattern design aspects. Some of the most identified scenarios where mechanical analyses are important are when a pattern material is hard and brittle and may be damaged during assembly and flexible pattern material may not retain its shape during the investment casting process (Chaudhari et al. 2009).

Table 5: Mechanical tests done on investment pattern materials.

Material form	Analysis	Equipment	Sample
Solid	Three-point bending test	Bending beam equipment	Rectangular solid bars
Hard paste	Torsion oscillatory	DMA	Rectangular solid bars
Soft paste	Shear oscillatory	DMA	Paste
Liquid	Shear oscillatory	Melt rheometer	Paste

Three- or four-point bending test and hardness determination are the most common mechanical analyses carried out on pattern material (Sabau 2005). Tensile analysis elaborates on the elongation, yield strength and the ultimate tensile strength of the pattern, using the three-point bending test. Shear modulus determination is obtained by using dynamic mechanical analysis equipment (DMA). Rutto and Focke (2009) carried out three-point bending analysis on paraffin wax-EVA blends and calculated the flexural strain and stress using equations described in the American Society for Testing Materials 790 (ASTM 790). At lower EVA contents, the pattern was weak and brittle with breakage at lower deflections. The authors also found that the toughness of the pattern increased with an increase in the amount of EVA polymer added, as shown by an increase in the fracture energy derived from the stress-strain curve. Krupa and Luyt (2000) investigated the tensile strength of wax/LLDPE blend. The authors concluded that the elongation at the yield point decreased with an increase in wax proportion in the blend. Krupa and Luyt (2000), from their studies on uncross- and cross-linked wax/LLDPE blends concluded that if the wax content is 30% or more, the wax and LLDPE blends are less phase separated. The mechanical properties of the blend lose its drawability since LLDPE has an influence and the yield point of the blend does not tend to exist and the blend elongation at the break-point strongly decreases.

DMA analysis works on the application of oscillatory strain on the pattern material; hence, stress is divided into viscous and elastic constituents (Larsson 2010). Elastic stress is associated with applied strain while viscous stress is associated with the strain application rate. DMA analysis gives information on the viscoelastic nature since, on heating, the time-temperature superposition principle of the pattern material is obeyed. The pressure-temperature-specific volume system (PVT) is used to determine the bulk modulus of the material (Larsson 2010). Furthermore, other important parameters such as glass transition temperature, melting point, and filler effects on the mechanical properties of the pattern material are obtained from DMA measurements. Studies by Everhart et al. (2013) revealed that desirable mechanical properties of a pattern material are contributed by low injection temperature and mold preheat temperature. A study on unfilled wax showed that when wax is heated, it experiences a transition from paste to a liquid, i.e. it softens gradually (Zhang and Gilchrist 2012). This transition is associated with the amorphous component of the wax and occurs at its softening point which is caused by the reduced viscosity as the temperature increases, due to the coordinated segments of molecular flow in the system (Larsson 2010).

3.4 Rheological characterization techniques

Rheology is defined as the study of deformation and flow of matter under stress. It focuses on the study of the properties that matter exhibits when mechanical force is applied to it (Lipatov et al. 1982). A clear, distinct difference between fluid dynamics and rheology is that the latter analyzes the three phases of matter: solid, liquid and gas. Undertaking initial rheological studies involves distinguishing between Newtonian and non-Newtonian fluids. A Newtonian fluid can be defined as a fluid, the viscosity of which is independent of the shear stress applied to it. A non-Newtonian fluid is defined as a fluid whose viscosity is dependent on the magnitude of shear applied to it and where the viscosity is independent of the time over which the shearing is applied (Zhang and Gilchrist 2012). All viscoelastic fluids are classified as non-Newtonian (Sadiku-Agboola et al. 2011). Rheological experimental data yield a mathematical, viscoelastic depiction of matter and its applications. Rheological studies are widely used in the plastics manufacturing industry, metal industries and other vital, highly filled materials. In investment casting processes, rheological studies are used for the determination and establishment of injection parameters and properties of investment pattern material characteristics and as well as its formulations (Argueso 1991).

Volume and viscosity measurements versus temperature relationships are the correlations used to describe the thermochemical properties of investment casting waxes. Studies by Piwonka et al. (2000) concluded that at temperatures considerably above their melting points, waxes exhibit Newtonian fluid characteristics. As temperatures are increased above the melting points, waxes start to exhibit viscoelastic behavior as non-Newtonian fluids. The incorporation of particulate filler materials into the wax pattern material results in an exponential increase in its viscosity. This happens because filler materials tend to flocculate owing to their even dispersion throughout the wax pattern material. This is an important factor in rheology studies of investment casting pattern materials since surface roughness is caused by large flocs in the pattern material (Sirin et al. 2012). Further studies were done by Piwonka et al. (2000) using an oscillatory shear rheometer to establish rheological characteristics of investment casting wax above its congealing point. The demand in the food industry to assess edible lipid substances led to the need for establishing their viscoelastic properties. The properties of candellila wax, carnauba wax and beeswax, at room temperature, were established using the stress relaxation method devised by Shellhammer et al. (1997) that established the viscoelasticity of all the waxes tested and which were outlined by the generalized Maxwell model. In conclusion, they found that beeswax can be easily deformed, is less elastic and more viscous, whereas carnauba wax and candellila wax were elastic and hard. Wax stress and relaxation properties greatly contribute to wax deformation, Moreover, the thermal stress relaxation of wax pattern materials and their induction needs to be established to determine their dimensional advancement as per the work of Cannell and Sabau (2006). A three-phase system, rheological property, is greatly altered by morphology based on the thermodynamic interrelationship between the polymer ingredients and their resultant flow. To establish the rheology of pattern material, the following properties must be established: mode of deformation, behavior under strain, geometric boundary conditions and behavior under stress (Manias and Utracki 2002).

4 Conclusions

This review imparts explicit knowledge on investment casting pattern development based on what has been researched and published in the scientific literature to date. Advancement in investment casting over the years has been on the improvement of ceramic coating and the overall development of pattern materials. The patterns used for investment casting have been appraised based on volumetric expansion, shrinkage, strength, flow and thermal properties.

The following conclusions were drawn based on the present review:

- The performance limitations exhibited by unfilled wax used for pattern making can be enhanced by blending it with other wax types or fillers and additives. Blending or incorporation of additives improves the rigidity characteristics, dimensional accuracy and the non-uniform flow behavior of unfilled wax, which has huge negative impacts on the injection parameters. Future research may be done on the use of other cheaper organic compounds with properties similar to that of polymeric compounds.
- There is considerable outstanding work to produce investment casting pattern materials using wax blends, polymers, oils, plasticizers, solid organic fillers, and resins in order to produce an improved ready-to-use soft pattern material. The patterns produced have improved physical, thermal, rheological and mechanical properties. However, most of these additives are quite costly and have a huge impact on the cost of the investment casting process. Thus, natural materials such as starch, waste from leguminous vines, etc. are preferred substitutes for synthetic polymers and other more costly additives.
- Although injection molding has been used for a long time to produce pattern material for the investment casting process, other advanced technologies have been developed to replace this conventional technique. The application of high-edge RP techniques to produce patterns for investment casting has been investigated. This technique has the capacity to revolutionize investment casting, and further improvements of the current new techniques are required to be completely applied in producing complex metal components.
- From the present review, to reduce the chance of green shell breakage, a pattern material should have a low melting point and congealing temperature. At low melting and congealing points, the pattern material solidifies faster. Consequently, during dewaxing, the pattern material starts to melt at the peripheral areas, which leads to a great reduction in shell breakage. The spherical morphology of filler materials has an effect on the injection pressure required for filling a pattern die cavity. The spherical morphology of fillers reduces the required injection pressure, resulting in a reduction in ceramic core breakages to minimum levels.
- Physical, thermal, mechanical and rheological studies of investment casting waxes and other pattern materials are important tools used to study their properties. Rheological characterization yields information on the flow and deformation characteristics of the pattern material when stress is applied to it. This helps in the determination of injection methods and properties in the manufacture of investment casting patterns. Thermal characterization provides data on the thermal properties such as melting and solidification which are important in injection as well as mold removal. Mechanical characterization affords information on the deformation and hardness properties. The design aspect depends hugely on the mechanical properties of the material.
- Further studies are required to investigate the advantages, disadvantages and any problems of incorporating RP techniques in the making of patterns. These studies will provide further insights into the application of RP techniques on the general practicability of the process, including the cost implications and the important technologies that can be exploited for the benefit of the investment casting process in general.

Acknowledgments: The authors gratefully acknowledge the financial support given by the Technology Innovation Authority, South Africa.

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