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An overview of direct metal laser sintering (DMLS) technology for metal 3D printing

Additive manufacturing is the process of building a component or a product layer-by-layer, as opposed to casting the component and then performing various subtractive machining processes like turning, drilling, milling which are the approach of subtractive manufacturing. The term 3D printing refers to the family of additive manufacturing processes, which utilize different mechanisms in order to build the product from a sliced computer aided design (CAD) model fed to the machine. direct metal laser sintering (DMLS) is the one method of 3D printing functional metal parts are suitable for engineering applications and has the potential to provide a viable alternative to conventional methods of manufacturing and produce superior quality components with great flexibility in design using a wide range of materials. This paper presents the overview of DMLS technology, process parameters, design considerations, case studies of parts manufactured by DMLS and its applications in metal casting and rapid tooling.

Keywords: Additive manufacturing; direct metal laser sintering; metal 3D printing.

1.0 Introduction

Direct metal laser sintering (DMLS) is an additive manufacturing technique; used to 3D print metal parts with powdered metal or alloys being the raw material. It belongs to the family of laser powder bed fusion technologies; which involve a precise high wattage laser selectively sintering the powdered metal such that the particles melt and fuse together to give rise to the final product based on the computer aided design (CAD) model. Fully functional complex parts that cannot be manufactured using conventional methods can be obtained using DMLS with high accuracy, superior properties and faster turnaround times in manufacturing [3].

Fig.1 shows the schematic layout of a typical DMLS machine which consists of :

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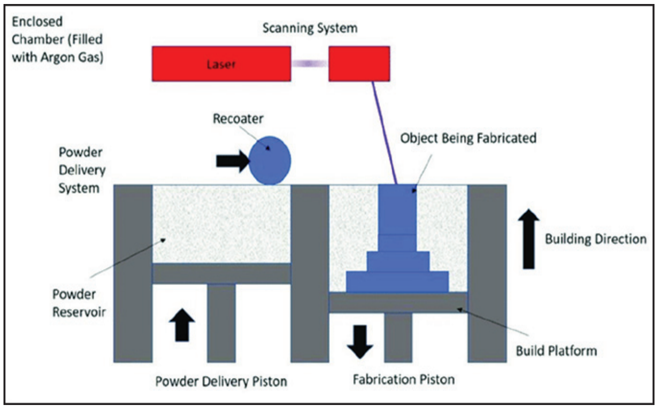

Fig.1: DMLS process

- Powder delivery piston, which holds the unsintered powdered material.
- Recoater, which rolls the powder from the powder delivery piston to the build piston.
- Build piston, where the product is built.
- The laser and scanning system, which places the laser beams at select points of the powdered material which was rolled from the delivery piston onto the build piston. This information is obtained based on the sliced CAD model that is fed into the machine.
- Inert atmosphere, usually argon gas.
- Space heating elements, to main uniform temperature distribution throughout the bulk of the powder.

Fig.2 illustrates the 3D printing process using DMLS. It begins with the delivery piston moving upwards by a distance equal to the layer thickness required. The recoater then rolls powder from a delivery piston to build piston. The laser scanning system takes in data from sliced CAD model and sinters powder in the build piston at select points in 2 dimensions; which causes the particles at those points to melt and fuse. Build piston then moves by a distance equal to the layer thickness and delivery piston moves up and process is repeated. This keeps adding the third dimension and printed model is obtained inside the block of unsintered or partly sintered powder which holds the model. This block of powder is removed and final part is obtained after cleaning [12].

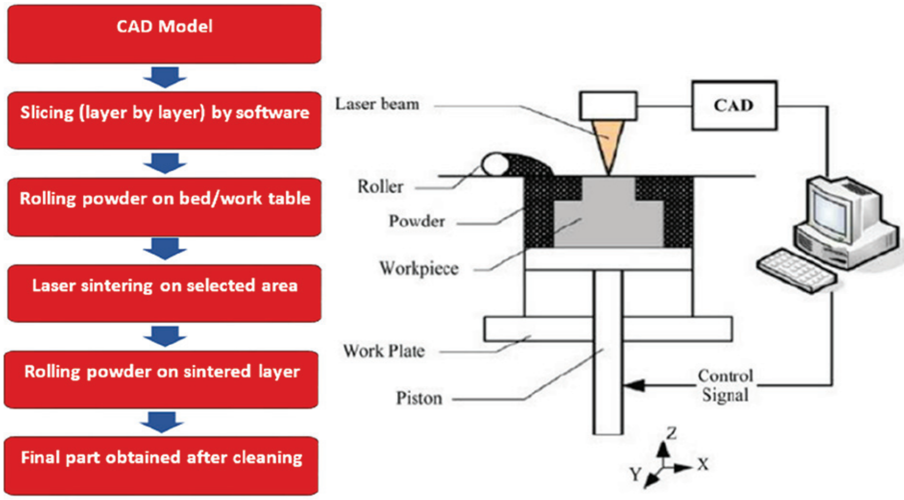

Fig.2: DMLS process

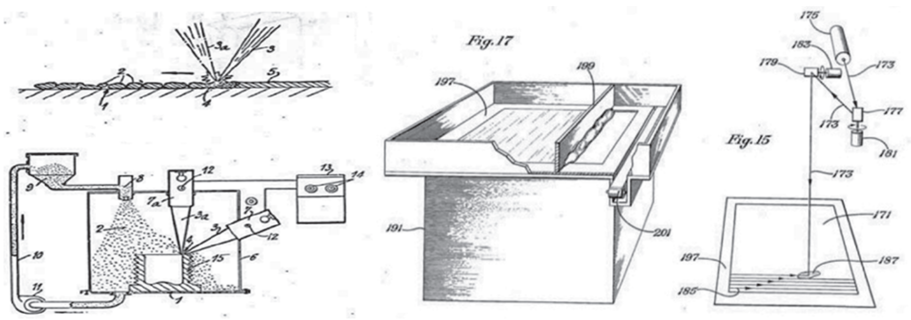

Fig.3: Pierre Ciraud's patent [7]

2.0 History of DMLS

The idea of additive manufacturing is not new. Back in 1971 a patent application for a manufacturing process that applies powdered material onto a substrate and solidifies it by an energy beam was filed by a Frenchman named Pierre Ciraud. Ciraud's patent (Fig.3.) was the first stepping stone towards the present age of additive manufacturing, but the technology was not ready to be commercialised [13].

Ross Householder filed a patent that uses scanning mirrors and resembles the current commercial laser-sintering systems. The objective of invention was "to provide a new and unique molding process for forming three-dimensional articles in layers and which process may be controlled by modern technology such as computers", but this invention had its limitations as lasers were expensive at the time. Householder's invention remained unfamiliar until it was revealed by DTM Corporation [10].

In mid-1980s the first step towards commercial additive manufacturing methods were taken, which includes powder-based additive manufacturing processes too. The first company to commercialize was called "3D systems" and it was founded by Chuck Hull. Hull filed multiple patents but none of them implicitly mentioned powder based fabrication [11]. Hull's patent described the working method to manufacture an object layer by layer and his company sparked interest in many others and this let to development by others. 3D systems build up a portfolio that cover most of today's additive manufacturing fundamentals; such as model preparation with STL files, slicing, hatching patterns, etc. Later in 1997, 3D systems was acquired by EOS systems.

In 1986, Carl Deckard, a PG Scholar at the University of Texas was investigating powder based manufacturing similar to Hull's method. He initially called this "Part generation by Layerwise Selective Sintering (PGLSS)", but later changed the name to "Selective Laser Sintering (SLS)". Deckard filed his patent in 1986 which narrated "computer aided laser apparatus which sequentially sinters a plurality of powder layers to build the desired part in a layer-by-layer fashion" [2].

The rise of laser-sintering

First commercial laser sintering machine – Sinterstation 2000 was introduced by DTM Corporation of Austin, Texas. Sinterstation was researched and developed by University of Texas but DTM took up the process of commercialization. EOS launched the second commercial laser sintering machine called EOSINT (P) 350.

DMLS gained popularity after the introduction of EOSINT M 250. In 1997, powder allowed a layer thickness of 50µm, but 2 years later a steel powder called direct steel 50, which allowed for the same layer height but high strength and durable parts were printed [14]. In 2001, with the introduction of direct steel 20, a major step in part quality was introduced which gave a layer height of 20µm. Recently, a tool steel material called direct steel H20 was introduced which produces parts with an ultimate tensile strength of 1,100 MPa and a Rockwell C hardness of 42 directly from the DMLS process[7].

For a long time DMLS systems used either CO_2 or Nd:YAG lasers, which were commonly used for laser cutting and welding. With the improvement in material quality, the laser had to be upgraded to meet the quality requirements. Hence, new types of lasers which offer better beam quality were being offered, fibre lasers and disc lasers to name a few. EOS adapted this and their EOSINT M270 uses a 200 Watt Ytterbium fibre laser, while Trumaform LF 250 used Disc laser [1].

TABLE 1: KEY FEATURES OF THE SINTERSTATION AND EOSINT (P) 350 LASER-SINTERING SYSTEMS

Feature	Sinterstation 2000	EOSINT (P) 350
Laser	CO_2, 50 Watt	CO_2, 50 Watt
Build volume	305mm × 410 mm = 30 litres	350mm×350mm×60mm = 73.5 litres
Powder dispensing	From below	From ablve
Layer application method	Counter-rotating roller	Vibrating channel
Scanning method	Raster	Vector
Part removal	From above	From below
Early materials	Wax; polycarbonate	Polystyrene; nylon mixture

3.0 Process parameters of DMLS

Process parameters are very important to control in order to obtain best quality of print as they control sintering quality in the process, which has a direct relation to the final print quality. Properties of the printed part like dimensional accuracy, mechanical strength, surface roughness, print time, and cost are evaluated to gauge quality of the print.

Process parameters which determine the quality of the print are listed as follows [3]:

(1) Part orientation

The normal direction to the sliced layers of the part plays an important role in determining its properties and is referred to as part orientation.

(2) Scan path pattern

The path followed by the laser for scanning determines the final sintering quality. The most widely used scan path patterns are the contour and parallel path patterns. A contour path pattern (Fig.4(a).) is that which the path follows the contour of the layer parallel with offset values. The parallel path pattern comprises parallel lines in a determined direction, as shown in Fig.4 (b)

(3) Hatch space

It is a distance between two consecutive hatch lines and determines the beam overlap area of continually sintering hatch lines that is related to the energy distribution [15].

(4) Offset and scaling

The focused laser beam raises the temperature of the powder at select points to its melting point and the material fuses together to build the part layer by layer. However, shrinkage occurs when the heated up powder cools down, thus leading to the material violating the determined dimensions. Additionally, the laser beam which has some diameter causes the material to fuse outside the determined dimensions. In order to compensate for the inaccuracy due to shrinkage the sliced files must be scaled and to compensate for the laser beam diameter, offsetting is necessary. So far, some different offset methods have been adopted such as dihedral offset, normal offset and constant offset. The dihedral offset has been used in the system because the dihedral offset method is more precise than the others (Beaman, 1997) [3].

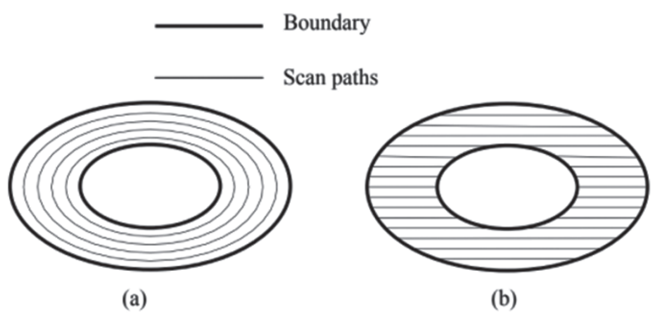

Fig.4: (a) Contour path pattern (b) Parallel path patterns [3].

(5) Layer thickness

Layer thickness is a parameter that controls multiple properties. It is inversely proportional to the total print time and surface quality. The strength of the part depends on its porosity which is in-turn inversely related to layer thickness.

(6) Scan speed and the laser power

The scan speed and laser power are properties between which a trade-off has to be made to obtain the optimum setting; which is decided based on the laser system and powder material properties. For metallic powder, the laser power needed to melt is higher than polymer powders used in the case of SLS and hence higher laser power and lower scan speed is used which ensures higher part strength; because the amount of energy absorbed by the powder is higher [8].

4.0 Stress, temperature and distortion distribution in DMLS printed parts

In SLM process, residual stresses are caused due to the heating cycle as the laser scans across each layer to solidify

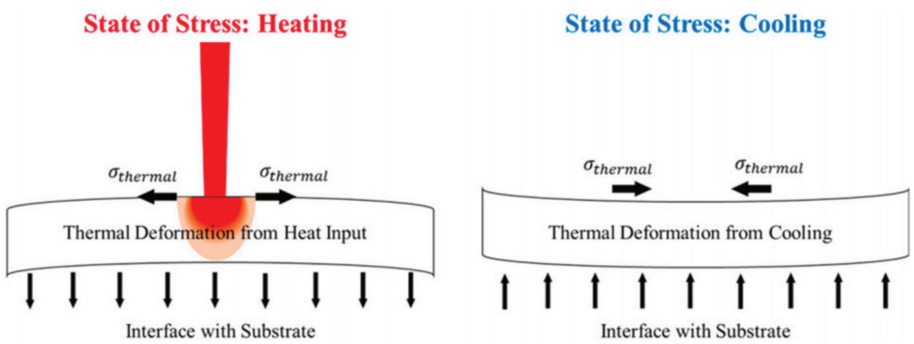

Fig.5: Stress gradient in single layer

a 2D section of a part [16]. The two main regions affecting residual stress are; top layer that is exposed to the laser and interface between the top layer and previous layer (Fig.5).

During scanning due to heat from the laser; top surface experiences tensile stresses while the bottom surface experiences compressive stress due to cooling from the previous layer. This would not be a problem of only one layer was printed, as the stress would dissipate naturally [4]. The stresses increase exponentially as the lower layers restrict the thermal expansion/contraction of the layers below the top surface. This leads to compressive strain and in the layers which induces stress gradients in the entire part.

FEA MODEL OF THERMAL DEFORMATION DURING LASER SCANNING

Patterson et al.[17] prepared an FEA model depicting thermal deformation during laser scanning during DMLS. The assumed material thickness for the analysis is six layers, with each layer being 8.5µm. The material is 316 stainless steel, and it was heated with a 200W laser an ambient temperature of 24 ÚC. No new material was added, hence this analysis only shows the material under laser load [17].

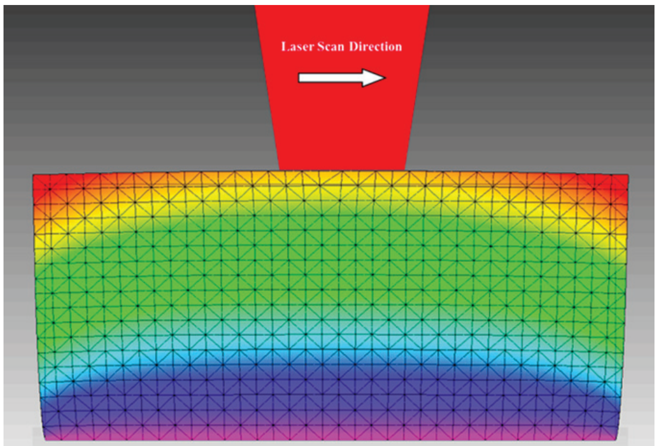

Fig.6: Stress between layers [17]

5.0 Case study – surface roughness of DMLS parts

DMLS has many benefits over conventional manufacturing methods which range from shorter lead time, to the ability manufacture complex geometries. Every manufacturing process comes with a con and with DMLS the major limitation is its surface finish. DMLS has comparatively better surface finish when compared to electron beam melting (EBM) and direct metal deposition (DMD), but it is not up to the mark when compared to conventional manufacturing techniques. The main factor affecting surface finish is the stair-stepping effect that produces in any additive manufacturing process [6].

TABLE 2: COMPOSITION OF IN625 POWDER MATERIAL [EOS MATERIAL DATASHEET FOR NICKEL ALLOY IN625

Element	Composition	Element	Composion
Ni	20-23%	Al	< 0.4%
Cr	20-23%	CO	< 0.1%
Mo	8-10%	C	< 0.1%
Nb	3.1-4.1%	Ta	< 0.05%
Fe	< 5%	Si, Mn	< 0.5%
Ti	< 0.4%	P,S	< 0.01%

Two methods are commonly used to improve surface quality in DMLS.

1. The print variables such as layer thickness, build directions, scan direction and speed or other process parameters can be evaluated to find the most optimum ones.
2. The prints can be post processed just like any other part which will significantly improve the surface quality.

Both actions will increase cost due to machine time and labour.

POYRAZ et al. [6] designed a test artefact (Fig.7) with minimum constant section and multiple surface patches with different radius values. The radius began from 0.5mm and reached a max of 10mm with a 0.5mm increment between the patches.

The model was printed on an EOS M290 DMLS system with a YAG fibre laser with a wavelength on 1064nm. The material selected was EOS nickel alloy IN625 which is widely used in the aerospace industry. Table 2 shows the chemical composition for the employed material.

The surface characteristics was measured using Mitutoyo SJ-400 device per ISO 4287:1997. During set up conditions, Gauss filter was applied for roughness and waviness. Table 3 shows set up conditions.

Due to set up limitations the smallest possible radius value less than 4mm could not be measured. Table 4 shows the surface quality measurement on radii.

Further a non-contact method was carried out using Mitutoyo CV-3200H4 Tracer.

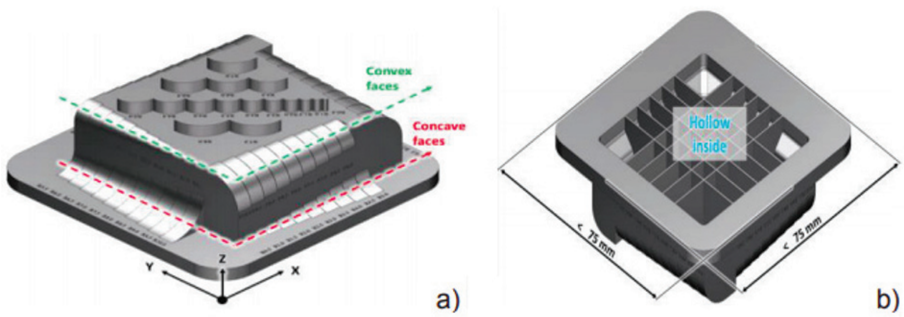

Fig.7: Test artefact (a) from top, (b) from bottom

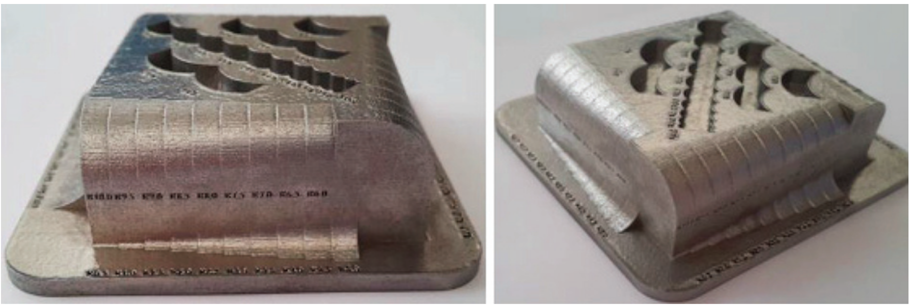

Fig.8: Manufactured artefact from different viewpoints

result was due to on error with reaching problems when the use of contact probe on the middle of radius faces gave a short evaluation length of 1.25mm.

With the non-contact method (Fig 9.) there is drastic change in the surface quality of different radius and different regions in one radius.

Table 3: Set-up conditions for surface quality measurement on radii

	Primary profile(P)	Waviness (W)	Roughness (R)
Sampling length	0.25 mm	0.25mm	0.25 mm
Evaluation length	1.25 mm	1.25 mm	1.25 mm
λs	2.5 µm	-	0.25 µm
λc	-	0.08 mm	0.25 mm
λf	-	0.25 mm	-
Filtering	None	Gauss	Gauss

6.0 Results and discussion

In the results obtained by POYRAZ et al. [6] the contact type device showed no change in roughness or waviness. The

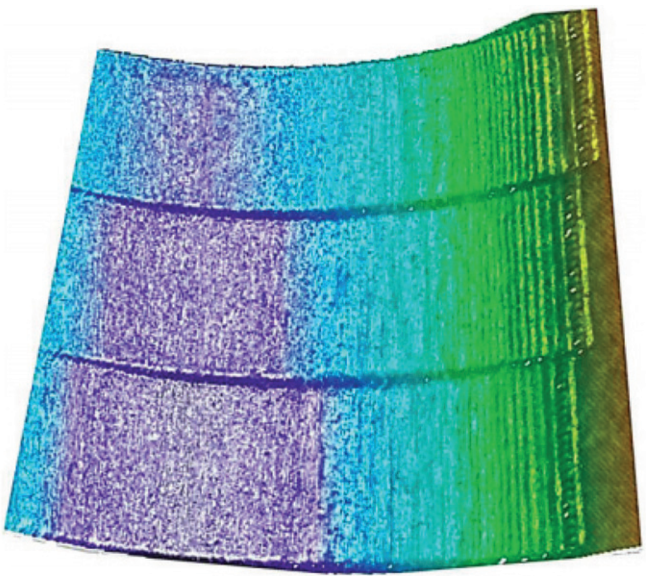

Fig.9: Surface measurement results with non-contact method

7.0 Applications of DMLS in rapid tooling

Rapid tooling refers to a set of practices, which combines rapid prototyping and tooling techniques to either create the part directly or to make the mould for a casting process. Presently, DMLS is implemented in rapid tooling in the following ways [1]:

1. Direct tooling

This refers to the direct use of a 3D printed part in tooling.

2. Indirect tooling

This refers to the use of a 3D printed part to produce actual tooling.

3. Tool-less processes

In these processes, 3D printing is used to create moulds, cores, patterns for casting without the use of any type of tooling [9].

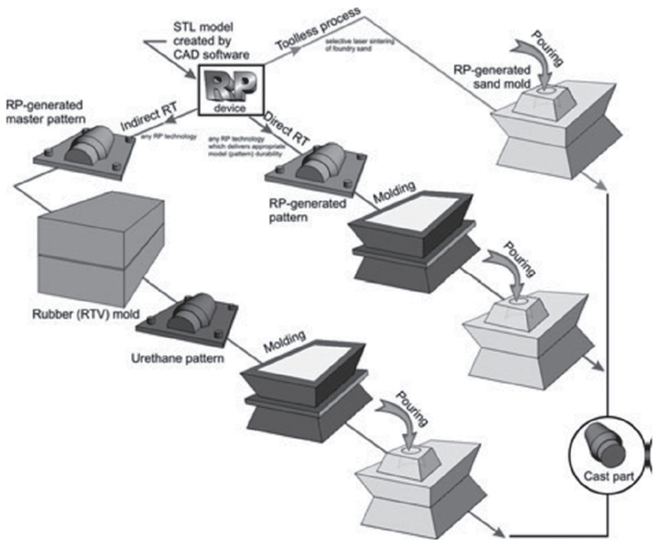

Fig 10: Rapid tooling in sand casting

Table 4: Average results of surface quality measurements

	Convex				Concave									
Radius (mm)	5.5	5.0	4.5	4.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	1.0
Ra (µm)	3.73	3.23	3.81	2.89	3.09	3.63	3.52	2.74	3.57	2.57	3.14	3.07	3.17	3.10
Wa (µm)	3.27	2.72	3.22	2.42	2.60	2.90	3.04	2.11	3.11	2.10	2.49	2.24	2.42	2.48
Pa (µm)	4.50	3.75	4.20	3.90	6.23	5.76	5.62	4.08	5.81	3.63	3.83	3.38	4.12	3.69

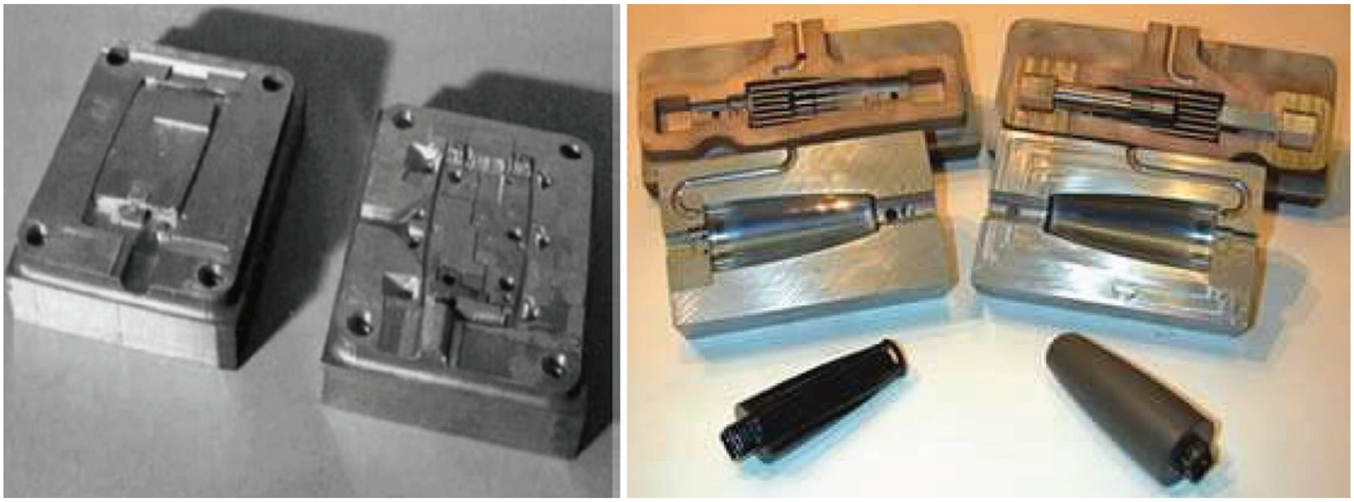

Fig 11: Tooling inserts by rapid tooling

In sand casting, rapid tooling is one of the major processes used to manufacture cast parts. Major requirements for sand casting tooling are:

- Highly accurate patterns and core boxes are produced using rapid tooling;
- Patterns must be made of a material which provides wear resistance, dimensional accuracy, and durability.

In investment casting, rapid tooling is used to make moulds of metal, usually aluminium in case of high production applications. This tooling is basically for reusable mould for lost pattern pouring in investment casting.

In permanent mould casting process, reusable permanent moulds and cores are made of a metal (cores may also be made from sand; referred to as disposable cores). Since metallic moulds and cores are reusable, they are the immediate tooling (direct tooling) in permanent mould casting. DMLS technologies may be utilized in the process of permanent mould making as direct or indirect implements.

Fig.11 shows tool inserts produced using a combination of DMLS and traditional tooling.

7.0 Conclusions

3D printing has made huge strides in the technological scene, especially in the last 5 years with companies actively looking for rapid prototyping solutions over traditional methods of manufacturing due to the flexibility that it offers in design leading to the development of innovative products. Although technologies like fused deposition modelling (FDM) continue to be the most popular, they are limited to products made of polymer-based materials and usually for DIY products. DMLS has proved to be very effective in producing fully functional metal parts having a superior mechanical property which has huge scope for industrial applications. The challenges lie in increasing the choice of materials compatible to be printed using DMLS as well as ensuring good mechanical properties. Additionally the challenge also lies with 3D printer manufacturers to make DMLS printers accessible and economical for not just for the manufacturing industry but also for medium, small and micro enterprises who can utilize it for in-house manufacturing and rapid prototyping, thus making huge strides in becoming more and more self-reliant.

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