SELECTIVE LASER SINTERING PROCESS –A REVIEW

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Abstract-Additive manufacturing technology is one of the rapidly growing areas of research and development since it has tremendous potential to replace some of the existing conventional manufacturing processes. Additive manufacturing is a way of manufacturing parts of building layer-by-layer thus fabricating three-dimensional physical models directly from a computer-aided design (CAD) model. The Additive manufacturing method can produce fully dense metal parts in a short time, with higher precision. Selective Laser Sintering (SLS) technique uses powder bed fusion, in which each powder bed layer is selectively fused by using a laser or electron beam, as an energy source. It is the most promising additive manufacturing technology that can be used for manufacturing smaller and medium volume, simpler or complex metal parts. This review presents evolution, current status and challenges of the SLS Technique. The article presented emphasises on metal material processed by SLS technique. It also talks about the SLS Technique in terms of advantages/disadvantages, materials, machines and applications.

Keywords- Additive Manufacturing, Aerospace Materials, Direct Metal laser sintering (DMLS) Rapid prototyping, SLS.

I. INTRODUCTION

Additive manufacturing processes have been developed over the past 10-15 years to shorten the product development time [1]. All the techniques are based on the principle of creating three-dimensional components directly using computer aided design (CAD) producing layer-by-layer technique without using moulds or tools as used in conventional manufacturing processes [2-4]. There are a variety of layer manufacturing techniques available today, especially for metal prototyping techniques SLS, inkjet 3D printing (3DP) technique, Selective Laser Melting (SLM), etc., are in use [5].

Laser-Sintering, which means, methods that helps in the manufacturing of solid parts by solidifying powder like materials layer-by-layer, exposing the surface of a powder bed with a laser or other high energy beam. The laser sintering process is characterised by extreme rapid sintering and solidification. The area of interest in this paper is all about SLS. The SLS technique has a great future potential for the rapid manufacturing of metal components that could be utilized in a variety of applications. SLS machines, such as, Direct Metal Laser Sintering (DMLS) uses single component metal powders. Powders are usually produced by ball milling technique and by other methods such as fluidized beds, blades, brushes, etc. The SLS process was originally developed at the University of Texas at Austin and then commercialized by the DTM Corporation (U.S.) [5]. The schematic diagram of SLS system is as shown in the Fig.1. The SLS uses a laser beam as an energy source to selectively fuse powdered materials into a solid object.

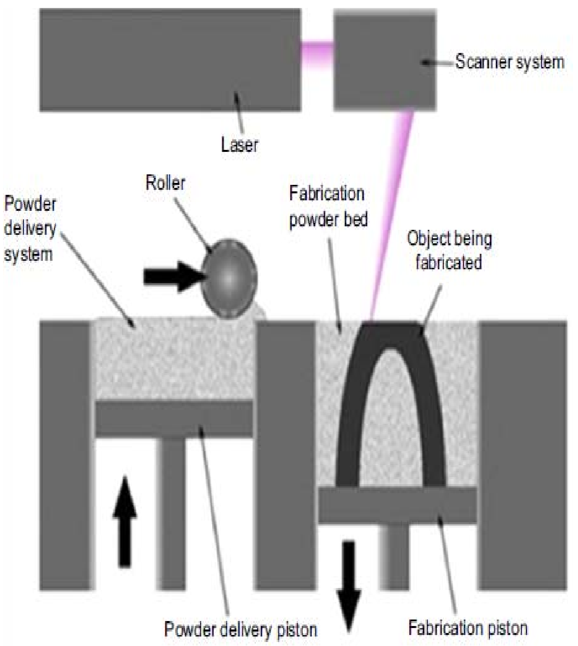

Figure 1. Schematic of the laser sintering process [6].

The process that is carried out in laser sintering techniques is that, the designer designs a part, next the part is sliced on the horizontal plane by using the required software. A chamber in the production machine is filled with powder. A laser runs over the powder, solidifying it and building up a thin layer of material. Layer after layer is built up from bottom to top, until the part is finished. The leftover powder is re-usable, leaving no waste.

The term SLS is used often to describe a number of laser-forming processes. SLS is sometime distinguished from SLM because of the difference between the two solidification methods in terms of bonding mechanisms, laser-melting related to fully melting the powdered material to its liquid phase, which results in a fully-dense part, whereas laser-sintering relates to liquefying only the surface of the powder particles for bonding the particles to each other. In terms of terminology, laser-sintering and laser-melting are often used somewhat mutually [7].

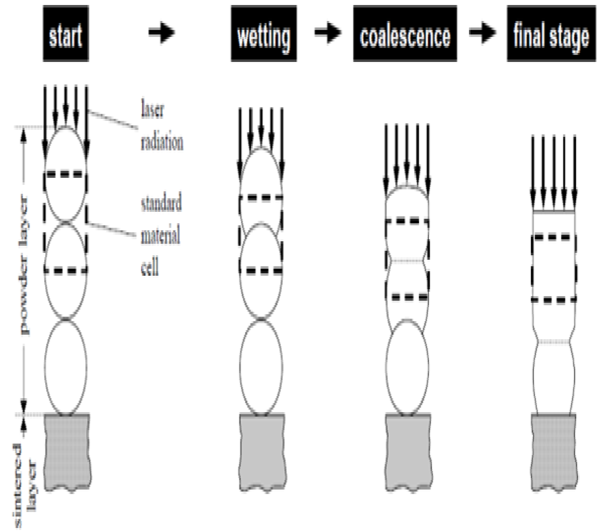

Figure 2 : Model of the standard material cell

Fig. 2 indicates the process that is going to take place when the powder is being sintered. Initially at the starting stage where the powders are arranged one above the other and through the laser activity powder starts to wet, then coalescence and finally bond to form a single part. SLS and DMLS are essentially the same thing, with SLS used to refer to the process as applied to a variety of materials—plastics, glass, ceramics—whereas DMLS refers to the process as applied to metal alloys.

The method of production of laser sintered parts depends on (a) laser sintering (b) hatch pattern (c) post processing (d) material type and the machine used for fabricating of the parts. The following sections provide an understanding of the above listed points.

1.1. Pre-processing

The deposition of powders and the mechanism of sintering depend totally on (a) the density of the powder, (b) the shape and size, (c) the flow rate. For better sintering of powdered metal layers, the density should increase. Ordinary particles produce porous layers of high density, appropriate size and appropriate composition. This can be achieved by optimizing the particle shape and surface, prior to optimizing the performance and the SLS process, the powder sintering ability must be improved by selecting proper process parameters viz., material, laser, and scan environmental parameters. Table 1 describes about the process parameters that are important from the SLS point of view. Sometimes the material and laser parameters are varied for the reason that they are machine dependent [8].

Table 1: Process parameters of SLS divided into, material, laser, scan and Environmental parameters.

Material	Laser	Scan	Environment
Composition	Mode	Scan speed	Preheating
Powder density	Wave length	Hatching space	Pressure
Morphology	Power	Layer thickness	Gas type
Diameter of grains	Frequency	Scan strategy	O_2 level
Distribution	Pulse width	Scan sectors	
Thermal properties	Offset	Pulse distance	
Flow properties	Spot size	Scaling factors	

1.2 Hatch pattern

For building part layer by layer choice for selecting a path for laser movement lies in the selection of the hatch pattern, the default value of the hatch pattern in the DMLS EOS machine is direction of scanning rotated of 67° between consecutive layers as shown in fig e. There are four choices for hatch pattern selection and they are along x, y, both in x-y or alternating in x-y as shown in Fig. 3. Fig 3a shows the scanning done along the x axis and Fig. 3b indicates scanning done along y. If both x and y options are selected then there will be double exposure on the layer, once along x and then along y as shown in (Fig. 3c). In alternating in x-y choice, direction of scanning is changed for alternating layers (Fig. 3d) [9].

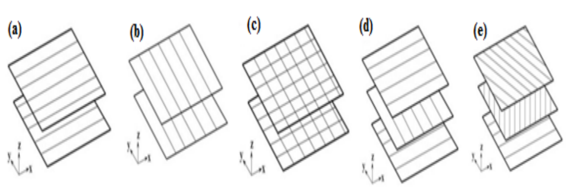

Figure 3. Different hatch patterns or scanning strategies [9].

1.3 Post Processing (Hybrid Direct Laser Fabrication)

Some of the direct laser fabrication processes like DLF, LENS, and DMD, where the objective is to fuse the powder to full density across each layer. SLS can produce complex shaped metal components with a part density exceeding 92 percent of the theoretical density. This is the fractional density at which porosity typically changes from interconnected or surface-connected to closed. The powder in the interior of each layer cross-section can be optionally laser sintered to an intermediate density typically exceeding 80 percent of the theoretical density. The net-shaped part produced by SLS is directly post-processed by container-less hot isostatic pressing (HIP) to achieve full density. SLS / HIP is a compound direct laser fabrication method that combines the strengths of both processes. Use of the compound fabrication method, conceived as a rapid, low-cost replacement for conventional metal. The microstructure and mechanical properties of hybrid fabrication (SLS processed and hot isostatically pressed) post-processed material correlate well with those of conventionally processed material [10]. M2 high speed steel powders used in SLS are not agreeable to processing to full density. The maximum density achieved in multi-layer samples, using pulsed Nd: YAG processing was only 70% relative. Much lower densities were obtained using CW CO2 and CW Nd:YAG processing operating in the same continuous melting regimes [25-27]. The laser sintering process is characterised by extremely rapid sintering and solidification. Due to the layer wise building method, the parts have a certain anisotropy, which can be reduced or removed by appropriate heat treatments and other processes. Parts built in titanium Ti6Al4V fulfil the requirements of ASTM F1472 (Standard Specification for Wrought Titanium-6Aluminum-4Vanadium Alloy for Surgical Implant Applications) regarding maximum concentration of impurities which leads to the post processing operation to achieve good mechanical properties [10].

Currently there are two manufacturers of laser sintering systems: 3D Systems, Inc. and EOS GmbH. Table 2 highlights the types of SLS machines and the materials used for producing

SLS components. Fig. 4 indicates the use of SLS processed materials in various applications.

Table 2: SLS Machines [11, 12, 13, 14, 15]

TECHNICAL DATA	EOSINT M270	Sinterstation ® HiQ™ SLS®	Vanguard™ HS	Sinterstation 2500 plus
Building volume (including building platform)	250 x 250x 215mm	W381 x D330 x H457 mm	W355.6 x D304.8 x H431.8 mm	380 x 330 x 450 mm
Laser type	Continuous wave Nd:YAG fiber laser 200 W	50 watt CO_2 laser	25 or 100 Watt CO_2	50- or 100- Watt CO_2
Scan speed	up to 7.0 m/s	upto 10 m/sec	upto 10 m/sec	Scan speed of 5m/s.
Power supply / Power consumption	32 A ,5.5 kW	240 VAC 12.5 kVA, 50/60 Hz, 3-phase 380 VAC 12.5 kVA, 50/60 Hz, 3-phase	240 VAC, 12.5 kVA, 50/60 Hz, 3-phase	240 VAC, 12.5 KVA, 50/60 Hz, 3-phase
Materials	EOS Maraging Steel AlSi10Mg EOS Stainless Steel 17-4 EOS Cobalt Chrome EOS Titanium Ti64* Ti6Al4V	LaserForm TM A6	LaserForm ST-200 LaserForm ST- 100	Laser form (Stainless steel)

(a) (b) (c) (d)

Figure 4: Application examples a) Sieve in Stainless Steel GP1, b) tool core in Maraging Steel MS1, c) Knee implant in Cobalt Chrome MP1, d) Humeral mount in Titanium Ti64 [16]

1.4 Materials used in Laser sintering operation

1.4.1: SLS Polymer Materials

A material processed by SLS technique includes thermoplastics such as Nylon / Polyamide (PA), Polystyrene, Elastomers, and Composites.

New grades of nylon powders (i.e. Duraform PA12, Fine Polyamide, PA2200) even yield a resolution and surface roughness close to those of polycarbonate, making PA also suited for casting silicone rubber and epoxy moulds. Other polymer-based materials available commercially are acrylic styrene for investment casting and an elastomer for rubber-like applications [17]. Recently, Windform XT is introduced into the commercial market, which is based on a carbon-filled PA and produces black parts with a smooth finish and a sparkling appearance.

For SLS treatment just a handful of different formulas are provided so far and almost all of them are based on polyamide 12 (PA12). A brief overview over the presently most common PA12 types on the SLS market is given in Table I.

TABLE 3. Most common PA12 powders used in SLS technology [18]

Trade name	Supplier
DuraForm_ PA	3D-Systems
PA 2200/2201	EOS
Orgasol Invent Smooth	Arkema
DuraForm_ HST	3D-Systems
Duraform_ GF	3D-Systems
PA3200 GF	EOS
Alumide	EOS
CarboMide	EOS

1.4.2 SLS (DMLS): Metal Materials

Direct Metal Laser Sintering (DMLS) is an additive manufacturing process where aerospace and medical industries rely heavily upon it. DMLS is considered as an offshoot of SLS technique. Titanium, Inconel, stainless steel, cobalt chrome and aluminum are all metals that can be built up, layer by layer, with this 3D printing technology. According to the DMLS machine manufacturers, DMLS parts will be able to exhibit stronger mechanical properties than cast parts in the near future. Researchers have confirmed that when evaluating a part cut from a solid chunk of metal to a cast part, the cast part will always have less strength. But DMLS parts are typically only 5 – 10% less strong than cut metal, which means DMLS is consistently stronger than cast parts [19]. Some of the metal materials used by DMLS processing techniques have been high lightened in the ensuing sections. Interested readers may kindly go through the references (22-32) for details regarding physical and mechanical properties.

1) 316L steel
2) Laserform A6
3) LaserForm™ ST-100 Powder
4) LaserForm ST-200
5) 17-4 Stainless Steel
6) 15-5 Stainless Steel
7) Cobalt Chrome
8) Maraging Steel MS1
9) M2 high-speed steel
10) Inco 718 and 625
11) Aluminium Alloy AlSi10MG
12) Titanium Ti6AI4V / ELI

1) 316L steel

316L steel belongs to a type of stainless steel classified to the surgical use, among others for the purposes of implantation [20]. That steel has found application in the production of screws supporting a broken bone, bone plates, complete sets for prosthetic use, wires for dental prosthetics, as well as in the manufacture of all kinds of medical instruments [21]. Stainless steel is used for jewellery and watches with 316L being the type commonly used for such applications where it can be re-surfaced and will not oxidize or turn black, the lower carbon content in 316L minimizes injurious carbide precipitation as a result of welding. Consequently, 316L is used when welding is needed in order to ensure maximum corrosion resistance. 316L is the lower carbon version of 316 and is immune from sensitization; therefore, it is very often used with welded components [22]. Applications include: chemical processing, textiles, pharmaceutical industries, etc.

2) LaserForm A6

LaserForm A6 steel is tool steel used in SLS technique. Laserform A6 is polymer (binder) coated steel powder. During part building process the binder is sintered. The resulting part is exposed for a period of 24h, where the binder is burnt off and bronze is infiltrated into the part. As a result, the metal prototype with 80 % stainless and 20% bronze is obtained.

LaserForm A6 steel material can be processed by any one of the technique like machining, EDM processing, polishing, etching, texturing, etc. LaserForm A6 material is magnetic and can be fixtured using magnetic chucks. SLS with LaserForm A6 provides benefits in the rapid tooling / prototyping fields, where LaserForm A6 steel find its application in mould making. Nearly 20-40% faster molding cycles are achieved by using inserts produced with LaserForm A6 material by offering added productivity and capacity. Parts or tools produced from the SLS system can have a polished surface hardness as high as HRc = 20, or heat treated to HRc = 39 for added wear resistance. The surface can be coated for even higher surface hardness. With thermal conductivity almost twice that of most tool steels, LaserForm objects can be easily finished and polished with conventional machining methods [23].

3) Laser Form ST-100

Laser Form ST-100, Characteristics similar to C35 tool steel is a metal material developed exclusively for SLS systems, this material is excellent for creating functional, durable metal prototypes, and tooling inserts directly from CAD files, without any costly time-consuming casting, CNC programming or extensive machining. Tool inserts made with Laser Form ST-100 material are so reliable that they can mould over 100,000 plastic parts, depending on the moulding material. Laser Form ST-100 material's high thermal conductivity results in cycle times equal to production moulding and high comparability. It finds its application in durable prototype tooling inserts, bridge tooling, short runs of metal parts and prototypes Laser Form ST-100 inserts are also suitable for die casting aluminium, magnesium and zinc. It can also be used for developing prototypes with complex geometries and features [24].

4) Accura LaserForm ST-200

Accura LaserForm ST-200 material's characteristics are very similar to P20 steel. This steel is a specialty stainless steel composite developed for SLS systems to produce durable, fully dense metal parts and tooling inserts for injection moulding and die casting applications. LaserForm ST- 200 material is ideal for both prototype and production applications. Inserts produced with LaserForm ST-200 material have high thermal conductivity, thus it can be used in metal tooling, and nearly 20% to 40% reduction in cycle time can be achieved compared with traditional tooling. The material finds its use in high-temperature applications, short runs of metal parts and prototypes and metal tooling inserts for complex geometries and features. [25]

5) Stainless Steel 17-4

Stainless Steel 17-4 is a pre-alloyed stainless steel in fine powder form. The material is characterised by having a very good corrosion resistance and mechanical properties, especially admirable ductility, and is extensively used in a variety of engineering applications. Parts produced from EOS Stainless Steel 17-4 by laser-sintering can be welded, machined, micro shot-peened, polished and can even be coated if required. Unexposed powder can be reused. Stainless Steel 17-4 is ideal for many part-building applications such as functional metal prototypes, small series products, individualized products or spare parts [26].

6) Stainless Steel 15-5

Stainless steel 15-5 (stainless steel PH1) is a material suitable for manufacturing prototypes via the DMLS process; also it is a pre-alloyed stainless steel in fine powder form. Stainless steel PH1 is distinguished by having very good corrosion resistance and mechanical properties, specifically in the precipitation hardened state. This kind of steel is widely used in a variety of aerospace, medical, and other engineering applications requiring high hardness, strength and corrosion resistance [26].

7) Cobalt Chrome

Cobalt Chrome is a cobalt-chrome molybdenum-based super alloy powder which has been especially developed to fulfil the requirements of dental rebuilding which have to be coated with a dental ceramic material and has been optimized especially for processing on EOSINT M270 systems. Cobalt Chrome has excellent corrosion resistance and is more favoured for medical and dental prototypes [26].

8) Maraging Steel MS1

One of the materials suitable for manufacturing using the DMLS process is Maraging Steel. The material has excellent strength combined with high toughness. It is ideal for creating parts and exclusively inserts or cores used in various tooling applications, which reduce moulding cycle times by serving as an improved conformal cooling application. Parts made from Maraging Steel can be easily machined and can also be polished and post hardened to 54 HRC [26].

9) M2

M2 is molybdenum based high-speed steel in tungsten–molybdenum series. The carbides in it are short and uniformly distributed. It has high wear resistance. Due to its comparatively low carbon content, M2 has excellent strength combined with toughness properties and abrasion resistance when properly hardened and tempered. M2 finds its application in manufacturing a variety of tools, such as drill bits, taps and reamers. [27-29].

10) Aluminium AlSi10Mg:

Aluminium AlSi10Mg can build faster than other DMLS materials. While it has good thermal properties, strength and hardness, its speed has made it a favourite among lower cost prototypes. EOS AlSi10Mg is a typical casting alloy with good casting properties and is used for cast parts with thin walls and complicated geometry. Aluminium AlSi10Mg having alloy combination of silicon / magnesium results in a significant increase in the strength and hardness. It is used for parts which subject to high loads. Parts made of EOS Aluminium AlSi10Mg can be machined, welded, wire eroded and electrical discharge machined micro-blasted, polished and coated. [30].

11) DMLS Inconel 718 & 625:

DMLS Inconel 718 (IN718) is the newest of the materials suitable for manufacturing using the DMLS process. In 718 has realized users to think about rapid manufacturing as a production process. Machining IN718 is tough and nobody likes to do it, whereas, the DMLS process allows to produce Inconel parts quickly, while being affordable. This material is ideal for many high temperature applications industries like power and process industry gas turbine parts, instrumentation parts, etc. DMLS IN718 also possesses excellent cryogenic properties and potential for cryogenic applications. EOS nickel alloy IN718 parts can be easily post-hardened to 40-47 HRC (370-450HB) by precipitation-hardening heat treatments. Nickel alloy IN718 in both as-built and age hardened states the parts can be machined, welded, spark-eroded micro shot-peened, coated and polished if required. Inconel 625 is perfect for high temperature and high-strength applications. It has excellent corrosion resistance in various corrosive environments, and has high tensile, creep and rupture strength. Typical applications includes: Aero and land based turbine engine parts, rocket and space components, chemical and process industry parts, oil well, petroleum and natural gas industry parts [30].

12) DMLS Titanium Alloy (Ti6Al4V):

Presently, most of the titanium based aerospace components are machined from solid stock, often cutting away 90% or more of the original material. As investment casting of titanium is difficult this becomes a time consuming and often has a high scrap rate, which leads to costly operation. This is completely eliminated with DMLS titanium, by using DMLS technique material wastage is reduced, also in relation with traditional processes shows a sign of rapid manufacturing [30]. Parts made by DMLS technique can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required [31]. Applications include: Direct manufacturing of functional prototypes, production of corrosion resistant parts, biomedical implants, etc.

2. Extended Applications of SLS process

Brief discussion on applications of SLS and DMLS processes in various sectors has been discussed in the previous section. The following section will help in having in-depth knowledge on the use of DMLS products and the materials that have been used in their fabrication. The SLS and DMLS have made an impression especially in the areas of, consumer products, automotive, aerospace, athletic footwear equipment, and motor sport industries and many more.

Among the most popular for medical and aerospace applications is the titanium alloy Ti-6Al-4V. The use of the investment casting process with the SLS process to quickly produce wax patterns allows for the rapid prototyping of parts which would normally take months to produce. In the transportation industry, wax patterns are utilized to quickly produce functional metal prototypes for use on the engine or drive train. These pieces would be about time consuming to prototype via traditional methods. In medical prosthetics industry, custom made prosthetic implants can be quickly made in investment casting wax from CAT scan data then cast in the alloy of choice [33].

SLS find its application in the field of bioengineering for the fabrication of tissue engineering scaffolds, drug delivery devices, and bone models. SLS is used to make models of skulls by using data from MRI and CT scans in developing accurate models of a certain person's anatomy, and also used in neuro-networks for neuro-surgeons to practice on, where it has been proven that models generated with SLS has higher dimensional accuracy than models generated with other 3-D printing methods such as PolyJet technique [34]. SLS allows the fabrication of devices such as ankle-foot orthoses, to progress the motion performance of people with impaired lower limb function"[35]. SLS is also a popular method for 3D printing customized products, such as hearing aids, dental retainers and prosthetics. Ti-based alloys are widely used for manufacturing orthopaedic and dental devices under load-bearing applications [36]. One of the major applications of laser sintering is the replacement of worn or damaged joints to restore lost structure and functions of human bone. When compared with common alloys used as biomaterials, such as 316L stainless steel (190–210 GPa) and Co-Cr alloys (210–253 GPa) , low elastic modulus Ti-based alloys display a more compatible behaviour to human bone [37]. Direct laser metal sintering verified to be an efficient way for constructing dental implants with a functionally graded material. In recent years, SLS technique has been explored to fabricate tissue engineering scaffolds and porous implants consisted mainly of polymer/ceramic and composites biocompatible polymers [38-41].

Laser sintering finds its application for patterns for investment casting, metal moulds for injection moulding and die casting, and moulds and cores for sand casting [42].

3. Pros and cons of SLS process

3.1 Pros

SLS finds it uniqueness in manufacturing parts from materials like Titanium and Nylon which are otherwise difficult to manufacture using traditional methods. SLS process does not require any additional support materials as the powder itself does the work of support material [43].

3.2 Cons

Post processing of the part generated is a time consuming process and requires use of machining. Materials used for processing is limited. Still SLS metal parts find its limited application in industrial use. Aerospace grade aluminium and other metals are in development.

4. Conclusions

The SLS process is a viable time and money saving method for generating complex prototype parts in the plastics and metals industries based on the materials employed in the system. The benefits of using the system include: The ability to utilize a variety of materials and the future ability to expand the variety of materials which will work in the process. It would appear that DMLS is currently on a threshold between limited application in prototyping applications and a much larger potential in the areas of series production tooling and in particular part production. Some of the research concluded that powder with smaller size particle distribution could be easily melted and yields high density, superior mechanical strength and productivity. Laser sintering does not, however, lend itself to the production of near-net-shape objects to close tolerances and a high quality surface finish. Another obstacle that these processes face is the presence of micro structural defects (e.g., voids, impurities, or inclusions) in the final product. Such weaknesses can lead to catastrophic failure. In view of the above, it can be appreciated that there are certain problems, shortcomings or disadvantages associated with laser sintering and melting techniques, and that it would be desirable if improved methods and equipment were available and capable of producing near-net- shape objects to close tolerances and/or to have high quality surface finishes, and/or capable reducing or eliminating cracks, inclusions, and pores between deposit layers in a finished object [42].

Further work necessary for major success in particular application areas is ongoing or still to be done as part developed by sintering cannot be maintained full density which leads to the post processing techniques to be introduced to process it. One important technique which researchers have failed to identify is the severe plastic deformation (SPD) technique. A preliminary evaluation of microstructure and mechanical properties (hardness and tensile) reveals that material processed by the SLS/HIP technique is equivalent to conventionally processed material. A simplified version of a Ti-6Al-4V demonstration component was successfully fabricated. This provides a scope for developing the different components using different materials which may be useful for industrial applications by Hybrid Direct Laser Fabrication technique to provide components well with those of conventionally processed material. The direct implementation of successive layers of metallic parts in the future lead to a replacement casting process for a satisfactory performance in terms of materials such as copper alloys; titanium alloys, tool steel, fire-resistant steel, and aluminium alloys.

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