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# The role and impact of 3D printing technologies in casting

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**Abstract:** 3D printing is such a magical technology that it extends into almost every sector relating to manufacturing, not to mention casting production. In this paper, the past, present and future of 3D printing in the foundry sector are profoundly reviewed. 3D printing has the potential to supplement or partially replace the casting method. Today, some castings can be directly printed by metal powders, for example, titanium alloys, nickel alloys and steel parts. Meanwhile, 3D printing has found an unique position in other casting aspects as well, such as printing the wax pattern, ceramic shell, sand core, sand mould, etc. Most importantly, 3D printing is not just a manufacturing method, it will also revolutionize the design of products, assemblies and parts, such as castings, patterns, cores, moulds and shells in casting production. The solid structure of castings and moulds will be redesigned in future into truss or spatially open and skeleton structures. This kind of revolution is just sprouting, but it will bring unimaginable impact on manufacturing including casting production. Nobody doubts the potential of 3D printing technologies in manufacturing, but they do have limitations and drawbacks.

**Key words:** 3D printing; additive manufacturing; rapid casting; casting; mould; core; design

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## 1 Introduction

3D printing has become such a hot research topic in recent years that it is talked about by almost everybody and it extends to almost every sector. It has been applied into all manufacturing areas, seemingly posing a potential replacement of manufacturing methods [1]. 3D printing originates from a rapid prototyping technology which began in the 1980s [2-3]. The meaning of prototype technology, as its definition, is simply a technology to assist the manufacturing of new products for demonstration, and to test geometry and dimensions. By this method, there is no need to prepare patterns and dies by traditional methods, which can save a lot of cost and time. 3D printing only makes prototypes, not real things for application; a prototype is mainly for shape analysis, for demonstration, or to be used for making a mould for producing a real casting. It is thought to be fast because it avoids the preparation of die or tools which usually takes a lot of time. There are several 3D printing methods to make a prototype, such as fused deposition modelling (FDM), lamination object manufacturing (LOM), stereo lithography (SLA), selective laser sintering (SLS), three dimensional printing (3DP), etc. FDM is an additive manufacturing technology that builds parts up layer-by-layer by heating and extruding thermoplastic filament. In the SLS process, wax, resin or plastic powder is swept as a layer, and then a laser beam burns the powder and sinters it together with the bottom layer. The trace of the beam is controlled by the section profile of the casting or part. LOM is a method to stack up a lot of pieces of paper being cut according to the sections of a part. SLA solidifies the liquid resin layer by layer based on section size, using laser or ultraviolent light. 3DP is a process that uses an inkjet system to deposit a low-viscosity binder onto a powdered material bed through the use of a pattern derived from a CAD model. Once the binder is dried, the completed part is removed from the machine and any excess powder

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is removed. In later years, high power laser beam appeared, making the melting of metal powder possible, and so the direct making of metal parts emerged. Laser Engineered Net Shaping (LENS), Laser Selective Melting (SLM), Direct Metal Deposition (DMD) and Direct Metal Laser Sintering (DMLS) can be used to directly print metal parts from metal powder. In these methods, parts are fabricated by dispersing powdered metal over a molten pool of metal substrate created by laser or by melting the powder bed. In early uses, these methods were used in the making of titanium alloy frame parts for aeronautic and aerospace crafts, which are very hard to make by traditional forging and casting methods [4-6]. So, direct printing of metal parts brings great hope in manufacturing and it suddenly comes to be a new trend for the future.

As a matter of fact, 3D printing cannot be named a brand new method in the foundryman's mind, for it is much more similar to welding and electroslag casting, and the solidification process of metals is the same as that in the casting process. Thus, foundrymen have doubted the potential of 3D printing from the beginning because of its low forming efficiency, weak metallurgical connection between layers, inferior mechanical properties of the 3D printed parts, which all come to be disadvantages compared with the casting method. Obviously, 3D printing can do a lot of things which are not possible by the traditional casting method. For example, some castings, such as titanium alloy parts, can be directly printed by metal powders. Meanwhile, 3D printing has found its unique position in casting production, such as printing a wax pattern, ceramic shell, sand core, sand mould, etc. In this paper, the application of 3D printing technology in the area of casting is reviewed. Both its advantages and disadvantages compared with the casting process are addressed. Most importantly, the impact of 3D printing on the design is brought to light for products, assemblies and parts, such as the casting, pattern, core, mould and shell in casting production. The future of 3D printing is also discussed.

## 2 Application of 3D printing technology in casting

The casting process is actually very complicated, involving the making of a pattern manually or by machining, making the core and mould separately, which gives room for the application of 3D printing technologies in casting production. The core is formed in the core box, the pattern is used to shape the cavity of the mould and core. So pattern, core and mould making is the first step for casting, but how are these actually made? Some manually, by machining, forging, clay baking, or even the simple casting method with alloys of low melting point. So it is very complicated, sometimes it seems to be a loop, hard to tell whether the pattern comes first or the casting comes first, like the chicken or the egg dilemma. There are many kinds of moulding methods, the above mainly refer to the most popularly used sand moulding methods. However, there are other moulding methods, such as lost foam casting, investment casting, shell moulding, etc. In lost foam casting, a foam pattern is used for each mould making. In investment casting, similarly, a wax pattern or a cluster of wax patterns are used each time during moulding. So the clay or foam pattern is firstly made by dies which has the casting shape cavity. How is the die made before the production of a casting? Actually, it can be made manually or machined, or by other casting methods. So, all of these patterns or cores or moulds or especially the castings themselves can be made by 3D printing technology, as shown in Fig.1.

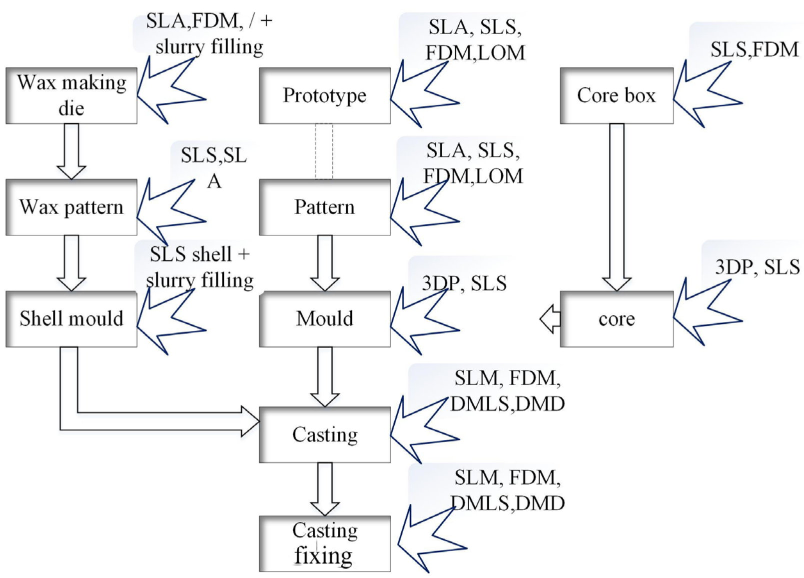
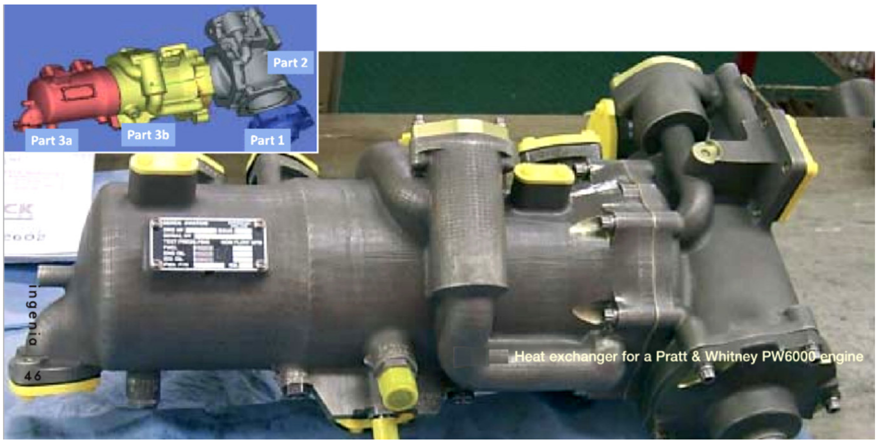


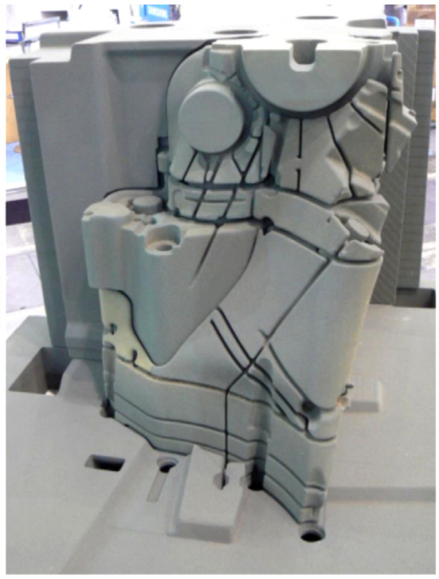

**Fig. 1: Application of 3D printing technology in different casting procedures**

At the beginning of inception, 3D printers could create models called prototypes to determine if a design met the customer's concept and functional expectations. It was also used to test parts for their forming method, and function with other parts in an assembly. Using printing technologies such as laser sintering and electron beam melting, rapid prototyping evolved into rapid tooling (RT) and rapid manufacturing (RM) [7], in which patterns, core boxes, dies, moulds and short runs of actual finished parts are made, respectively. The application of additive manufacturing technologies for producing cast parts is often termed as rapid casting.

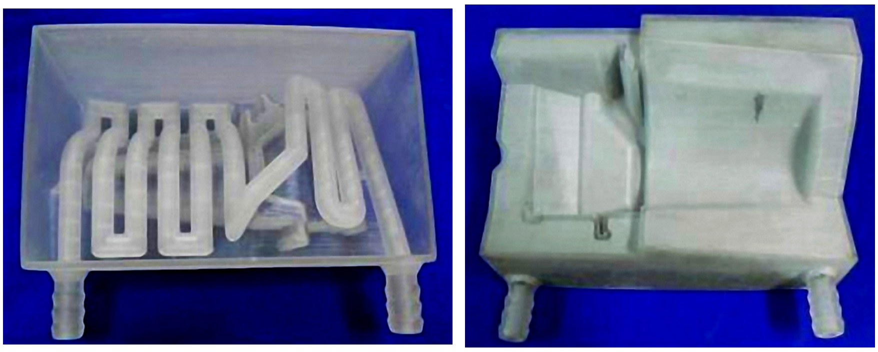
Examples of 3D printed pattern, shell, wax pattern, core and mould are shown in Fig. 2.



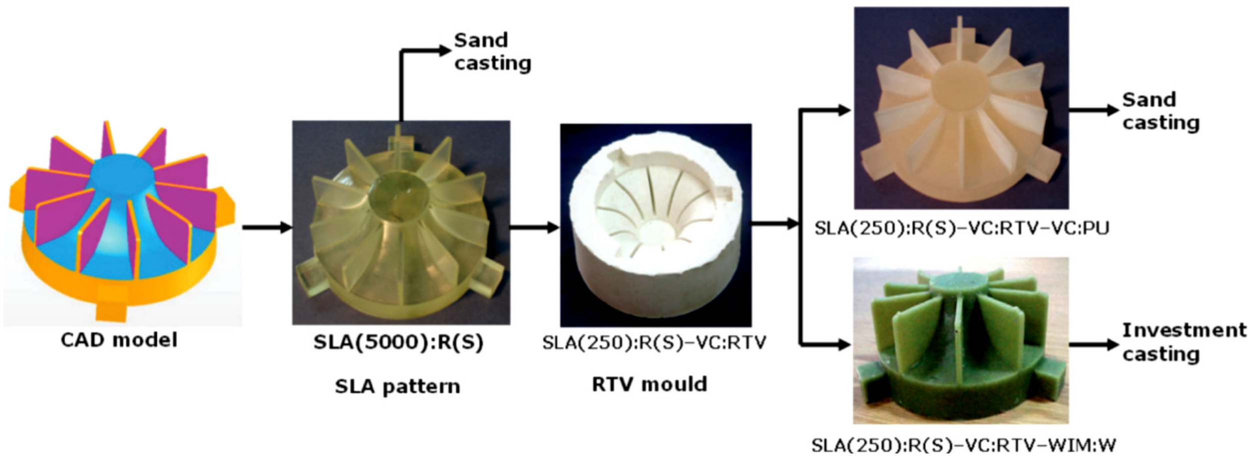

(a) SLS made polyamide-based models of heat exchanger for a Pratt & Whitney PW6000 engine [13]



(d) Assembled core and mould fabricated by 3DP [35]



(b) Resin shell + slurry filling for wax making die [26]




(c) Patterns fabricated by direct and indirect RT routes for sand and investment casting [23]: R-resin, W-wax, PU-polyurethane, RTV- a rubber, S-solid, VC-vacuum casting, WIM-wax injection moulding

**Fig. 2: Application examples of 3D printing technologies in casting**

## 2.1 Rapid tooling—3D printing of prototype, pattern, core box and wax injection mould

A number of direct routes using 3D printing methods such as FDM, LOM, SLA, SLS, etc., as well as indirect routes (3D printing methods coupled with secondary or soft-tooling processes like vacuum casting), are available for rapid fabrication of a prototype, pattern, core box, etc. for the first step in the casting process [8-20]. This is also called rapid tooling (RT).

In the direct routes, 3D printing is used solely to directly print prototypes, patterns or core boxes. SLA can be used to create functional or conceptual polymeric products. In the 1990s, Daimler-Benz AG applied the LOM method to make patterns for cylinder block and several automobile castings, and pointed out that the sensitivity of paper to moisture leads to the expansion of LOM patterns vertical to the layers by absorption of water from the atmosphere [15]. Wang et al. [16] discussed geometry, error sources and propagation, and shrinkage effects in LOM-based rapid tooling for sand casting. 3D printing can also be used to make consumable patterns for investment casting. The SLA investment casting build structure called QuickCastTM was introduced in 1993 and has been used to create functional parts in a variety of different metals [17,18]. The main advantage of SLA is the creation of complex structures with very thin walls. However, SLA parts age rapidly, resulting in warping and brittleness. Thermojet printing was used to print wax patterns for investment casting [19]. Thin layer thickness enables very smooth part surfaces, so it is suitable for small parts such as jewellery. FDM has also been used to make wax parts [20]. Wax casting patterns can also be manufactured by spraying layers of fluidized wax by DodJet, Solidscape and the ProJet technologies of the 3D Systems company as well.

The direct investment casting patterns produced by SLA and LOM leave an undesirable ash residue during burnout. This can be overcome by adopting indirect routes, such as silicone rubber moulding, polyurethane/epoxy casting, and investment casting, which can be used to convert RP master patterns into moulds (or vice-versa) [9,21-26]. These secondary processes aim to comprehensively optimize the development time, cost, quality, and lifespan. SLA parts can be used as patterns to prepare moulds for injection moulding (Direct AIM) [22]. SLA was used for indirect RT to create master patterns for moulding and casting processes [23]. LOM was also used to create patterns for silicone moulding and wax injection moulds for investment casting [24]. FDM made plastic parts were used to produce RTV moulds and then to create wax investment casting patterns [25]. For wax patterns, the de-waxing/burnout step leaves ash-residues in the mould, which will cause severe porosity in castings because of a reaction of the melt with shell that is catalyzed by the ash residues in the mould.

Forno et al.[27] studied the relationship between RP patterns and investment casting outcomes, trying to overcome problems related to burning out of moulds containing resins and obtaining a good surface quality for castings. Shawn [28] investigated the availability of 3D printed polymers and the burnout of 3D printed materials, nylon, thermosetting photopolymer, epoxy resin, acrylonitrile butadiene styrene (ABS) and poly methyl methacrylate (PMMA) used as expandable patterns in the investment casting. Another severe problem is cracks in the mould material during heating due to incompatibility of thermal expansion of these types of waxes/resins and shell [29]. For better release of the 3D printed pattern from the investment shell, 3D-printed starch patterns were used for investment casting by the ZCast process for the production of cavities for light-alloys castings [30-31]. Marutani and Kamitani [32] used pure salt powder and flour-salt mixed powder to manufacture sacrificial patterns which can be easily removed from moulds by soaking in water.

The combination of additive and subtractive techniques was proposed to realize a smooth side surface [33-34]. Luo [33] milled each bonded layer by using layered tool paths during layer by layer forming. As such, patterns are grown in a bottom-up fashion, eliminating the need for multi-axis operations and meanwhile allowing geometrical features in deep cavities.

## 2.2 3D printing of sand core, mould and shell

SLS can be used to directly create sand moulds or cores using resin coated sand [34-40]. Firstly, sand coated with resin is swept on a sand bed, then a laser beam selectively melts the resin coating and causes sand grains to stack together. After many layers, a core or mould forms. Usually, silica sand was used in SLS to make moulds or cores. $Al_2O_3$, zircon and man-made ceramsite (Baozhu) sands were also tested to improve the properties of the mould or core and to meanwhile reduce cost [41-45]. The use of resin is usually a little bit greater than that of a traditional moulding method because of the slight burn off during laser sintering and insufficient flow of the binder resulted by the high speed moving laser spot. The effect of processing parameters on the forming capability has been the research focus. These parameters include laser power, laser spot size, scanning speed, preheating temperature of the sand and layer thickness [43,45-47]. Usually the resin coated sand is preheated to 60–70 ºC [47]. The preheating of the current sand layer is very important, as it will then make the sand surface slightly bonded to resist the abrasion with the sweeping roll during sand sweeping and then prevent the displacement of the already printed part. Meanwhile, preheating can decrease the contraction of the printed sand mould or core and then increase the dimension accuracy. It is also good for the cleaning of loose sand. The strength of the formed moulds or cores after SLS is usually less than 1 MPa, not great enough for use, so they have to be baked in an oven. Wen [42] and Yang et al. [47] investigated the relationship of mechanical strengths and baking temperature. The strength will increase with the baking temperature and then decrease suddenly because of the burn off of the binder. So, there is an optimized temperature for the strength. A high baking temperature can also decrease gas release during the casting process. Therefore, as the strength requirements of the moulds and cores are satisfied, the baking temperature can be as high as possible. Fan et al.[48] investigated the hardening mechanism of the laser sintering of resin coated sand. During the laser sintering process, the sintered sand is not totally hardened. Actually, there are three layers from the surface, the top layer is sufficiently hardened, the sub layer is half hardened, while the bottom layer is still in loose condition. During the post curing process, the sub and bottom layers will be hardened, so the strength is totally increased. However, the top layer remains at the same strength level. After post curing treatment, its strength can be increased to 3–6 MPa. Beyond the requirement of mechanical strength of the printed mould or core, its gas release and air permeability are more critical to the quality of castings. After post curing treatment, Yang et al. [47] found that the gas release of the sintered sand can be reduced to around 12 $mL \cdot g^{-1}$. Zhao et al. [46] investigated the influence of sand grain size and the methods for preparing resin sand on these effects, and the contraction in different directions and deformation of the formed sand block.

Because the laser beam is very slim, usually less than 1 mm, SLS is time consuming although the movement of the laser beam is very fast in terms of meters per second. Thus, this method is suitable for complicated cores of a small quantity requirement, for example, the sand cores for cylinder blocks or heads during development of new products. Other problems during SLS process are displacement of the isolated sintered area during sand sweeping, shrinkage and warping, crack and uneven surface of the sintered sand part [45,49-50].

Many years later following the sintering method, the 3DP method was proposed for sand core and mould making [51-52]. Firstly, clear sand grains are swept on a sand bed, then a nozzle moves over the sand bed, spraying bonding resin, its movement controlled according to the shape of the 2D sections. The sand area accepting the bonding resin will be bonded, so finally a core or mould can be made. The setting time of the resin is properly controlled to allow it to set before the next layer begins. Finally, the formed sand mould or core is taken out and transferred to the oven for the post curing treatment. Agents can be used to facilitate the setting process, so the post curing process may be omitted. The agent is sprayed by another nozzle or it is mixed with sand in advance of sweeping on the sand bed. To improve the efficiency, a group of nozzles can be integrated, just like printers. For example, the ExOne 3DP printer integrates thousands of nozzles. So, its trace can vary from micro meter to several millimetres. The spraying nozzle technology has developed over many years with the printing technology, so it greatly facilitates the application of this technology in printing sand cores. ExOne and Voxeljet, ProMetal RCT technology, 3DP-ZCast method are commercial 3D printer brands for sand core or mould printing. Currently, the forming size is as big as 4,000 mm × 2,000 mm × 1,000 mm, which can greatly increase the production rate of cores and moulds for small castings by many per batch and satisfy the requirement of large castings. The printing time for a set of cores for a four cylinder block on a 4,000 mm × 2,000 mm × 1,000 mm 3D printer only takes 20 hours.

The situation of the 3DP method is similar to that of SLS method: the mould material and resin are the most important factors for a sound core or mould with high strength and lower gas release for the casting process [52-53]. Snelling et al. [52] compared the binder burnout characteristics and the tensile strength of sand created by 3DP and conventional chemically bonded moulding materials. Increased binder content can strengthen the mould but have an adverse effect on part quality. Z Corporation developed a special powder material, basically a plaster-ceramic composite, for casting low-temperature materials such as aluminium, magnesium and zinc alloys. Sometimes, there are also veining defects in iron and steel castings by using 3DP printed sand core or mould. Tomita and Fukuda [54] used 65% artificial sand and 35% natural silica sand to print the sand mould and avoided the veining defect. One big problem for the 3DP method is the clogging of the nozzles of 3DP machines by viscous binder [55]. To guarantee the operation of printers and the mechanical and performance properties during casting process of sand core or mould, some 3D printer companies provide their own specific binders and sands for 3D printing. For example, ExOne provides PHENOLIC Binder – FB101 and SILICATE Binder – FB901. Phenolic binder is for castings with lower melting points such as aluminium alloys and silicate binder is for alloys with a higher melting point such as cast steel. ExOne printers can take furan resin, phenolic resin and sodium silicate binders for quartz sand, and the former one also for aluminium oxide, the latter two can be used for synthetic sand. For phenolic resin and sodium silicate, post curing is necessary, however, the furan resin made sand block is free of post curing, and 3D Systems (ZCorp earlier) currently utilize a specific form of plaster together with olivine sand as a possible material system for rapid production of pattern-less moulds for nonferrous casting. It needs post curing to improve strength. The special binder and sand proscribed by 3DP printer manufacturers increase the cost. Some local customers try to find substitutes for sand or binder, but it is difficult to achieve both high strength and low gas release and high permeability. Regardless of SLS or 3DP methods, the formed sand block usually exhibits low initial strength before the post curing. Thus, it is always necessary to design supports for the sand mould or cores [56]. After post curing treatment, the supports have to be removed.

The sand moulds and cores produced by SLS and 3DP methods have been successfully used to produce complicated castings such as cast iron and aluminium cylinder blocks, cylinder heads, gear boxes, etc. during the development of new castings and small batch production[47, 50, 56-58]. The final dimension of the castings, internal quality, mechanical properties and surface finish all meet the requirements. Meanwhile, both of these methods are proved to greatly shorten the lead time and production time and reduce cost. Gongxiang Co. Ltd, automaker FAW? Yto Group Corporation, Guangxi Yuchai Machinery Co. Ltd., Japanese automaker KOIWAI, and others, are managing 3DP and SLS methods in developing new castings for automobiles.

The 3DP method can also be used to print ceramic shells and ceramic cores with ceramic powder and selected binder [59]. The formed object, the shell or core, must be baked in an oven to achieve strength. Singh [60] investigated shell wall thickness of a mould cavity for a rapid casting solution for aluminium alloys using 3DP. His finding of the best shell wall thickness is 5 mm for aluminium alloys.

Yang et al. [61] proposed a method called Profile Failed Rapid Prototyping (PFRP) to make sand core or mould. In this method, a layer of coated sand is swept, a heating source sweeps the whole layer of sand to make the whole layer bonded, then a laser beam scans this layer according to the 2D profile of the sand core or mould, burning the coating off to prevent its consolidation. Finally, the sand core or mould can be taken out by breaking the outside sand block. The advantage of this method is high speed because only the profile of each layer needs to be burned by laser beam. The disadvantage is the withdrawing of the printed sand part from the consolidated sand block, similar to the shake-out of a casting surrounded by sand mould. It also wastes a lot of binder.

### 2.3 Direct 3D printing of metal parts

LENS, DMD, DLMS and SLM methods can be used to directly print metal parts from metal powder [62-66]. The 3D direct making of metal parts is also called fast manufacturing: without the making of patterns, dies or moulds. 3D laser melting can be used for superalloys, titanium alloys, steels, especially stainless steels and aluminium alloys.

3D printing of metal parts depends on metal powders and laser beam energy. Titanium alloy is an example which is difficult to make by traditional methods, and its reflection, absorption, and density are properly suitable for laser melting. However, the most widely used aluminium alloy is a poor example for laser melting. Because it has a higher laser reflection rate, it is difficult to melt by laser, and as it has high thermal conductivity, the heat is quickly dissipated to the base plate. Meanwhile, it is susceptible to oxidation, and is very light. Thus, the forming of aluminium parts by SLM is still a challenge. Currently, some people are trying to mix aluminium powder with some other metal powders or use aluminium alloys such as AlSi10Mg to counteract the drawbacks in making parts by 3D printing [62].

Borescope boss of nickel-based alloy was produced by additive manufacturing instead of casting and was equipped in an airbus turbine engine [63]. GE Aviation produced the 19 fuel nozzles in its LEAP jet engine via powder bed fusion in large quantities [64]. 3D direct metal part making is also used to directly make automotive parts such as the gearbox and intake manifold.

However, the microstructure, the compactness of the metal parts, and the surface finish are still far from satisfying requirements, so there is a long way to go before wide application.

An electron beam has the advantage over a laser beam of direct coupling into a metal powder bed without reflection and loss of energy. The electron beam can also be controlled without mechanical scanners, which potentially can lead to faster scanning speed.

If just limited to the shape forming process, casting is much faster than 3D printing. 3D printing is done point by point, profile by profile and layer by layer, so it is very time consuming, while tons, or hundreds of tons, of liquid metal can be poured into a mould cavity in less than an hour. Therefore, foundry engineers are not so optimistic about the replacement of casting by 3D printing. The comparison of the 3D direct printing and casting is listed in Table 1.

### 2.4 3D printing of green parts and sintering

3D printing is also used to make green parts similar to that in powder metallurgy. Metal powders are mixed with resin, and then are sprayed as tooth paste to form green parts layer by layer, and then the bonded part is sintered in furnace so that the metal powders are sintered together to form a pure metal part with the resin burned off. The sintered metal part can be further infiltrated with a material of lower melting point, such as Keltool™ from 3D Systems [67], RapidTool™ from DTM [68], EOSINT Metal from EOS [69] and Soligen [70]. The RapidTool is taken here as an example [71]. In RapidTool, the green part is made from a low-carbon steel powder coated with a polymer with a low melting point which allows it to be processed in the SLS machine without heating the feed and part bed. After the green part is built, it is infiltrated with an aqueous acrylic emulsion and dried in an oven to prevent part distortion during the low-temperature portion of the subsequent furnace cycle. The acrylic emulsion serves as a binding agent, providing strength to the green part when the polymer is burnt away in the furnace. Finally, the green part is converted into a fully dense metal part by infiltration with molten copper. Between 350 and 450 °C, the polymer evaporates. Then, the temperature is increased up to 1,000 °C to allow the sintering of the steel powder. Finally, the part is heated up to 1,120 °C where copper infiltration driven by capillary action occurs. Thus, the final part is fully dense with 60% steel and 40 % copper [71].

Ceramic green bodies can be also created by SLA method using an ultraviolet curable suspension of ceramic powders in place of the usual resin — a "ceramic resin"[72].

Table 2 shows typical 3D printing methods in casting industry.

## 3 Outlook

### 3.1 3D printing — driven design of mould and final products

As mentioned in section 2, the production of castings involves many procedures and pairs of master and negative shaped items.

**Table 1: Comparison of casting method and 3D direct printing of metal parts**

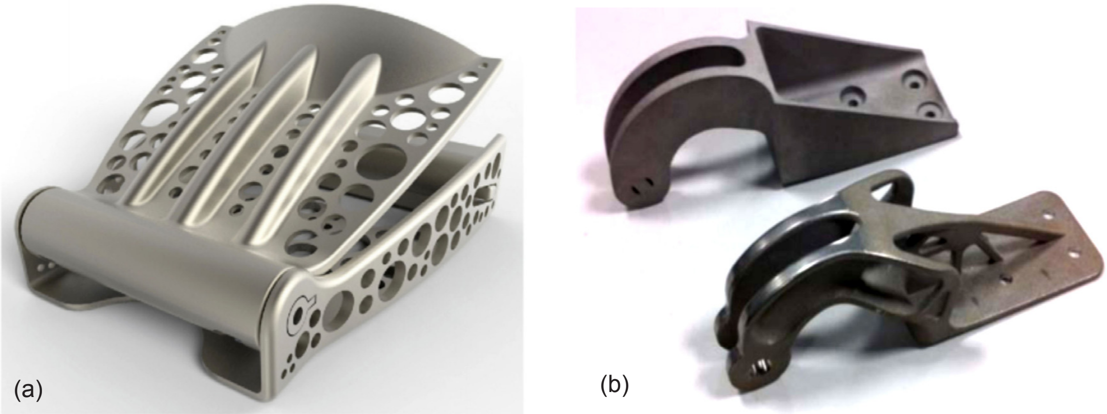
| Items | Casting | 3D printing by metal powder |
|---|---|---|
| Pattern and its manufacturing | Pattern needed.<br>Manual or machined pattern. 2D drawings are needed.<br>It takes a long time, measured in days. | No need of pattern.<br>3D CAD model is necessary. |
| Mould or die | Yes | No or partially |
| Rigging system | Yes, gating system, risers, chills | No, but base plate and support structures |
| Metal initial condition | Melt with a certain overheat | Powder or wire |
| Forming method | Fast pouring without interruption, pouring rate in the range of $kg \cdot s^{-1}$. Whatever casting type, it should be poured in less than an hour, even a thousand ton melt. | Stacking point by point, line by line and layer by layer with small laser focus varying from μm to mm, moving speed in $m \cdot s^{-1}$. Even a small part will take hours or days. |
| Solidification | Slow solidification continuously in volume, ranging in minutes to hours. | Fast solidification point by point, in less than seconds. |
| Cooling after solidification | Slow cooling in mould | Cooling quickly in air or gas protected atmosphere, or cooling in powder bed |
| Microstructure | Continuous microstructure.<br>Grain size varies a lot from thin to thick sections, from central line to surface.<br>Composition varies from bottom to top, and macro segregation exists in heavy castings. | Boundary exists among spots and layers.<br>Grain size and composition are uniform. Grain is very fine. |
| Suitable parts | Covering small to super heavy castings from several grams to thousand tons. | Small parts by SLM, larger by DMD, limited in weight and size. |
| Compactness | Compact with concentrated shrinkage in risers | Less compact with possible pores |
| Metal materials | Nearly all metal materials with high fluidity in melting conditions and short solidification range. | Currently few metal materials. |

**Table 2: Typical 3D printing methods in casting industry**

| Issues | 3D printing method | Materials | Application in casting | Problem |
|---|---|---|---|---|
| 3D printing metal parts | SLM, DMLS, DMD | Metals and alloys | Aerospace and airplane parts such as turbine wheel, fuel nozzle | Limited alloys |
| 3D printing of sand mould, core | 3DP, SLS | Loose sand, resin coated sand | Sand casting, Al, Mg, alloys, cast iron cylinder block/ head | Low efficiency by SLS |
| 3D printing of expandable pattern | SLS, 3DP, FDM, SLA | PMMA, epoxy resin, ABS, wax, acrylic | Investment casting, Jewelry | Residue after burn-out and expansion resulted cracks of shell |
| 3D printing of pattern | FDM, PolyJet, LOM | PMMA, ABS, PLA, PA, PU, Nylon, epoxy, paper | Sand casting, Cast iron and steel casting | Wearable and deformation |
| 3D printing of ceramic core, shell | 3DP, SLA | Ceramic Powder +binder, Resin + required ceramic | Investment casting nickel alloy castings, such as airfoil | Size contraction |
| 3D printing of wax making die | SLS, FDM | ABS, PLA, PA, PM | Investment casting | |

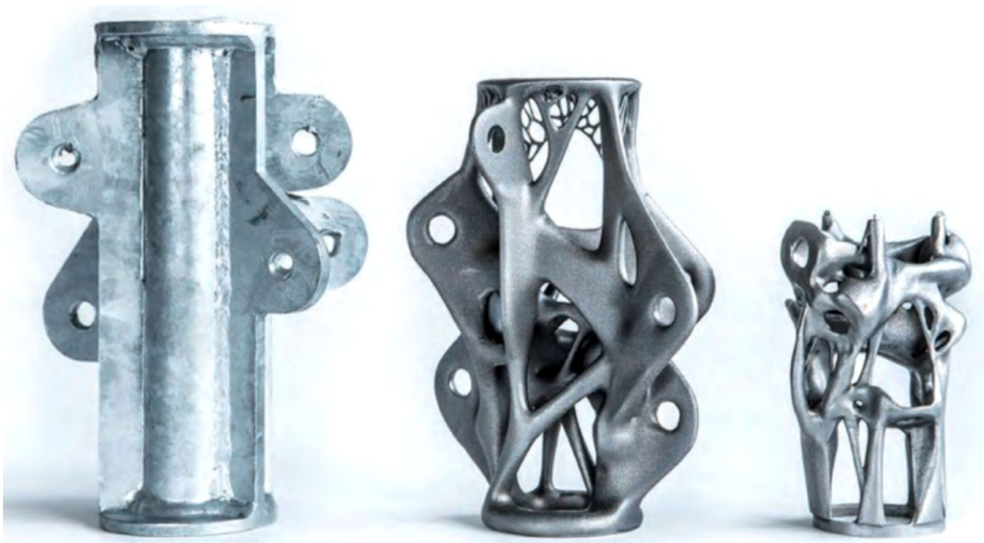
These items need to be placed inside the mould and taken out of the mould, so the casting design, pattern, core design are based on the possibility of easy putting inside and taking out. For example, there are parting lines for patterns and castings, because patterns should be able to be withdrawn from the sand mould after moulding. Traditionally, the forming of pattern, core or mould is by volume forming method; therefore, there are closely compacted structures. Now, 3D printing technology is not simply a layer by layer forming method, it also means there is no need to place solid items in or taking them out. For example, in SLS, SLM or 3DP, the sintered parts are formed in a powdered bed, so the parts can be taken out of the loose powder bed by directly shaking it out and clearing the loose powder from the part surface. No parting lines or parting surfaces need to be considered because of the unit piece forming in 3D printing. By this method, many kinds of items can be redesigned and reorganized. Shell, foam, and truss structures will be the trend of casting in the future. For example, the seat buckle produced by DMLS method is a light structure full of holes in replacement of traditional solid walls [73], and a hinge for the cover of a jet engine is optimized into intricate geometry[74], as shown in Fig. 3. Wang [75] optimized a part with solid walls into a wireframe shape with the same function but lighter weight, as shown in Fig. 4. While it is far beyond the traditional fabrication concept, the complicated shape can be 3D printed. The structure with voids is light, and at the same time, its mechanical properties are guaranteed. So in future, the casting, pattern, core, and mould will be a structure full of voids, the solid wall will be a shell with ribs stuffed inside. This kind of pattern, core and mould and casting can only be 3D printed. With these voids, the materials, manufacturing time and cost can be saved. Meanwhile weight can be reduced, which is totally in agreement with light weight concept in products. More importantly, in the casting process, the voids in the net shaped mould can hold thermal couples, strain gauges and displacement sensors to monitor the status of the sand mould, so as to control the cooling rate of a certain point of the net sand mould, to realize non-uniform cooling conditions for a specified area. And, the voids provide cooling channels in the sand mould. 3D printing can be used to cast complicated structures, not just regular castings, for example, a mesostructure (a lattice truss structure) [76]. However, the current CAD tools are limited by the feature-based solid model construction method. It is difficult to construct models of truss or lattice structures.

This additive manufacturing technology will profoundly reshape castings' shape and structure, and the casting industry as a whole. As 3D printed items do not need to consider the issues of placing in and taking out, so many separated parts can be integrated into a single piece, just as in investment casting, several parts can be integrated by gluing the resin patterns together. And, the cores can also be integrated into a single piece. A single piece means there is no parting line or surface, so



(a) Seat buckle produced by DMLS technology [73] (b) A conventional hinge for the cover of a jet engine (top) was replaced by a more intricate one at bottom [74]

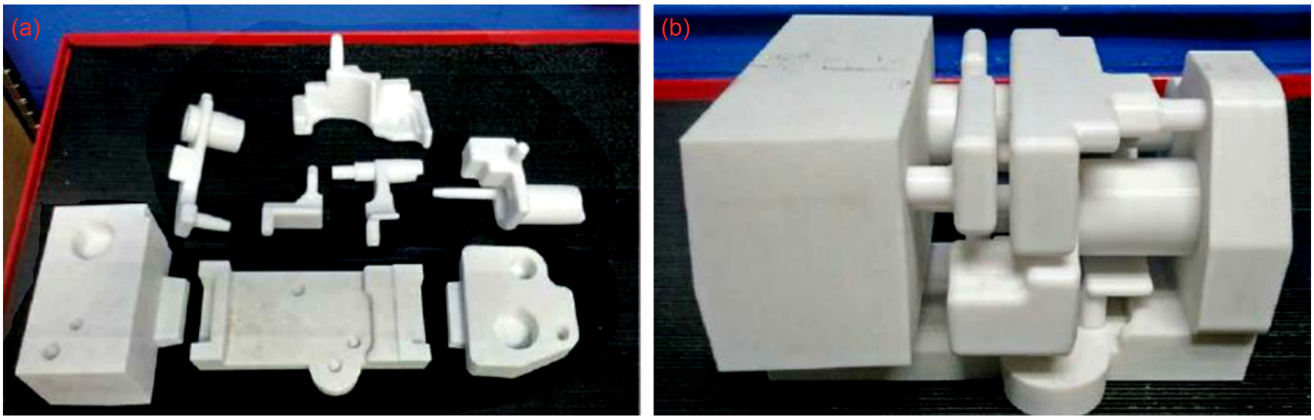
**Fig. 3: 3D metal direct printing with optimized structure**



(a) Original shape (b) Improved (c) Optimized

**Fig. 4: Optimization of a part facing to 3D printing method [75]**

the integrated shape and dimensions is guaranteed, and the parts can be more accurate in size. Multiple cores in no-bake or cold box systems were printed in a single piece with a 3D printer with reduced stacking tolerances and improved dimensional accuracy, such as a single core converted from traditionally eight different cores for a train's airbrake [77], as shown in Fig.5. Wu et al. [78] use the 3D printing of ceramic materials to make a single piece of ceramic shell and core to replace the assembly of shell and several pieces of cores which were susceptible to mismatch or displacement when shaking. The integration of shell and core greatly improved the soundness of castings and reduced scrap rate. For 3D printing methods, a design engineer has more freedom in designing castings and does not have to consider limitations such as drafts and undercuts, and a vent can be easily placed at the very spot of possible air entrapment.




(a) Original cold box core for airbrake included eight different sections (b) Core was reduced to a single piece after conversion to 3D printing method

**Fig. 5: Integration of cores into a single piece for an airbrake casting [77]**

## 3.2 Understanding the mechanism

The reaction involved in the melting of the laser and metal powders, and the solidification of metal powder is of great importance for the control of the final microstructure and final mechanical properties. The heat transfer, stress evolution, void formation and cracking still remain unsolved to researchers.

## 3.3 Uniform microstructure and composition

Currently, it is difficult to make large or heavy products with 3D printing due to limits in cost and equipment. In future, there will be large equipment and methods to produce large products to supplement heavy castings and forgings. In heavy ingots, there are severe macro-segregation problems. By 3D printing, each layer has the same composition so as to avoid macro-segregation and achieve uniform forging and performance properties in duty.

## 3.4 Special materials and special conditions

3D printing can fill the gaps in the casting of alloys difficult to cast, such as titanium, which has a high melting point. Casting requires the melt to have good fluidability, a narrow solidification zone, and less thermal expansion (or shrinking). Usually, pure metals and alloys with eutectic or close to eutectic structure are used for casting, which limits the selection of alloys, skipping most of alloys. And, filling is not so easy for light alloys because of their low density. So, 3D printing is possible applied in these areas.

In future, 3D printing will find more and more unique application conditions. For example, 3D printers are brought to ships, space station, asteroids such as Mars, etc. to prepare spare parts for repair and maintenance. It may be possible for the military to print replacement parts on the battlefield instead of relying on limited spares or the supply chain. There continues to be an overwhelming need for new materials development and validation of existing materials for fabricating quality parts.

## 3.5 Energy, efficiency and cost

Currently, 3D printing is high energy consumptive, and includes the preparation of powder and the following sintering process. High energy intensity is also a pursuing goal so as to melt the hard working materials such as TC4, Inconel718, etc.

The cost of 3D printing is high, it usually counts in grams for nylon, plastic, and in kilograms for metal powder and sand, while for traditional manufacturing methods, it is calculated in tons. So, cost is one of the bottlenecks for the wide application of 3D printing. Once the price of the printing machinery decreases and productivity increases, the cost of the process will decrease. As machinery and materials patents expire over the next few years, competition will increase and product prices will fall as well.

The efficiency of 3D printing has been increased greatly by increasing the movement speed of laser beam or by integrating more spraying nozzles. Another efficiency factor is by new method, for example, 3DP is several times faster than SLS method. Meanwhile, the printer can work a long time without interruption without operators' attendance. That counterbalances some of its efficiency problems. Now the efficiency is roughly in the order of liters per hour.

## 4 Limitation of 3D printing

Additive manufacturing, or 3D printing, is such a magical method that is anticipated to replace traditional manufacturing methods but there are definitely limitations of 3D printing. The stepped contour reduces the roundness of circular features, which cannot be entirely eliminated by decreasing the layer thickness. The most serious limitation is the same as that involved in traditional manufacturing methods: taking out of the unwanted materials such as support materials from cavities, specifically, long and narrow or closed cavities, such as a hollow ball. In fact, the 3D printing method does not hold intrinsic advantage over traditional manufacturing methods. Sacrificial structures must be used to support and hold overhanging features during 3D printing and they will be removed after the build [57,79-80]. Even the cleaning of loose powder does not seem always easy from deep and narrow passages. It may be misunderstood that it is not necessary to use support for laser sintering powdered bed, but the truth is that during the transportation after cleaning, the sintered parts may need support, so some supports have to be made during 3D printing. An example is shown in Fig. 6. Therefore, the design of supports and ribs, and the cleaning of unwanted materials and loose powders needs to be considered at the beginning of 3D printing. Stratasys' direct manufacturing has given some rules on how to optimize the design of metal parts so as to realize self supports or to realize no access features without trapped supports [81]. But, the technical design for cleaning has not yet been profoundly considered and relative software should be in urgent need in the future.

## 5 Summary

3D printing technologies have evolved from rapid prototyping to rapid tooling, rapid manufacturing and rapid casting. They can be used to directly print some specific castings; however, mostly they are adopted to make sacrificial patterns and ceramic shells for investment casting, sand cores and moulds for sand casting.

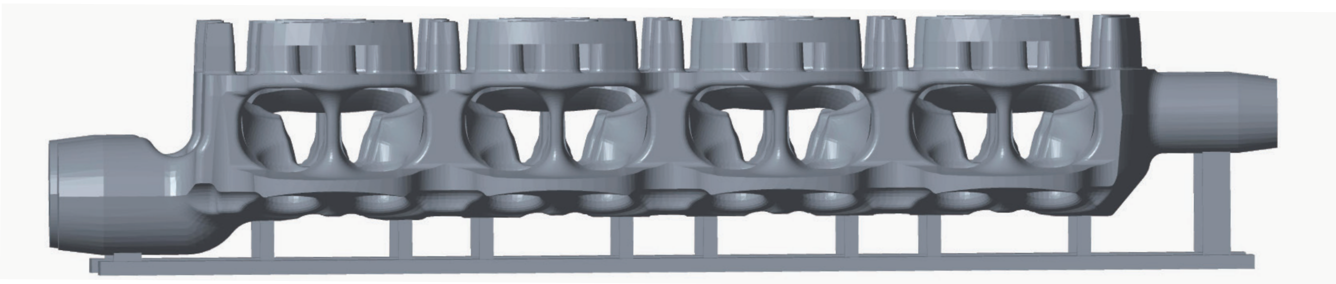


**Fig. 6: A water passage core for a cylinder head with supports [57]**

The layer by layer manufacturing method provides much more freedom for designers as well as high efficiency and lower cost. Some traditional casting designs such as draft and parting line are not necessary, but new designs, such as supports and ribs, have to be considered. The most important thing is that the layer by layer additive manufacturing methods will revolutionize the design of castings, patterns, cores and moulds. The net or lattice like structure, shell supported by truss structure will replace the solid wall structure. 3D printing can also realize the integration of traditionally separated parts and items, finally leading to the saving of material, time, cost and weight. It is possible to achieve high dimension accuracy of castings and smart manufacturing by placing sensors for positive monitoring and control of the mould of a truss structure. It is difficult for 3D printing to replace traditional casting production methods, but it will definitely revolutionize the casting industry.

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