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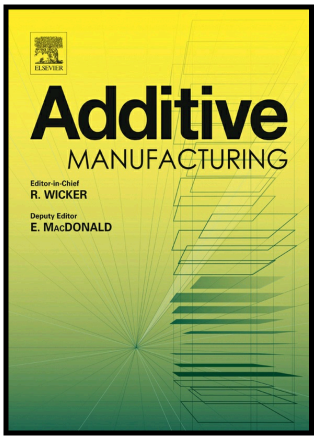

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A review on the progress and challenges of binder jet 3D printing of sand moulds for advanced casting

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Abstract

3D sand mould printing through binder jetting can solve many technical issues in casting including part consolidation, design of parts to optimise the consumption of materials and hazardous chemicals, and on-demand and any size part manufacturing near the customer. Incorporating artificial intelligence in optimising the design of moulds, printing process parameters, and solidification processes may help automate a production facility and reduce labour time. Elimination of hazardous chemicals from industrial use may be a challenge. Therefore, an alternative technology to fuse the sand particles during printing or an environmentally friendlier alternative option for the binders and other consumables should be utilised with the 3D sand printing process. Properties of parts produced using 3D printed sand moulds are better than the properties of parts produced using traditional casting due to this technology's benefits mentioned above. Though this technology is a supportive enabling technology for the traditional casting processes rather than a competing technology. This technology is causing a paradigm shift in casting design because of the mould geometries achievable using the sand moulds' additive manufacturing. This paper reviews the first twenty years of research and challenges in developing 3D sand printing as an innovation for sustainable manufacturing.

1 Introduction

Traditional sand casting mould making process involves the mixing of sand and binding materials, and then the mixture is poured into a wood pattern to shape pieces for a sand mould assembly. Molten metal or an alloy is allowed to solidify to shape into the desired mould cavity within a sand mould assembly. Sand moulds can now be 3D (three dimensional) printed by binder jetting or laser sintering processes.

A relatively low-power laser (200 W CO_2 laser) is used, to sinter the silica sand without any binder [1]. The Selective Laser Sintering (SLS) can also be applied on resin-coated foundry sand particles to induce phenolic resin's thermo-polymerization process; phenol, a solid and dry at room temperature, is mixed with the sand and is easily poured/spread onto a job-box. When irradiating resin-coated sand particles with a laser, to attain a temperature of about 180 °C the resin thermo-polymerization is activated. Using a similar approach, the binder jetting sand mould printing involves the spreading of acid-coated sand particles onto a job-box and spraying of resin layer-by-layer in order to induce the polymerization and bond the sand particles to form a mould or a section of a mould—a review by Néel et al.[2] provides further insights into the selective laser sintering process. This review focused on addressing the recent developments and challenges in binder jetting process for sand mould printing. This article focusses on the binder jetting process of sand mould printing. An example of a printed sand mould and the casting obtained using such a mould is shown in Figure 1

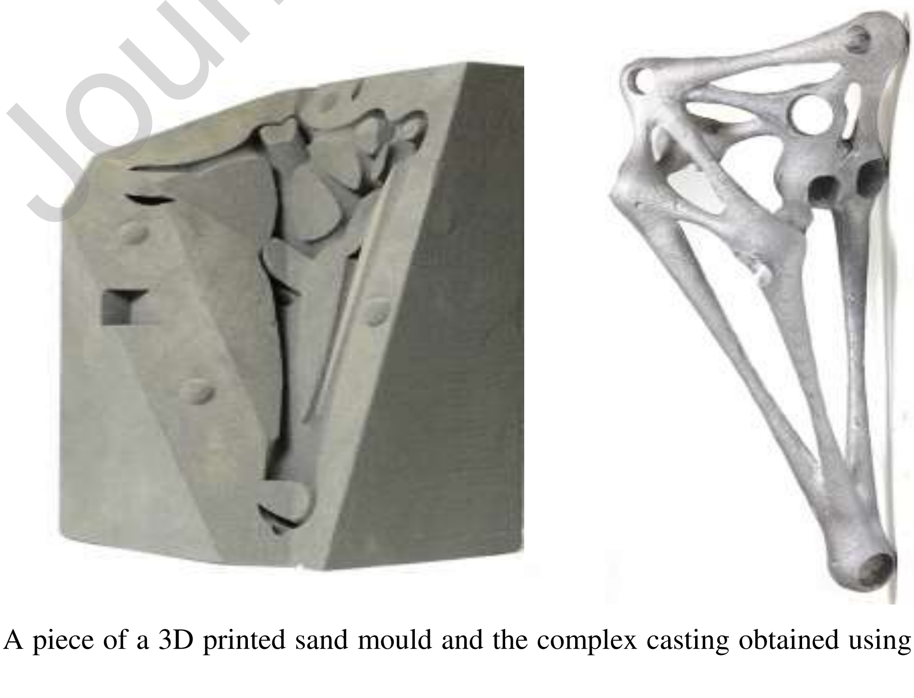

Figure 1: A piece of a 3D printed sand mould and the complex casting obtained using such mould parts.

Almost all of the additive manufacturing (AM) techniques require specific material and shape for 3D printing any components [3] but the metal part production through 3D sand mould printing does not rely on the metal's shape. However, it may be beneficial to have a specific sand particle type and size to produce moulds. Different stages and processing variables involved in 3D sand mould printing, casting and characterisation for quality control are shown in Figure 2. Firstly, designing a model on a computer software package, choice of sand particles size and printing process parameters, choice of binder and activator, and then the mould sections are printed. These can be assembled into a mould of any size if the design is castable with acceptable defect limit. Therefore, a final casting is obtained with minimal post-processing. Binder jetting 3D printing offers distinct advantages compared to other additive manufacturing methods due to the possibility of rapid production of complex structures to achieve isotropic properties using metal powders directly [4] or to cast alloys into moulds manufactured by jetting monomer liquid droplets onto a powder-bed, e.g. acid mixed sand, to bind them through a polymerisation process. The sand moulds can even be used for cold casting materials such as concrete [5]. Although it is reported that the sand moulds produced through this process exhibit anisotropic properties, e.g., three-point bending strength is weak in the z-direction [6-8], there is no significant influence on the isotropic properties of the final casting as this depends on the solidification behaviour of the molten alloy. Any complex geometry can be manufactured rapidly using 3D printed moulds, even those are difficult to be produced with computer numerical control (CNC); 5-axis machining can fail [9] with undercuts, enclosures, sharp internal corners, and other features. Consequently, 3D printing of sand moulds has been revolutionising the casting industry by providing energy-saving options [10, 11], defect optimisation [12], as well as the ability to combine multiple components, previously separated due to the limitations of traditional manufacturing. Production facilities can now shift towards a customer base, e.g. on a naval ship or very close to a large city, but the design can be done from home.

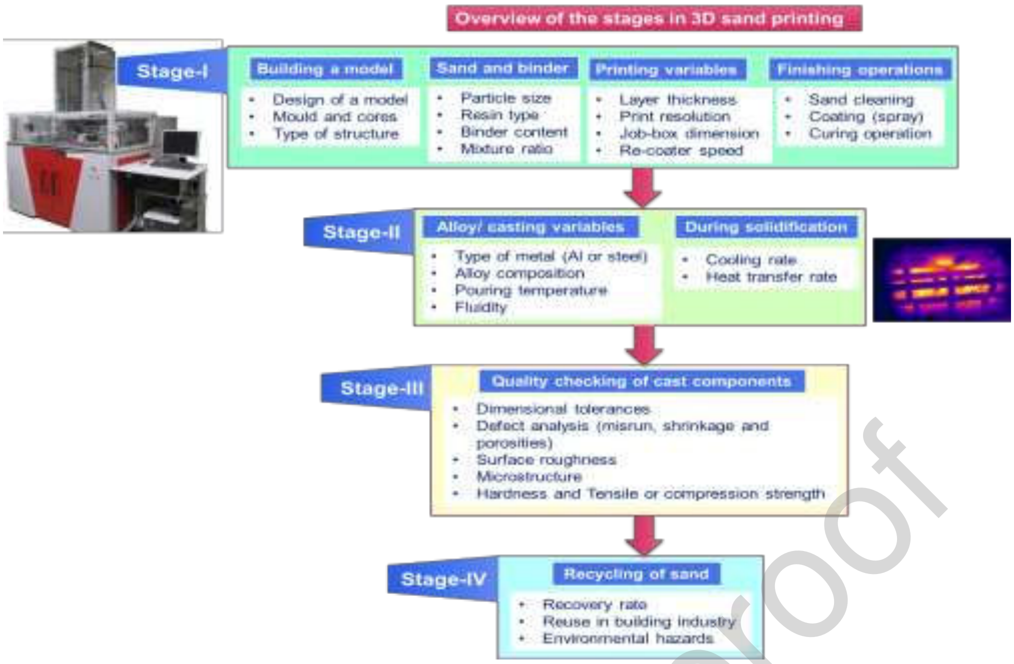

Figure 2: Stages and processing variables involved in 3D sand mould printing, casting and characterisation for quality control.

Research in the area of 3D sand mould printing technology has been trending, Figure 3. Over the past ten years, the authors have published several papers [6-8, 10, 13-18] related to the 3D printing of sand moulds, including a review article which summarises several important attributes and processing variables with a focus on further improvements needed in this field [18]. Most of the research focused on the optimisation of process parameters [6-8, 19] while other proposals include an alternative or improved method of design [20-24] for casting using 3D printed sand moulds and new mechanical property testing methods using acoustical and optical techniques [25] for inorganically bound granular materials, with conclusions for the benefits of this technology [10].

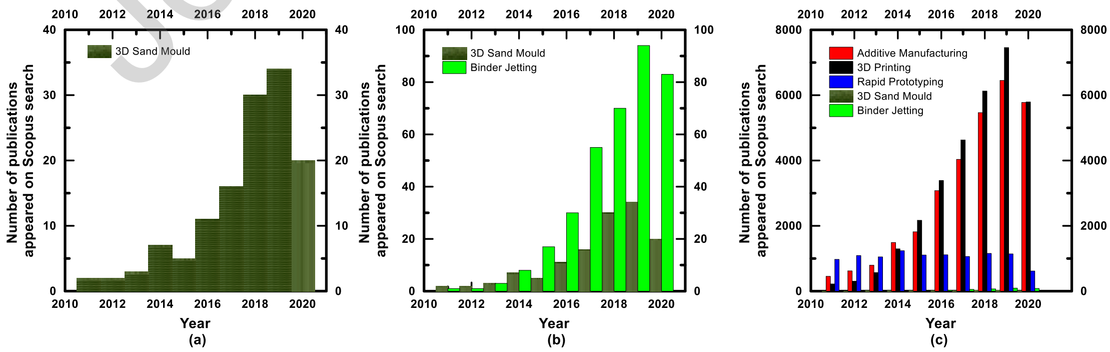

Figure 3: From 2010 to 2020, the number of publications appeared on Scopus search for the keyword of (a) “3D sand mould printing”; a total of around 130 publications, (b) “Binder jetting-362” and “3D sand mould printing-130”, (c)“additive manufacturing-29983”, “3D printing-31958”, “rapid proto typing-10551”, 3D sand mould printing-130, and “Binder jetting-362”.

It is well established that any engineering applications involving high temperatures and/or complex stress states demand cast products due to the isotropic nature of material properties that are produced during casting. Sand casting is one of the major industrially employed mass-casting techniques used to manufacture high melting point alloys and thin-wall sectioned engineering components [26]. Nevertheless, sand casting suffers from considerable limitations on geometry and higher lead times due to the involvement of pattern making in the process [27]. In recent times, the increasing complexity in the design of many engineering components requires complex pattern making, which in turn limits the usage of the sand-casting process. In order to overcome this issue, 3D printing of sand moulds started replacing the conventional pattern making process and has been successfully utilised for the production of complex-shaped sand cast products [27-29].

The main advantage of using 3D sand printing (3DSP) for making sand casting moulds is that the direct fabrication of complex-shaped moulds and cores without the necessity of using any hard toolings [28, 30]. The final properties and quality of the 3D sand printed (3DSP) moulds depend on the process parameters used for the 3DSP process. The most critical parameters are the sand characteristics [31-36], types and concentrations of resin, binder, and activator [35, 37-40], the printing or powder recoating speed [35], layer thickness [37, 41], and curing temperature and time [42-44].

3D printing sand moulds can address challenges in centralised manufacturing, especially the fabrication of custom-made, single production products. The hard tooling requirement is significantly reduced if the initial investment on a large 3D sand mould printer is absorbed. Operational costs are comparable to conventional casting, with additional energy and material savings, from the ability to manufacture non-traditional shapes. It is expected that the initial capital cost of the printing machine will be affordable as the market pull increases, though, in the current market, the total cost of such printers and related equipment are on the scale of a million US dollars. Nonetheless, the network of on-demand production facilities around the world made custom part production at the minimum affordable price. This is the only indirect 3D printing technology used to construct a significantly large casting in a production facility within a room. Therefore, it can be easily accessed by a large-scale city considerably in a small-time frame. The technique is not just for parts with high dimensional tolerance (layer thickness in 280 μm -500 μm), but it can also be used for line forming methods for large scale (volume) parts to speed up the printing process by increasing the layer thickness up to 2 mm [45-47]. Another possibility of printing multi-material moulds that can provide geometry dependent properties has been proposed and studied [48, 49].

Figure 3 indicates a growing trend in sand mould printing research compared to the other vital aspects of additive manufacturing. Although the “3D sand mould printing” research is much smaller compared to overall “Additive Manufacturing” or “3D Printing” research, A significant advancement of 3D sand printing for metal casting process is evident. It is still a much larger portion of the binder jetting technology. Also, it emphasises the paradigm shift in casting or metal industry from Design for Manufacture to Manufacture for Design. Research on this layer by layer manufacturing technology is progressing rapidly.

Some of the commercially available 3D printers are shown in Table 1, and it shows the largest such printer is having a job-box volume of 8000 L with a build speed greater than 135 L/h. A new sand printer model released by Voxeljet company overcomes this volume restriction due to the inclined printing method; the continuous sand printing method has only two-dimensional limitations, and the third one is infinite. This is further discussed in the later paragraphs.

Table 1: 3D sand printing machines. Manufacturers and scale of sand printing machines.

Manufacturer	Size (mm) and (Volume (L))	Layer thickness (mm)	Build speed (L/h)
ExOne	1800×1000×700 (1260)	0.26 – 0.38	135
	1800×1000×700 (1260)	0.26 – 0.38	105
	800×500×400 (160)	0.26 – 0.38	36
Voxeljet	300×200×150 (9)	0.15 or 0.3	Not available
	500×400×300 (60)	0.15 or 0.3	Not available
	1000×600×500 (300)	0.15 or 0.3	Not available

	2000×1000×1000 (2000)	0.15 or 0.3	Not available
	4000×2000×1000 (8000)	0.15 or 0.3	Not available
3D systems (previously ZCorp)	Discontinued sand printers/using different material	Not available	Not available

2 Progress in 3D sand moulds printing

2.1 Computer design and simulations

The computer simulation of mould filling and solidification has been widely used for the design of traditional sand casting since the mid-1980'. However, the real advantages of using computer simulations are achieved better with the design of 3D printed sand moulds. This is where the generative design or topology optimisation can be incorporated. Modelling software packages started having additive manufacturing-focused functionalities even though none of those packages has a specialised module for 3D sand mould printing. It would be an added advantage and reduce human time on modelling and optimisation if these packages could incorporate functionalities such as optimum mould sectioning for a dimension specified job-box of a sand mould printer. This would assist the users to minimise sand waste and printing time, thereby improving the economic performance. Traditional casting processes have been utilising computer technology in order to simulate the mould filling and solidification processes when a molten alloy is poured into a sand mould assembly (gating system, casting cavity, and risers). There are several commercial software producers such as QuikCAST/ProCAST, MAGMA SOFT/ MAGMA5, FLOW 3D, and Altair Inspire Cast. A comprehensive study on the simulation software packages has been reviewed [50]. The benefit of casting simulation highly depends on the boundary conditions, materials properties, and meshing of the computer-aided design (CAD) model at a high cost to benefit ratio [50]. The major problem of modelling traditional casting processes is providing the exact boundary conditions for the simulations. The input of the correct data is crucial for the accurate simulation outcome. Functional design and manufacturing of 3D sand mould will address these issues by providing geometry dependent gas permeability and thermal information with minimal deviation. Improved input data in all boundary conditions not only simulates the casting process with more realistically, but also leads to materials and energy savings as well as quality and economic improvements. This issue has been well-reviewed on a publication by one of the current authors [51] and concluded with suggestions for the integration of simulation techniques on the atomic level, e.g. a Molecular Dynamics simulation, on a real-time scale which would result in better decision making to optimise the energy consumption as well as most importantly the possibility towards defect elimination.

2.2 Flexible design methodologies

Castings produced by conventional sand moulds require extensive preparation by skilled labour, including pattern and core making, that have inadequacies in facilitating new designs. Limitations of the conventional method include the pattern making process with expensive machining works, storage of patterns, degradation of dimensional tolerances due to prolonged storage or usage, undercut in design requiring additional cores, and other geometrical design considerations for gating, feeding and runner systems. On the other hand, 3D printing facilitates rapid fabrication of moulds by reducing the processing time, tooling complexities associated with core and undercuts [12, 49, 52]. Figure 4 highlights some of the essential attributes of the design freedom achieved with the 3D printing compared to conventional sand moulds. Sama et al. showed the potential of 3D printing and hybrid approaches through three case studies of a vane impeller, a complex nested bracket, and a centre bearing housing for a duplex stainless-steel casting. As opposed to the closed vane impeller's conventional design, the 3D printed sand mould consists of only three risers and one ingate that eliminates shrinkage porosities with a design that has a vertical parting line. The intricate bracket design using 3D printing enables the reduction of the turbulence (velocity of 1.81 m/s in conventional moulds is reduced to 0.5 m/s in 3DSP moulds) and thermal losses, thereby decreasing the propensity for misruns. Misruns occur when the liquid metal is too cold/ too viscous to flow to the extremities of the mould cavity before solidifying. Therefore, it would not be able to fill the mould cavity completely. The unfilled portion of space in the mould is referred to as misrun. Providing additional sprues to the design enhances the metal feeding at the locations of misrun.

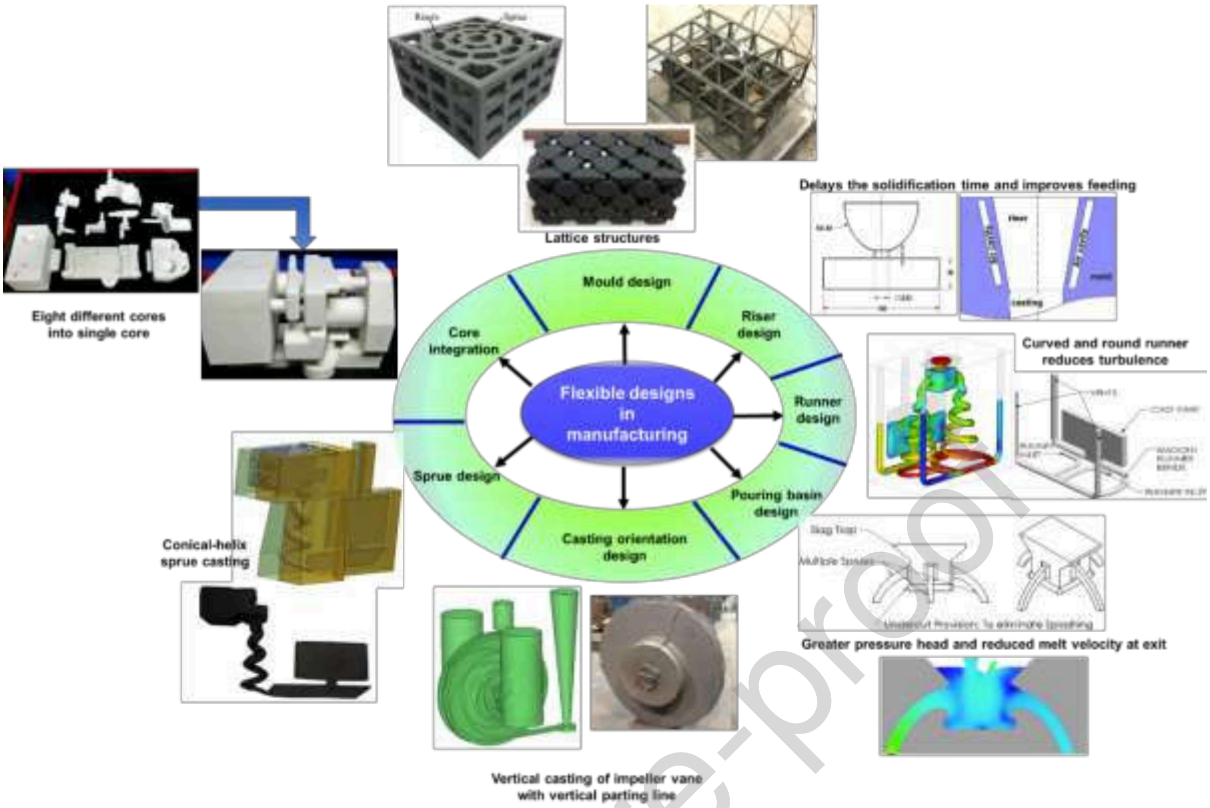

Figure 4: Design flexibility and the advantages associated with 3DP. [12, 21-23, 49, 52-54]

Provision for easy drain off for the loose sands and seamless integration with conventional mould design is also possible to eliminate defects in the casting process. Often the component geometry decides the orientation, location of the riser, and size, whereas 3D printing enables the incorporation of suitable orientation for increased metallic yield and reduced defects. A parabolic and conical-helix sprue offers a smooth flow of liquid melt, reducing the turbulence at the in-gate compared to the conventional straight sprue. Significant reductions of (i) void spaces or internal flaws in the casting (56 % and 99 %), (ii) inclusions, mainly oxides or sand particles (21 % and 35 % area) and (iii) centreline shrinkage defect (1.5 % and 0.6 % area) have been measured for parabolic and conical-helix design respectively (for the values indicated in the brackets) A decrease in the melt flow also reduces the sand inclusions and increases flexural strength in the conical-helix design, which could be used as a novel design for hybrid moulding for Al and steel, or cast-iron melts [49].

Several improvements are also achieved with novel designs of the pouring basin, runner and riser. Increasing the number of sprues while reducing the width allows for less air entrapment, and the multiple sprue design reduces the flow velocity due to frictional forces. The higher-pressure head with the pouring basin shown in Figure 4, avoids common casting defects observed in thin-section castings and eliminates metal splashing. A complex runner network shown in Figure 4 avoids gas entrapment at the entrance of the runner and in the gating system. Additional vents act as a reservoir to reduce entrapped air and regulate the flow velocity by maintaining backpressure during mould filling. Round corners, instead of the rectangular cross-section, further decrease the turbulence issues. Generally, cylindrical feeders or risers are standard in traditional casting. Modifications to the existing design by the addition of air vents or a novel spherical design by 3DP delays the solidification time and enhances the feeding. For instance, a spherical design showed a total solidification time of 7 min compared to the cylindrical counterpart that solidified in 4 min for a particular casting design [55].

In comparison to the traditional thick sand mould fabricated by the conventional process, lattice or shell type of moulds with varying thickness and adequate strength can be produced in the 3DSP process. Few design models of these moulds are shown in Figure 4 [20-22, 24]. A rib-reinforced design on the outer side of the casting shell forms a network-like structure that enables increased cooling rates to reach the shakeout temperature quickly and a significant reduction of sand consumption (nearly 90 %) [22]. Kang et al. proposed several lattice frames (skeleton mould design) [24], including a basic cross-frame, internal and surface enforced cross frame, diamond, cellular and radial types. These frames are associated with higher cooling power, reduced sand consumption, and reduced weight of the mould. Forced cooling can be effectively introduced into this type of mould structure to reduce production time and increase production efficiency without defects in the casings.

A case study reported for the A-356 Al alloy wheel hub casting (0.3 m diameter) with a mould that has no parting line showed that the lattice design saved 50 % of the sand used while achieving higher heat transfer for adequate cooling, castings devoid of shrinkage, and better surface finish compared to traditional castings [21]. Distinct cooling behaviour was observed for the shell mould and the dense traditional mould. Initially, the dense mould extracts heat from the melt, whereas the shell mould cools at a relatively lower rate. The shift in the cooling rate occurs at temperatures approximately below 300 °C (for A356 Al alloy), where the shell mould cools faster to reach the shakeout temperature of 200 °C than the solid mould [20].

Deng et al. [23] investigated the effect of hollow structures around the riser and evaluated the solidification and heat transfer characteristics. A series of riser structures having one to three hollow cavities are designed with a wall thickness of 3 mm and an air cavity of 12 mm. Aluminium alloy (A-356) solidified in a riser with a single layer of cavity delayed the solidification time by 11.7 %, and it was further extended to 30 % for a riser with three layers of air cavities when compared to the conventional riser without hollow structure. The shrinkage area between riser and casting was increased by 6 % and 18 % for the risers with single and three layers of cavities respectively. In addition, no shrinkage porosities were found on the risers with air cavities indicating that the solidification was delayed with enhanced feeding, and it also reduced residual stresses in the casting [23].

The design flexibility with moulds can also be extended to core design, where several small components of the core can be integrated into one part. An example is shown in Figure 4 for a train's air brake in which eight different cores are consolidated into one 3DSP core that reduces the misalignment errors and undercut difficulties in design [53, 56].

Snelling et al. [54] fabricated a cellular structure of A-356 Al alloy using 3D printed sand mould using an ExOne (leading 3D sand printer manufacturer by market capital) S-print machine without a curing cycle. The model was created using CAD or similar software specialised for creating cellular materials. Initially, a single unit cell was designed, which was then patterned to create the whole structure (using Netfabb SSS software). The printed mould was used as a core, which creates a cavity in the resultant casting, and an outer mould with gates and down sprue arrangement was fabricated, and this setup brings liquid metal into the cavity. Castings made from the printed mould exhibited no sand burn or metal penetration. Compression tests revealed that the castings could withstand a maximum load of 120 kN to 130 kN. Figure 4 shows the manufacturing process of the cellular structure.

A case study on the comparison of cost estimation between conventional and 3D printing of a train air brake (8 cores) and turbocharger (3 cores) reveals that the total cost (tooling and fabrication) for a conventional process increases as a function of part complexity (estimated by a complexity factor). 3D printing becomes the cost-effective approach for high volume production, and time spent on the tool design or pattern and core making process can be significantly reduced [28].

The 3D sand printing offers the new paradigm of Manufacture for Design. 3DSP offers a flexible intermediate stage, not creating the part directly, but the disposable mould tool without other hard tooling and with a creative and functional mould design such as one described in the next section.

2.3 A new avenue for manufacturing

3D printed sand models can be coated with, for example, carbon fibre sheets with resin and hardener, a flexible material that can set into a rigid shape; then the sand mould can be washed out to create a large-scale, complex and lightweight hollow structure (composite structure), e.g., aircraft ducting, pressure tanks, struts, and mandrels [57]. The pattern making is challenging with other polymer 3D printing techniques due to their non-recyclability and the scale of the job-box of those printers as well as their dimensional stability. In this case, suitable bonding material can be chosen, instead of furan resin. The mould making can be implemented at room temperature using a water-soluble substance that can bond the sand particles and keep the structure until washout. Not limited to this, but there are possible alternative applications of 3DSPsuch as the cold casting of concrete; these moulds can be used to produce a complex structure in concrete.

3 Challenges with sand handling and processing variables

3.1 Binders

The use of furan binders or any other polymer materials are not new to the casting industry, but these are considered as hazardous materials and need to be replaced with substances that can provide better properties to the printed mould with improved environmental properties [56], including energy-efficient production [10]. A list of currently used sand particles and binders are tabulated in Table 2 and Table 3, respectively. However, foundries have already started using epoxy/SO_2 based curing system to minimise the carbon emission [58]. Koltygin et al. [59] investigated an alternate mixture for ZCast 501 powder and Zb56 inorganic binder (Z Corporation, the US, known as 3D Systems since 2012) using a sand-gypsum mixture. Using XRD analysis, the authors found out that the ZCast mixture composed of gypsum

$CaSO_4 \cdot 2H_2O$, calcium silicate $Ca_2(SiO_4)$, calcite $CaCO_3$, magnesite $MgCO_3$, magnetite Fe_3O_4, Olivine $(Mg, Fe)_2(SiO4)$, forsterite Mg_2SiO_4 and other compounds. A sand-gypsum mixture with Iron (III) sulphate (0.2 vol.%) as hardening accelerator and dolomite (2 vol %) as moisture absorber were found to contain adequate strength to that of ZCast 501 powder. The details of the alternative binder used instead of Zb56 was not provided. A matched tensile strength and a good dimensional tolerance were obtained for the new binder to that of the ZCast powder and binder showed the mould obtained using the new sand mixture has sufficient strength.

Ramakrishnan et al. [60] investigated the organic binder system for printing sand moulds using a Voxeljet VX-500 3D printer, which was initially designed for processing polymer powders. The quartz sand was mixed with dry sodium silicate powder (acting as a binder), and the printing fluid comprised of thickened water that can dissolve the sodium silicate (dispensed by the printing head). The influence of fluid migration and strength of the printed parts were evaluated by varying two parameters, namely, the concentration ratio of binder to printing fluid and heat input. Fluid migration can be reduced by reducing the fluid input to the sand binder system or heating the specimen while printing. An increase in fluid migration has the highest mean strength of 5.65 $N/mm^{2,}$ which is reduced to 4.14 N/mm^2 when heating is applied during printing. It should be noted that the printed parts that can withstand high mechanical load can lead to low dimensional tolerances between thin walls due to sand adhesion.

3.2 Processing

Processing stages involved in 3D printing of sand moulds before reaching the pouring stage are schematically shown in Figure 5. Cleaning or removal of unbound sand particles from the job-box is a time consuming and labour-intensive process and hence reduces the ultimate production speed ultimately. Voxel jet, a manufacturer of sand printers, produced a design (model VXC 800) to overcome these issues partly. It allows the user to continuously print the part of the mould with any length (width and height are limited by the size of the job-box); inclined printing on a conveyer belt enables part removal without stopping the printing process. This design is based on the principle of the critical angle of repose of a granular material. That is, the print head is inclined on an angle less than the critical angle of repose of the sand particles. There is a scarcity of literature available highlighting the dimensional tolerance of each design. The design of moulds can be slightly improved with the help of proposed lattice-shell and rib enforced shell mould designs by Kang et al. [24] if the unbound sand particles within the mould cavity can be removed with much ease.

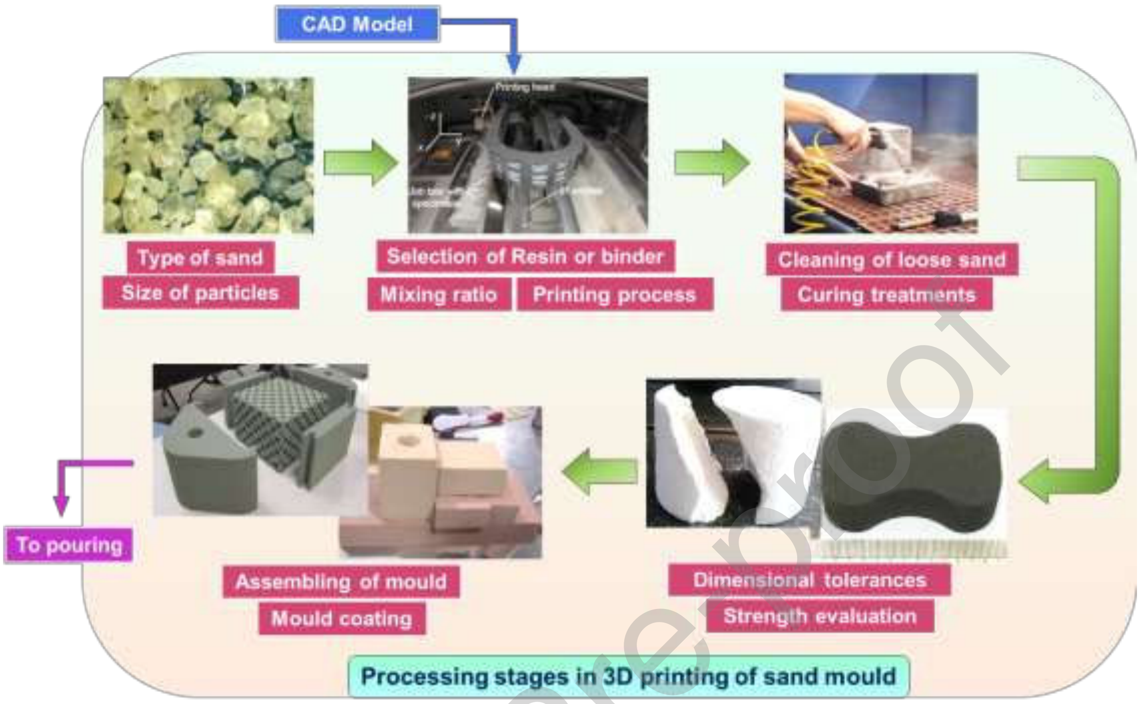

Figure 5: Processing stages involved in 3D printing of sand moulds before reaching the pouring stage.

Although it has been shown that traditional foundry sand can be utilised to print sand moulds the dimensional tolerance is affected due to the less optimal flowability (prone to clogging) of the non-engineered sand particles [61]. Therefore, recycling of acid-wetted or unbound sand particles after printing faces the same issue before they can be processed again; recycling the bound sand particles (recycling the sand within the mould after casting) requires extreme processing before they can be used for printing processes. The price of engineered sand particles is relatively cheap, but the cleaning process and re-transporting to the manufacturer may significantly increase casting price. A case was presented for the waste foundry sand to be utilised in the building industry; Mitterpach et al. [62] proposed that it would be necessary to thoroughly verify the eco-toxicological properties of not only the created waste foundry sand and other foundry waste, but mainly the building products for which this waste could be used. The authors [62] further suggested that handling foundry sand significantly increases particulates' emission, which penetrates the working environment and the atmosphere due to their dustiness. Therefore, the subsequent environmental analysis of waste foundry sand must be monitored for the concentrations of particulate matter PM10 and PM2.5 entering the environment in all processes that create waste foundry sand and must thoroughly quantify and assess their impact upon human health. Lack of knowledge in how to safely transport the 3D printed moulds and cores [63] is challenging due to their fragile nature.

Many research studies focused on optimising the process parameters due to the vast range of process parameters used in the printing process, such as sand particles size, layer thickness, print resolution in all directions and ink (polymer) droplet volume, job-box dimension, re-coater speed (sand spreading speed). Increasing the binder content can increase the strength; however results in low dimensional tolerance [19, 64] that will produce a significant amount of gases during casting. A comparative study was performed by Gill et al. [65] on dimensional tolerances, surface roughness, gas holes, and shrinkage defects of A356 Al alloy castings fabricated through moulds made from the investment casting process and 3D printed sand moulds with varying thickness (2 mm to 12 mm). Though the investment casting process using plaster-based powder produced consistent results in surface finish and defect control, the ZCast process (ZCast 501 powder) also produced promising results for 6 mm shell thickness. A further improvement is needed to increase the surface finish of the 3D printed moulds. The authors also investigated the comparative qualities of the castings produced by 3D printing of a die-cast Zn alloy (ZA12 alloy) with an A356 alloy [66]. It was found that the shell thickness for the A356 and ZA12 can be as small as 1 mm and 3 mm respectively, thus the cost and materials consumption can be reduced to maximise the production efficiency. On the other hand, microstructure studies revealed that the investment castings (0.125 mm) produced uniform grain structures compared to the ZCast process, in which large dendrites were observed in A356 alloy. This study also emphasised that the casting process and alloy compositions' attributes included the thermal gradient during solidification (with respect to mould thickness), pouring temperature, cooling rate, and the effect of constitutional undercooling are necessary to be established for the ZCast process [65, 66].

Singamneni et al. [67] investigated the effect of curing time and temperature on the compressive strength and surface roughness of the A356 Al alloy's castings. A prolonged heating time or increase in temperature resulted in reduced permeability due to the fusion of low melting phases during baking. A similar observation was also noted for the compressive strength as a result of phase transformation in the plaster binder regions. The Al alloys' surface roughness cast in the moulds was tested with and without various mould coatings. Brush coated and spray-coated moulds produced smaller average roughness (12 μm to 17 μm) with better tensile properties than the uncoated moulds (12 μm to 17 μm).

3.3 Properties

Thermal properties/mechanical properties/gas permeability

Thermophysical and heat transfer properties of mould materials in the sand-casting process are critical to understanding the microstructure formation and the associated defects (due to gas evolution). Two types of bond mixtures based on phenolic and furan binder in 3D printed cores were comparatively reported by Toth et al. [39]. Inverse Fourier analysis was conducted to extract the total absorbed heat and the rate of heat absorption in liquid Al and iron. Results showed that the furan-based binder using quartz sand absorbs 30 % more heat than the phenolic binder. Higher water content in the phenolic binder with high heat absorption capacity at the initial stages of the solidification process can give rise to defects, while furan facilitates smooth decomposition profiles. Although the 3D printed sand mould using furan binder could be used to cast parts without heat treatment, Primkulov et al. [68] found that curing at temperatures of nearly 60 °C to 150 °C for an appropriate duration (30 h to 60 h) showed optimal unconfined compressive strength (UCS); with optimal UCS at 80 °C. On the other hand, Mitra et al.[15] studied the same for 3PB (three-point bending) strength and permeability. The authors reported that only the permeability improved due to natural ageing (evaporation of bound water) and there was no significant change in 3PB strength even at 100 °C. They further suggested that the mould could be stored for a long term while roughly preserving the strength. It appears that the tensile and compressive behaviour of the printed sand mould is affected by the bound water/other fluid content; therefore, it is apparent that properties of the sand mould is controlled by the acid/furan ratio and pore connectivity within the sand mould.

There are challenges to implementing industrial hybrid technology of rapid casting that combines 3D sand additive manufacturing of moulds and the traditional casting processes. The idea is to master the effect of direct 3D powder binding to achieve high and sustainable productivity in the casting industry. The research challenge can be appreciated as gap-bridging between fundamental powder metallurgy engineering and manufacturing applications, between measurement methods and process control of production diagnostics and data-based experimentation.

3.4 Factors influencing the quality of the 3D printed sand moulds

Reviewing the recent developments in 3D sand mould printing since the authors' previous publication [69], the effect of two sand mould making processes, conventional and 3D printing, on the weight savings, allowances provided to the moulds, surface finish and fettling work of the castings of a pump bowl were investigated [36]. The results [36] indicated that the employment of 3D printing for making a pump bowl moulds and cores has significant advantages over the conventional process. The amount of sand that was used in the conventional pattern making was 301 kg, whereas the 3D printing process consumed only 99 kg. A significantly high weight saving of 67.11 % was observed due to the usage of the additive manufacturing process for the production of the sand mould and core for the pump bowl. The weight saving was predominantly due to the elimination of the draft, machining, and finishing allowances provided to the casting, which is not necessary for the 3D printing process.

Additionally, the average surface roughness was improved for the 3D printing process (~200 μm) than the conventional process (~ 500 μm), and the mechanical strength of the 3D printed sand moulds was found to be superior to the conventional process due to better bonding between the sand particles of the process. Moreover, the fettling time was reduced to 15 min from 60 min due to the very close tolerances of the 3D printed sand moulds and subsequent little machining of the final pump bowl castings [36]. The authors [36] also stated that the 3D sand mould printing technique is effective, in terms of cost and lead-time savings with minimum wastage of material, only when a small quantity of sand mould is manufactured, whereas the conventional sand mould making process is more favourable when large quantities are produced.

On the contrary, the applicability of Binder Jetting technology to 3D print sand moulds for the fabrication of complicated bespoke cast aluminium space-frame structure was investigated [30], and the authors suggested that rather than using conventional sand casting or direct 3D metal printing for making non-standard customised metal joints, it is useful to combine conventional sand casting with 3D printed sand moulds so that large numbers of non-standard customised structures can be made in a shorter time. Besides, 3D printing of sand moulds offered more design freedom while fabricating such complicated structures. Neither conventional sand casting nor direct 3D metal printing offered such geometric freedom or fabrication flexibility for making complicated structures [30].

The inherent benefit of design freedom of 3D printing and the ability to make complicated sand moulds increased the complexity of the casting process and led to more casting defects due to the inability to predict heat dissipation within the complicated moulds [70]. An instrument methodology comprising of wired and wireless sensors was developed to improve the understanding of such complex castings [70]. These sensors were housed at different strategic locations within the mould to collect diversified data such as temperature, pressure, moisture, gas chemistry, the motion of moulds and magnetic field, from the moulds. The design freedom offered by 3D printing leveraged the usage of different sensors and helped in understanding the thermodynamics and physics of the process.

A lightweight structure in a smaller length scale instead of the macroscopic design was implemented to reduce the manufacturing cost and processing time of 3D printed sand moulds [71]. Two types of lightweight structures or geometrical unit patterns, a box with a square hole (Type-I) and a lattice or mesh structure with top and bottom pads (Type-II), were designed and mechanically analysed. It was observed that the Type-II pattern was more flexible in taking out sand particles than the Type-I pattern. Similarly, both lightweight structure types were suitable only for rigid single component materials such as metals or plastics and not suitable for ceramic or polymer composites, which have different mechanical behaviours.

The effect of a traditional dense mould compared to a rib-enforced shell mould constructed with 3D sand printing technique on the cooling efficiency of the Al alloy A356 casting for stress-frame applications has been investigated [72]. The authors observed that the cooling efficiency of the rib-enforced 3D sand printed shell mould castings was significantly larger with cooling time savings of approximately 40 % in natural conditions and further 35 % in air blown conditions before shakeout. Furthermore, the rib-enforced 3D sand printed shell mould enabled the adjustment of cooling conditions at locations of interest and produced good dimensional tolerance and surface quality in the A-356 aluminium alloy stress frame. Moreover, the 3D sand printing of the rib-enforced shell moulds saved almost nine-tenths of sand per mould [72].

The effectiveness of the application of new technologies, additive manufacturing (ink-jet bonding 3D printing) and subtractive manufacturing (sand mould milling), in terms of resource consumption, environmental impact and production efficiency in a traditional foundry industry were investigated [73]. Material, energy, and human resources were considered evaluation parameters for estimating resource consumption, carbon emission as an evaluation index for environmental impact, and actual casting output to evaluate production efficiency. The results indicated that the 3D sand mould printing process combined with traditional casting has better resource utilisation, reducing about 20.78 % carbon emission. Also, the production efficiency of the 3D printing process was 92.66 %, which has more significant economic benefits. The authors provided a summary of whether and which new technologies could be combined in a traditional manufacturing process to realise sustainability, which has practical significance.

The mass transport properties, i.e., permeability and microstructural features of the 3D printed sand moulds were characterised [74] using X-ray micro-computed tomography to achieve reproducibility and for controlling gas defects in the final castings. The results showed that the 3D printed sand moulds' mass transport properties could be precisely predicted using the in-situ non-destructive methods like X-ray micro-computed tomography, and the data can be used to improve the quality of the castings and create optimised 3D printed sand mould structures for foundry applications. Figure 6 illustrates the processing-oriented advantages and the research areas to be focused on improving the capabilities of 3DSP.

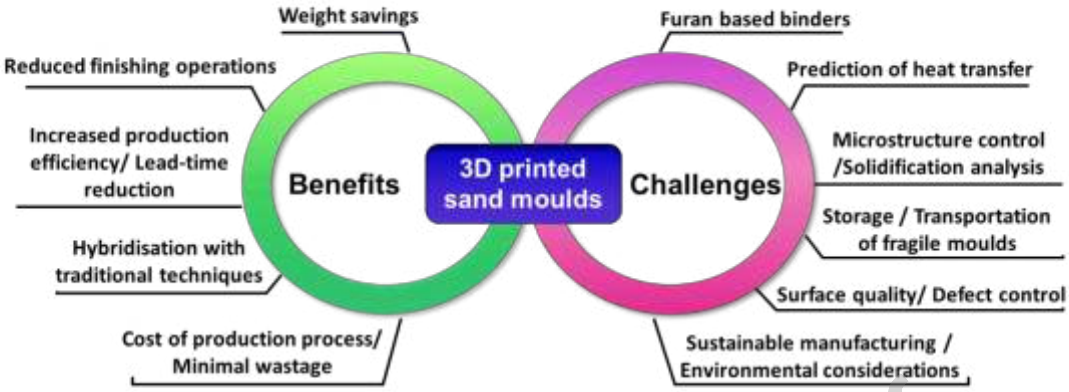

Figure 6: Processing oriented advantages and the research areas to be focused on improving the capabilities of 3DP.

Properties such as gas permeability and strength of the mould are not always required to be at their maximum for good casting. Therefore, flexibility in controlling these parameters is the strength of this technology. To summarise, the following would give a user a better understanding of the process.

-The printing process parameter such as layer thickness which is determined by the sand particle size.

-Furan droplet size and distribution influence the mass distribution of bonding material which can determine the density of the 3DSP mould, hence the gas permeability.

-Viscosity of the binder is a function of temperature. Therefore, the printer should be maintained within a controlled environment.

3.5 Printhead and re-coater

The most important part of the binder jetting machine is the printhead. The resolution, both in x- and y- directions, is determined by the space between the nozzles and the speed of the printhead as well as the volume (controlled by the applied electrical potential difference, voltage, on the printhead) of the ink droplet; the volume is typically around 78 pL to 104 pL (average diameter is between 50 µm and 60 µm; not perfect spheres) [75], and this will occupy around 2 % - 3 % of the interstitial region between the sand particles. The volume of each droplet may affect the dimensional tolerance even though the sand particle (140 µm – 250 µm) is much greater in size than these droplets; therefore, the effect of the layer thickness of sand particles (usually two times the particle size) will determine the final tolerance. Regardless of this, the binder's distribution within the mould is determined by the size of the droplet and therefore, it should be kept minimal. The printing process's speed is mainly controlled by the speed of the printhead and the sand re-coater and the dimension of the x-y plane within the job-box. This binder fluid's viscosity is a function of temperature that is hard to control within a continuously moving printhead; hundreds or thousands of nozzles in the printhead are in µm scale. Therefore, a frequent clogging problem is inevitable and needs attention.

The strength of the sand mould depends on the porosity, Figure 7. When perfect spheres of sand particles are compacted in a Face Centered Cubic (FCC) / Hexagonal Closest Packed (HCP), Body-Centred Cubic (BCC), Simple Cubic (SC)manner, the density of the printed part takes the maximum achievable density of these structures, corresponding to 74.06 %, 68.02 %, 52.36 % of the bulk sand density respectively, ignoring the binder density. The binder/activator is added to the sand mix on a certain wt.%, and the binder within the 3D printed sand mould is distributed within the interstitial gaps. Therefore the extra mass within a unit volume can be calculated, and the density or strength related using Eq.1 [76].

$$\sigma_t = \frac{M_s \rho_b}{M_b \rho_s}(1-\varepsilon)\sigma_s \qquad \text{Equation (1)}$$

Interparticle friction has a significant effect on filling fine-scale particles, and the sphericity of these sand particles is in the range of 70 %; therefore, the packing fraction can be expected to deviate from these predictions. Despite this, the maximum density achieved experimentally was nearly 52 % of the bulk sand density [6], corresponding to the density of a simple cubic packing arrangement of these sand particles. This structure's primary advantage is that the capillary action of the binder fluid may shift the sand particles from their original interlocked status after the recoating iteration. Therefore, the binder should be dispersed either in a ((b)-1) pendular or ((b)-2) funicular manner, as shown in Figure 7 (b). The binder distribution depends on the fluid penetration method within the compacted sand; therefore, the binder distribution can be controlled by optimising the voltage waveform of the printhead [76]. Well-connected pore regions are the key to achieving better permeability of the printed mould.

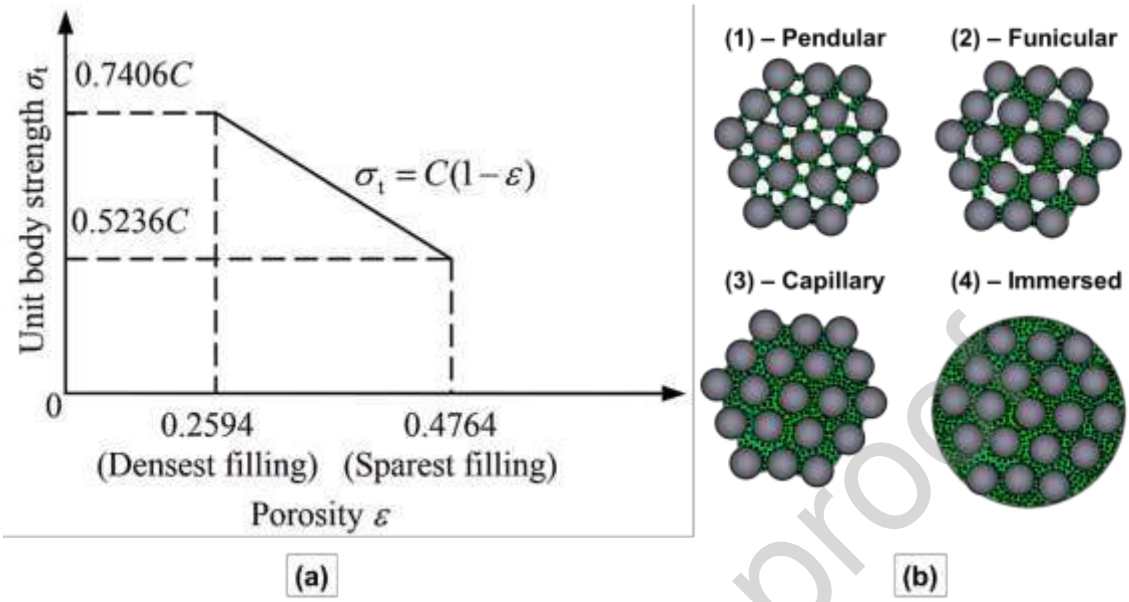

Figure 7: Strength of the 3D printed sand mould as a function of porosity when considering C as a constant. Where C= M_s ρ_b/(M_b ρ_s) σ_s, ρ_p and ρ_b are the densities of sand and binder, Ms/Mb is the weight rate of binder and sand particles [76]. (b) The binder filling methods within the 3D printed sand.

3.6 Functional sand mould

Significant drawbacks of 3D sand printing are the binder and sand material capabilities and characteristics in creating functional soft sand mould tool without hard tools. The section documents the research methodology to overcome these critical points, using several traditional and advanced characterisation approaches. The use of selectively printed micro-droplets of different foundry binders into a fine layer of permeable activator coated traditional and advanced ceramic materials, could lead to functionalise the sand mould. For this reason, there is a need to focus with further research on the process physics involved in the 3D printing technology. Moreover, to address the characterisation of the powder to form a primitive building element and the final printed product, more attention should be paid the to the characterisation techniques regarding mechanical performances and transport properties of 3D sand printed moulds [74].

The current sand moulds are manufactured using only one type of sand particles. This provides uniform thermal properties in the mould assembly. As the molten metal enters the sprue, the temperature drop is significantly high, and hence a very high superheat may be required for the molten alloy during pouring. This not only results in waste of energy but also negatively influences the solidification characteristics of the alloy. If the mould is designed with geometry-dependent thermal properties, the molten alloy can fill the mould without severe temperature loss but can cool rapidly once entering the mould cavity where the actual part is created. This means that the sprue can be made with materials of the low volumetric heat capacity and low heat conductivity but the mould cavity with exceptionally high volumetric heat capacity and high thermal conductivity to speed up the solidification process. Shan et al. [77] showed that the sand re-coater could be modified to spread various sand layers during each iteration of the sand recoating process. In this way, mould can be manufactured with geometry dependent thermal properties. Silica sand has very low thermal conductivity and volumetric heat capacity, Figure 8. Therefore, it may be suitable sand for the sprue section of the mould assembly. In contrast, zirconia has slightly higher volumetric heat capacity and is, therefore, a better candidate for the mould cavity section so that it can provide better heat absorption from the molten alloy. In addition, silicon carbide sand (currently used for casting) has high volumetric heat capacity and high thermal conductivity, compared in Figure 9. However, the particle shape is angular [78] due to the production method and therefore presents difficulties in finding suitable printing process parameters. Silica sand is cheap and abundant on the earth's crust. It has poor heat conductivity and lower volumetric heat capacity, Figure 8, compared to the currently used sands. It would be a better choice for the gating system in the sand mould assembly where the molten alloy should be kept in liquid form until the solidification in the cavity is complete.

Table 2:List of a few currently used (traditional casting) sand materials.

Material	Properties	Limitations	Advantages
Silica (SiO_2)	Low volumetric heat capacity	Low heat conductivity	Good for gating system Cheap/most abundant
Zirconia (ZrO_2), Olivine ((Mg^{2+}/Fe^{2+})SO4), Chromite (FeCr2O4), Zircon (ZrSO4), Chamotte	high volumetric heat capacity	high heat conductivity	Expensive Good for mould cavity surface

Table 3:Summary of the commercially available binders and activators and their properties [79].

Binder	activator	Properties
Furan (chemically cured furfuryl alcohol-based)	Sulfonic acid	Can be used with/without heat treatment to remove any moisture.
CHP binders (ester-cured alkaline phenolic resole)	--	additional post-curing at elevated temperatures
HHP Binders (acid-cured phenolic resole)	--	additional post-curing at elevated temperatures.
Inorganic Binders (water-based, alkali-silicate binder)	--	additional post-curing at elevated temperatures.

Thermal conductivity (W/(m.K))

Figure 8: Volumetric heat capacity ($J.m^{-3}.K^{-1}$) as a function of thermal conductivity. The chart produced by CES-Edu pack software and material property database [80] containing a collection of material property data from published sources.

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