Title: Review of ceramic mold casting of metal-based materials via the Shaw process

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Abstract

A mini review mold casting of metal-based materials via the Shaw process

Ceramic mold casting refers to metal casting processes that employ ceramics as the mold material. The Shaw process and the Unicast process are types of ceramic mold casting that are used to manufacture items (e.g. golf clubs, impellers, etc.) from low to high volume, and from small to large tonnage. This mini review covers the academic and patent literature that focus on metal casting via the Shaw process.

Keywords: Ceramic mold casting, Shaw process, slurry, manufacture.

Introduction

Casting is the process in which a molten metal is transferred to a hollow 3-dimensional container (mold) where the hollow is the desired shape of the product [1–3]. After the molten metal has been transferred to the mold, the metal and mold are cooled, and once sufficiently cool the product (i.e. the metal casting) is removed from the mold. Casting processes (e.g. investment casting, including lost-wax casting [4–13], plaster mold casting and sand casting [14–17] have been employed for hundreds of years and are well suited to producing complex shapes that are challenging or uneconomical to make by other methods [18,19], commonly (albeit not exclusively) employing ceramic molds to withstand the temperatures of molten metals [20–22]; we direct the avid reader to reference texts [23].

The Shaw process is a metal casting technique that combines investment casting with plaster mold casting and employs ceramic molds (with a 3-dimensional hollow generated from a reusable mold template/pattern), depicted in **Figure 1**. The ceramic molds are prepared from slurries composed of a mixture of ethyl silicate (also known as tetraethyl orthosilicate) that has been hydrolysed [24–32], alcohol, gelling agent, and mineral particles (chosen for their chemical, mechanical and thermal resistance to the conditions used in the casting process) [33–35]. The slurries solidify enabling removal of the mold template/pattern, and volatile substances (e.g. alcohol, water) are burned off by ignited/evaporated by exposure to a flame, yielding a ceramic mold with microscopic cracks [36,37]. The microscopic cracks enable gases to escape from the ceramic, and enable expansion/contraction during subsequent processes, but are too small for significant quantities of the metals cast within them to penetrate. The ceramic molds are cured/baked at ca. 980 °C to remove any residual volatiles, then cooled and stored. It is important to note that the Shaw process is the only casting process where cold ceramic molds can be filled with molten metal without cracking, nevertheless the molds are often warmed prior to being filled with molten metal to minimize shrinkage [18,19], although this can adversely affect the surface microstructure quality of the casting [38].

The Unicast process is a subtle variation on the Shaw process using molds that have been partially cured (without being ignited and cured/baked) so the reusable mold template/pattern imparting the 3-dimensional hollow can be removed [39]. For metals with high melting points the mold is then cured/baked at ca. 1040 °C prior to the metal casting, whereas for metals with low melting points the curing/baking is avoided, because the partially cured mold will withstand the casting process.

Benefits of using ceramic molds include: the breadth of different metals/alloys that can be cast (ferrous/non-ferrous [e.g. Al, Cu, Mg, Ti, Zn]); being able to reuse the mold template/pattern (enabling storage of the bespoke template/pattern for long periods so the casting process can be repeated as/when necessary); high quality surface finish (µm scale roughness) and dimensional tolerances (minimising the necessity for polishing/defect removal); the ability to produce materials with intricate features (optionally combining ceramic mold casting and lost wax casting by employing resin/wax mold templates/patterns). For economic reasons it is predominantly used for small/medium batch production (most often for casting bespoke high value items).[40]

Skilled toolmakers or patternmakers have traditionally manufactured tooling, and it is noteworthy that the material used by the toolmaker is determined by the same selection criteria as for the casting process. Metal tooling can be expensive as it is usually associated with high volume casting requirements or for high precision castings where longevity is also a consideration; wood patterns (soft wood) are traditionally associated with lower volume casting requirements; materials such as epoxy resins and hardwood offer a longer life and less wear than the softwood option. Tooling manufacture was traditionally done by hand but has evolved to the point where today small patterns can be manufactured by 3D stereolithography or if possible machined from resin bonded board on 5 Axis machines. The availability of a wide range of wood and manmade materials has enabled the manufacture of large skeletal wrapped patterns resulting in cheaper costs and quicker production times. Disposable or single use patterns can be manufactured from polystyrene, and low-cost tooling is also available from low-cost countries.[40]

Additive manufacturing approaches can be employed to manufacture components with various dimensions, with tolerance ranges being dependent on the type of machine and operator (tolerances of 10-50 µm have been achieved). It is important to note that the mechanical properties of parts currently produced this way are likely to be inferior to those produced by casting, because even though casting can produce faults, selective laser melting/sintering (SLM/SLS) processes are limited by the powder size and will inherently have microporosity which can manifest in parts having lower stiffness and being more brittle. The range and grade of materials, and sizes of products produced by additive manufacturing approaches is increasing due in part to interest from specialised industries (e.g. aerospace/automotive) and the mass market. The mechanical properties of metal-based products are determined by the grain structure of the materials and the ability to be able to modify the microstructure by post cast treatments; use of SLS offers the additional benefit of being able to improve the surface properties (e.g. microstructure) and quality by conducting in situ laser processing. By comparison with casting approaches, additive manufacturing approaches tend to be somewhat slower and more costly, however, energy consumption per item can be lower and there are opportunities to automate processes with robotics [41–43].

This short review covers the patent and academic literature focusing on the Shaw process that is used worldwide to produce items for specialist applications (e.g. bowls, diffusers, fluid handling, impellers), in a variety of metals/alloys (including ferrous and non-ferrous materials) for a variety of industries, examples of which are depicted in **Figures 2-6**.

Literature collection

Literature searches with no publication date restriction were conducted in the Web of

Science, Google Scholar, and Google Patents databases for the search term "Shaw process" and more broad terms for literature related to sustainability of foundry processes and environmental regulations. The titles and abstracts of published studies were reviewed, and inclusion criteria were full text records, primary research papers, review articles, and patent literature. We excluded duplicate studies, papers/patents published in non-English languages, and studies with unclear specifications.

The Shaw process to prepare metal-based materials: materials science and engineering

The metal casting process has been developed in a multitude of ways, commonly with a view to increase throughput. In the early 20th century, advances focused on homogenization of metal liquids within the cast to reduce the occurrence of defects throughout the material. Croning introduced a method of metal casting which resolves formation challenges from the air present within the hollow space inside of the casting mold, via utilization of electrical induction furnaces coupled with copper cooling tubes to reduce the presence of "dead heads" and hollow space present in the mold [44]. Siegfried introduced an alternative cooling technique for the casting of metal rods [45]. Instead of the inclusion of induction cooling via copper piping, Siegfried introduced a mold that is continuously chilled to provide the precise thermal conditions for a continuous process of casting metal rods, wherein molten metal is passed through a vertically aligned mold at a constant flow rate, which is in turn cooled, producing the solidified metal rod at the opposite end of the mold [45]. In addition, a similar continuous flow model has been applied for casting metal sheets. Hazelett used a continuous motion casting via the use of metal belts [46]. Rather than having a processed mold to shape the metal, the belts act as the mold, pressing the molten metal to the desired thickness whilst being cooled themselves to cool the metal, producing the metal sheets [46]. The continuous casting process has been applied and advanced in many ways. Atkin introduced a continuous casting process that reduced the levels of harmful surface deposits on the casting mold due to variations in the properties of metals in the alloy [47]. The process involves reversing the metal cast to allow any condensed metal on the surface of the molds to be reabsorbed, and thus preventing both build-up of metal deposits on the casting mold itself, and any harmful effects the condensed metal may possess [47]. Jolly et al. reported a method of forming metal patterns with the inclusion of fibrous reinforcement membrane composed of silicon [48]; such preforms act as the template for the metal to bind to within the mold, potentially enhancing physical properties (e.g. microstructure) of the metal solid.

These technical improvements aim to prevent/reduce the presence of defects that may arise during the casting process. One issue with the casting process is the presence and movement of air within the mold. Air unable to leave the mold during casting can lead to defects on the metal surface or form cavities within the metals solids themselves, giving rise to poor quality structure/performance of the cast parts. Sutton et al. reported a method of inverted casting, using a bottom filling process to force the movement of air upwards [49]. The casting process also attempts to improve the quality of the metal parts by means of continuous casting using sand molds that are sequentially produced, controlling the flow velocity and pressure of the system. Although this method improves the quality of the product, the process was time consuming in comparison to previous techniques therefore best suited to small runs of bespoke parts. Paine reported an alternative method for reducing the air content and thus porosity within the product that involves the use of secondary casting chambers and reduction of pressure [50]. Using two chambers (an initial casting chamber and a cooling chamber) resulted in an increased rate of processing and output, allowing molten metal to be cast whilst another cools and solidifies [50]. While the presence of air can cause major defects in cast metals, turbulence defects caused by the movement of the molten metal in the casting system also has an impact on the quality of the products. The use of reduced pressure casting is advantageous for counteracting these associated problems. In addition, rapid thermal exchange coupled with reduced pressure can potentially increase the cooling rate of the solid within the mold. Poteri et al. reported a sealed casting mold that includes thermally conducting regions located at the bottom of the casting mold [51]. Having the thermally conducting regions at the bottom and the liquid inlets at the top, offers an instantaneous exchange of heat during the introduction of the metal to the mold, and having this in a sealed system offers pressure control, and therefore cooling control [51].

Vincent et al. reported a distributor device that has potential to further reduce the turbulence during casting [52]. The directional flow of metal through the distributor offers control over how the liquid is introduced to the mold. Reducing the flow rate of the metal reduces the entropy of the liquid during pouring, which in turn reduces any turbulence related problems [52]. Defects occurring in metal casting can be readily managed via means of controlling airflow, pressure, and heat exchange. One challenge of the latter is the rate of cooling, and the control of metal shrinkage during the cooling process. Powell et al. [53] reported a controlled mechanism that communicates with the casting mold and cooling metal to reduce the size and presence of shrinkage cavities in the mold. Imperfections, such as roughness of the metal surface and porosity within the metal, are a result of shrinkage cavities, leading to poor quality products. The use of feeder sleeves or risers that move during the cooling process reduces the presence of shrinkage cavities. Feeder sleeves allow molten metal present within them to flow back into the casting mold, compensating for the shrinkage of the cast metal, and further reducing the potential defects present within each product [53].

The process of manufacturing and the composition of casting molds has been altered and advanced in many ways over the previous century. Casting molds are required to withstand high temperatures that are a constant necessity when liquidizing and casting metals. A wide variety of materials has been used to process casting molds. Most typically used molds are comprised of sand and other silicates as they can withstand the high temperatures required [4,54,55]. Alternatives have included silicone, epoxy, and other low temperature molds for manufacturing low-melting-point materials. Shaw reported a method of developing casting molds that combines refractory materials with binders composed of alkyl compounds that, when forming the mold, are converted into combustible alcohols. This technique applies a "freezing" process on the mold from the combustion of the alcohol. As the alcohol is burnt off, heat transfer to the body of the mold is applied. This hardens the mold exterior, leading to a contraction of the mold interior and rendering it uniformly porous, which is beneficial for the removal of gases in the system [36,56].

Most casting processes utilize investment casting (or "lost-wax" casting) to form metal products. Despite its advantages over solid mold techniques, disadvantages have arisen from the use of wax as the casting mold, with several issues with the removal and recycling of the mold material itself. Removal of wax molds from the product in the early years were time consuming, as removing wax molds from the patterns requires very specific conditions (e.g. temperatures and solvents to dissolve the materials). Carter reported a combination of slurry solutions to use as molds for casting that overcome these disadvantages by using reagents that make up low temperature binders. In comparison to previously used high temperature binders, these low temperature binders were stable, do not break down with temperature changes, and maintain their rigid shape [57]; however, many low temperature and wax molds are non-reusable. Because of this, the more traditional sand and ceramic molds are more frequently applied to retain cost-effectiveness. Several methods were developed around the 1970s for the manufacturing of solid molds [58–60]. Subsequent developments of the mold manufacturing process have led to alterations in how the mold is formed, and the chemical composition of the mold itself [61]. The use of a ceramic slurry accompanied by alumina and mullite were shown to reduce the rate of cooling [62]. The combination of alumina and mullite led to further research into the chemical composition of the ceramic slurry, and zircon, chromite, and calcined clay are amongst a few of the materials incorporated into the slurry. The formed slurries possess greater particle sizes which allow for greater cool-down times, as well as hardened strength in comparison to ceramic molds reported in earlier developments [63]. Indeed, studies on the effects of binder composition on the structural and physical properties of the zircon ceramic mold by with the use of two different binders (ethyl silicate and ethyl silicate mixed with aluminium tri-sec-butoxide) showed the binder was very effective to produce a ceramic mold with homogeneously distributed pores that helped to remove gases evolved during casting. It was also found that the ceramic mold obtained using the ethyl silicate aluminium tri-sec-butoxide did not react with the liquid metal, and as a result burn on casting defects encountered in stainless steel castings were effectively eliminated (a potential solution to the chronic problems of decarburization and pitting defects, as no oxygen was coming from the silica) [64]. The use of alumina and camphor in slurries resulted in increased green strength of all the ceramics with increments of the slurry additives, with alumina increasing green, fired and corner strengths, and camphor improved the permeability of the shell at the expense of its strength [65,66]. The use of silicon nitride in slurries increases the cast density and resultant strength of the castings [67,68], likewise, slurries containing particulate metal oxides (e.g. silicon dioxide, aluminum oxide, titanium oxide and zinc oxide) and polyphosphates of the formula ($(PO_3)_n$) can improve the mechanical strength of casting molds at high thermal loads [69].

Post-processing after casting consumes large amounts of labour and energy. The effective removal of mold material that has adhered/fused to the casting, is traditionally achieved by air blasting (e.g. steel shot, aluminosilicates) to remove the media, however, foundries have begun to adopt the use of high pressure water blasting and ultrasonics to make the process more rapid; the effective removal of excess metal associated with feeding and introducing the metal into the mold cavity is traditionally removed by sawing, hammering, oxyacetylene and abrasive discs, and foundries have also begun to adopt the use of high pressure water blasting, ultrasonics, pneumatic shears, and/or plasma cutters to make the process more rapid [70]. Smoothing of cast surfaces was traditionally achieved by application of handheld power tools with grinding stones and metal burrs, however, attention is being devoted to carrying out the minimum amount of smoothing/polishing. One approach to this is the development of slurries with two or more refractory materials with different densities and particle size distributions, where the smaller denser refractory material migrates downward through the slurry toward the upward-facing mold surface, thereby yielding smoother and more accurate surfaces [71]. Waste heat recovery offers potential for cost cutting [72–77], and wastewater treatment to minimise/remove contamination from liquids (e.g. oil), solids (e.g. metal/alloy particulates, sand) etc. minimises disposal costs and potentially allows recycling of components [78–83]. Clearly, the ability to produce bespoke high precision castings of high value will motivate continuing innovation in this manufacture process.

The Shaw process to prepare metal-based materials: sustainability

Sustainability is an increasingly important focus of industry, and a driver of innovation in manufacture processes (e.g. investment in robotics to undertake hazardous/repetitive activities). Life cycle assessments evaluate the environmental, social and economic impacts of products, facilitating the development of more sustainable products, including initiatives to reduce the amount of waste we create, and reuse/recycle waste, and has been employed to assess metal casting processes [84]. The Shaw process consists of a series of steps which can be viewed through a sustainability lens, noting that the process is labour and energy intensive and can be hazardous: preparation of a reusable pattern made of metal (high volume and long lifetime), plaster (low volume as can easily be replaced and short lifetime), resin (medium volume and medium lifetime), wood (medium to low volume and medium lifetime), etc.; wherein production volumes are high (10,000s), medium (ca. 1000), low (100s); the lifetime of pattern equipment is determined by the quality of the storage facilities, and lifetimes are long (50 years), medium (20 years) or short (7 years); followed by fabrication of a mold on the pattern, removal of the mold (optional reuse of the pattern), removal of volatiles from the ceramic molds by burn off, casting (filling the ceramic molds with metals/alloy), hardening of the metals/alloys and cleaning to remove the mold material, finishing the product (smoothing cast surfaces). As noted above, the Shaw process is predominantly used for small/medium batch production (most often for casting bespoke high value items), and compliance with environmental regulations (e.g. the Department for Environmental, Food & Rural Affairs, DEFRA [85], in the United Kingdom; the Environmental Protection Agency, EPA, in the United States) in the countries in which the foundries are based affect the economics of this manufacturing process.

Conclusion

The Shaw process of metal casting is well established and enables the small/medium batch production of bespoke high value items. As highlighted in this short review, there has been significant investment of time and effort in the optimisation of this process with significant beneficial economic impacts for the industries involved. Additive manufacturing approaches to prepare metal-based materials represent an opportunity for the casting industry to produce items with bespoke properties for their customer base (e.g. for producing novel tooling [86–89], however, additive manufacturing approaches are still somewhat nascent by comparison with established casting approaches and require investment in new production facilities and staff (new hires and training/upskilling of the existing workforce). However, it is likely that additive manufacturing for rapid tooling will be increasingly important in the foreseeable future for both prototype modelling and final product development [21,44,90], due to its complementarity in terms of fit to the production of bespoke high value items and increasing realisation of the potential of industry 4.0.

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CRediT author statement

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Disclosure statement

Unless otherwise stated, the authors have no conflicts of interest to declare. Andrew Dodd is a former Managing Director of Bonds Precision Castings and has over 40 years of experience with the manufacturing and procurement of cast metal components.

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Figures and legends/captions

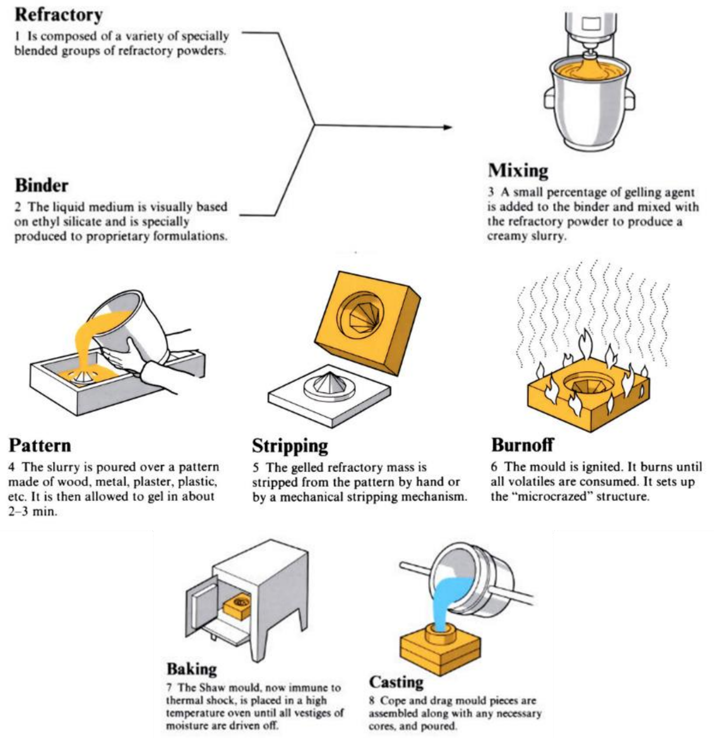

Figure 1. Schematic of the casting process. Figure reproduced with permission from The Open University (the OU), published under a Creative Commons BY-NC-SA 4.0. https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/ceramic-mould-casting

Figure 2. Part produced by the Shaw Process. Courtesy of Bonds Precision Castings.

Figure 3. Parts produced by the Shaw Process. Courtesy of Bonds Precision Castings.

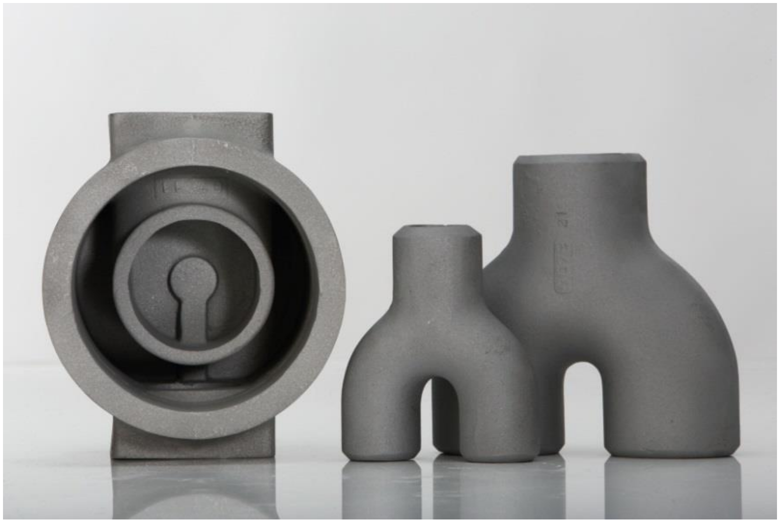

Figure 4. Parts produced by the Shaw Process. Courtesy of Bonds Precision Castings.

Figure 5. Parts produced by the Shaw Process. Courtesy of Bonds Precision Castings.

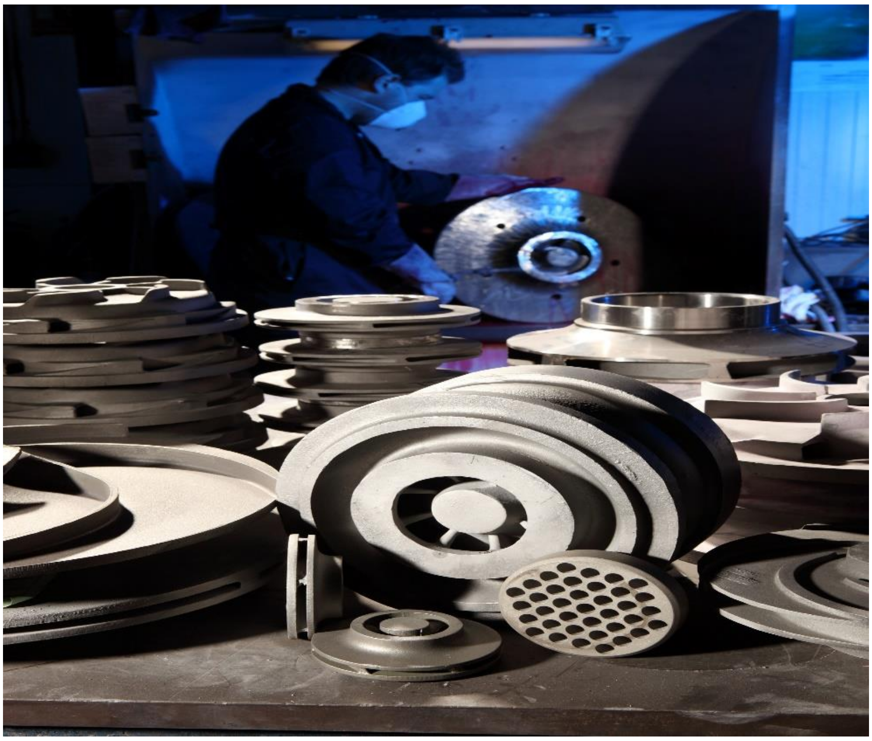

Figure 6. Parts produced by the Shaw Process. Courtesy of Bonds Precision Castings.