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Selective Laser Melting Process: A Review Paper

***Anshul Yadav*[1]**, *Nirma Kumari*[2]*, *Saurabh Babu*[3]*, *Swati Gupta*[4]**
[1]Department of Mechanical Engineering, Indian Institute of Technology-Kanpur, Kanpur (Uttar Pradesh), India
[2]Department of Material Science & Engineering, Indian Institute of Technology-Kanpur, Kanpur (Uttar Pradesh), India
[3]Department of Chemical Technology, Harcourt Butler Technological Institute, Kanpur (Uttar Pradesh), India
[4]Department of Computer Science and Engineering, Ajay Kumar Garg Engineering College, Ghaziabad (Uttar Pradesh), India

Abstract
Selective Laser Melting (SLM) is special among other Additive Manufacturing (AM) processes due to its flexibility of materials used, and the ability to create functional components, which have their mechanical properties comparable to those properties of bulk materials. The SLM process begins by slicing a 3D-CAD model into a number of layers. For each sliced layer the laser scan path is calculated which defines both boundary contours and form of the fill sequence which is often a raster pattern. Each of these layers is sequentially created by depositing powder on top of the previous layer, and melting the surface by scanning a laser beam. A high power-density fiber laser melts the powder layer. The melted particles fuse and solidify to form a layer of the component. During this process, successive layers of powder (metal) are melted completely and consolidated on top of each other by the energy of a high intensity laser beam. In this review, an attempt has been made to provide the recent developments in the field of SLM in terms of heat transfer, Mechanical Properties and many other aspects.

Keywords: *Selective Laser Melting (SLM), Additive Manufacturing (AM), mechanical strength, Selective Laser Sintering (SLS), microstructure, Laser based Processes*

* ***Corresponding Author***
Email ID: anshulyadav.iitk@gmail.com

INTRODUCTION

Additive Manufacturing (AM) has emerged as direct development from the Rapid Prototyping (RP) technologies that has revolutionized 3D model preparation. RP processes were only used to produce replicas or/and models of parts for the evaluation purposes only whereas AM can be used to produce not only prototypes but also fully functional parts in a variety of materials, and hence can be used as a primary manufacturing process. AM technologies build near-net shape components one layer at a time using data from 3D CAD models. AM Technologies can easily produce highly complex structured parts directly from CAD data.

A number of sectors such as aerospace, oil, gas and the medical industries are extensively working with additive manufacturing. This technology suites best to create geometrically complex components that cannot be feasibly made by any other means. Selective Laser Melting (SLM) can build parts with large aspect ratios and surface areas with low volume. This makes it fit for the heat exchanger applications. It allows the creation of parts for low-volume fabrication, which means that parts can be individually customized to suit any need.

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SLM allows better product development, which means reduced time to design test and ultimately more for iterative design evolution. Low-volume fabrication is possible due to its ability to by-pass the need for expensive tooling. Functionally graded structures allow new possible design routes for components; this also enables a combination of low cost parts with high wear resistance.

LITERATURE REVIEW

Laser sintering (LS) was first developed at the University of Texas at Austin[1]. LS are a process in which a high-energy laser beam scans the surface of a powder bed (the powder can be metal, polymer or ceramics) and the melted powder solidifies to form the bulk part. Selective Laser Melting (SLM) is the most commonly used terminology to describe laser sintering of metals, however, the terms Laser Cutting and Direct Metal Laser Sintering (DMLS) are also used by certain manufacturers[2]. Now fully functional parts can be created using SLM from metals without using any intermediate binders or any additional processing steps after laser melting operation[3]. Laser sintering is very complicated because of its fast laser scan rates and material transformations in a very short timeframe. The temperature field was found to be homogeneous by many previous researchers. [4–8] The physical processes associated to SLS include heat transfer and sintering of powder. Recently, many researches have been performed to develop numerical models for the SLS process[9–11]. The investigation of the resulting surface morphologies revealed that a narrow process parameter window where minimum balling occurred was by using high energy densities creating large agglomerates. It was suggested that the cause of this balling phenomenon was the excessive size of the melt pool accompanied by a long liquid lifetime. [12]

Researchers have compared the mechanical properties of parts made of steel obtained from SLM processing with those of the bulk material and concluded that mechanical properties are comparable to bulk material except ductility, which is strongly reduced. [13] They also suggested a possibility to combine structural material and binder to coat the structural material with the binder phase. This will ensure that the laser radiation that hits the powder particles, is preferentially absorbed by the binder material which is expected to be melted. The use of AM for the production of parts for final products continues to grow. In last ten years, it has increased from almost nothing to 28.3% of the total product and services revenue from AM worldwide. Within AM industry, there has been a greater increase in direct part production, as opposed to prototyping (AM's traditional area of dominance)[14]. Within direct part production, AM serves a diverse list of products and sectors including consumer electronics, textiles, film effects, jewelleries and musical instruments.

EXPERIMENAL SETUP

Laser-Melting-System (LMS)

The laser system in the machine provides nearly constant intensity over the building chamber (F-Theta-lens) and is able to apply a constant output power of around 30 W. The laser scans with a maximum velocity of 10 m/s and its focus radius is set to about 200 lm. Three different mechanisms for powder deposition exist: manual coating for single layer experiments, a rotating roller, and a fixed blade. All these mechanisms can be applied in the same machine. Accordingly, effects caused by the powder coating system can be investigated and eliminated. Mechanism of manual coating is used more often to avoid disturbance caused by the fully automated machine coating systems. In order to guarantee constant experimental conditions for different

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experiments, it is necessary to use a special temperature stabilized and homogenized machine (Figure 1).

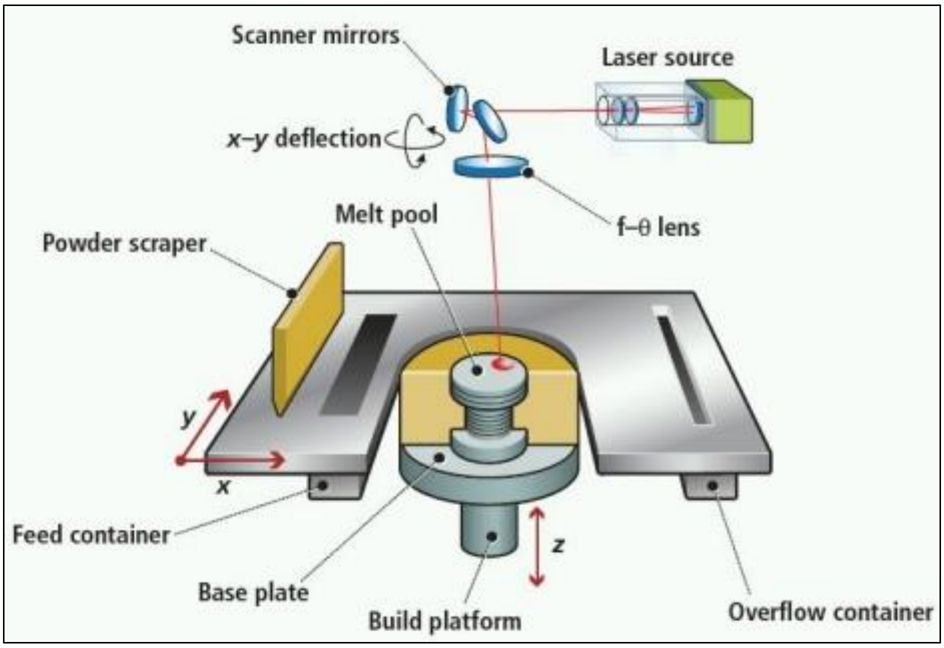

Fig. 1: *SLM Setup.*

Technical Specifications

The typical geometric accuracy of AM parts is 50 microns, or approximately 0.1% of the size of larger parts (for which the volume exceeds a cube of 100 millimeter). For serial-produced parts, selected surfaces can be produced with 30 micron accuracy. The printing resolution is 5 microns. In general, all AM parts can be post-processes conventionally to further increase accuracy.

MATERIALS

The variety of materials and possibility of manufacturing free-form elements causes SLM technology to find application in various industries. SLM technology allows manufacturing components without need of any additional operations. It is especially important from the economical point of view, reducing time and total costs of manufacturing of elements with complex geometry.

Stainless steel- 316L (1.4404)

Tool steel- Maraging X3NiCoMoTi 18-9-5 (1.2709) – Hardenable 54 HRC

Titanium-Ti commercially pure – Grade 1 – Very pure Ti, very ductile

Ti commercially pure – Grade 2 – Very ductile

Ti6Al4V ELI medical quality – Grade 23

Ti6Al4V ELI – Grade 23 – Almost identical to grade 5

Ti6Al4V – Grade 5 – High strength

Ti6Al4V medical quality – Grade 5

Super alloys-

CoCrMo-LC – ASTM F75 – implants, high strength

CoCrWMo – Dental

Inconel 718 – NiCr19FeNbMo3

Aluminum- AlSi10Mg

PROCESS PARAMETERS

Process parameters development for aluminum alloys has been explained by E Louis *et al.* [15] The scanning speed that was set using the point distances 65, 75 and 85 µm at varying exposure time. Then, they were applied to different hatch distances resulting in different relative densities of the part. Balling of the melt pool is a significant problem, especially at low scanning speeds. The surface profilometry as depicted in Figure 3 shows that low scan speeds generate roughness greater than the set layer thickness. On the contrary, high scanning speeds led to lower relative densities due to insufficient powder melting. However, on further increase of the laser scanning speed leads to the breakage of the molten track into a series of balls due to Rayleigh instability. The experiments with a laser power of 100 W led to increase maximum relative density by 5%. At both power settings, 50 and 100 W, hatch distances greater than 0.3 mm resulted in delamination as shown in Figure 2. Balling was also present in case of 100 W at low scanning speeds as shown by the surface profilometry scans as represented in Figure 4.

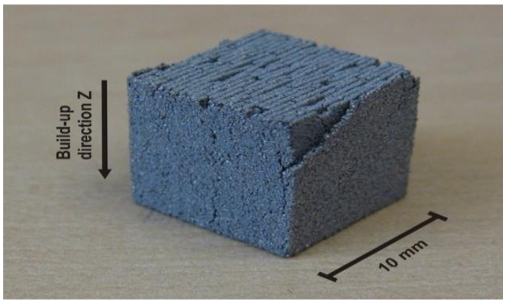

Fig. 2: *Wall Delamination Shown at the Bottom Surface of a 6061 Specimen made at 50 W Laser Power; the Selected Hatch Distance is 0.4 mm, which is Larger than the Limit Imposed by the Molten Track Width*[15].

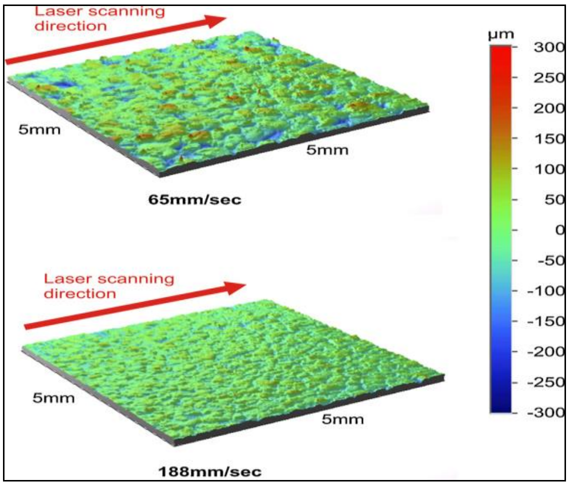

Fig. 3: *Top Surface Roughness Profile of 6061 Samples that were made using Different Laser Scanning Speeds. The Rest of the SLM Process Parameters that was used are Laser Power 50 W, Hatch Distance 0.15 mm*[15].

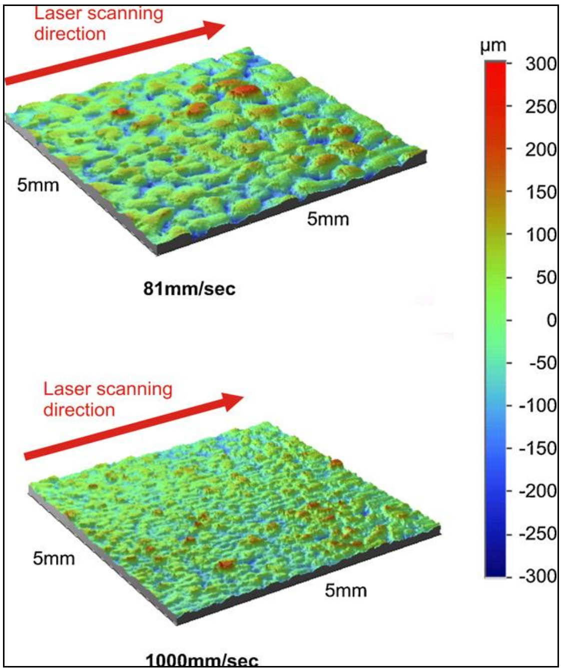

Fig. 4: *Top Surface Roughness Profile of 6061 Samples that were made Using Different Laser Scanning Speeds (Laser Power 100 W, Hatch Distance 0.15 mm) 100–200 mm/s. At Higher Speeds than these, the Overlapping Area of Two Adjacent Melt Tracks Reduces Resulting in Increased Porosity, Especially at Large Hatch Distances*[15].

MECHANISM

Microstructure after SLM

The fast cooling rate in SLM gives rise to a martensitic phase. Due to partial re-melting of the previous layers, elongated grains of several hundred micrometers develop. The direction of the elongated grains depends on the local heat transfer condition, which is determined by scanning strategy.

SLM part may differ in different views due to the line and layerwise building pattern. As represented in the Figure 5(a) which displays three views of a Ti6Al4V [16] part produced with process parameters by optimizing for the maximum density (laser power 42 W, scanning speed was 200 mm/s and scan spacing was 75 μm), using bi-directional scanning strategy. As a result, the present phase is high temperature gradients, as expected were very fine acicular martensite. After comparing microstructure of the top view, as depicted in Figure 5(b), to the used scanning pattern, we can recognize what scanning strategy was applied. Here the spacing, i.e. 75 μm is equal to the width of the individual tracks. So, different tracks are represented by different scan vectors. The herringbone patterns are caused by alternations in scanning direction. If the laser beam is moved from left to right, the grains are slanted as /, and from right to left as \. This suggests that the heat transfer direction plays a huge role in determination of the orientation of grains. In side and front views, as shown in Figure 5(c) and (d), we can clearly see elongated grains appear more or less along the building direction. They are the result of epitaxial solidification. The horizontal bands are clearly visible in the side view as shown in Figure 5(c), which were located at the difference of 30 μm and hence assumed result from the layerwise building.

The grains visible in the front view shown in Figure 5(d), were aligned with the building direction at a width of 75 μm approximately, confirming one-to-one correlation of the scan tracks and grains formed in the process (Figures 6–8)[16].

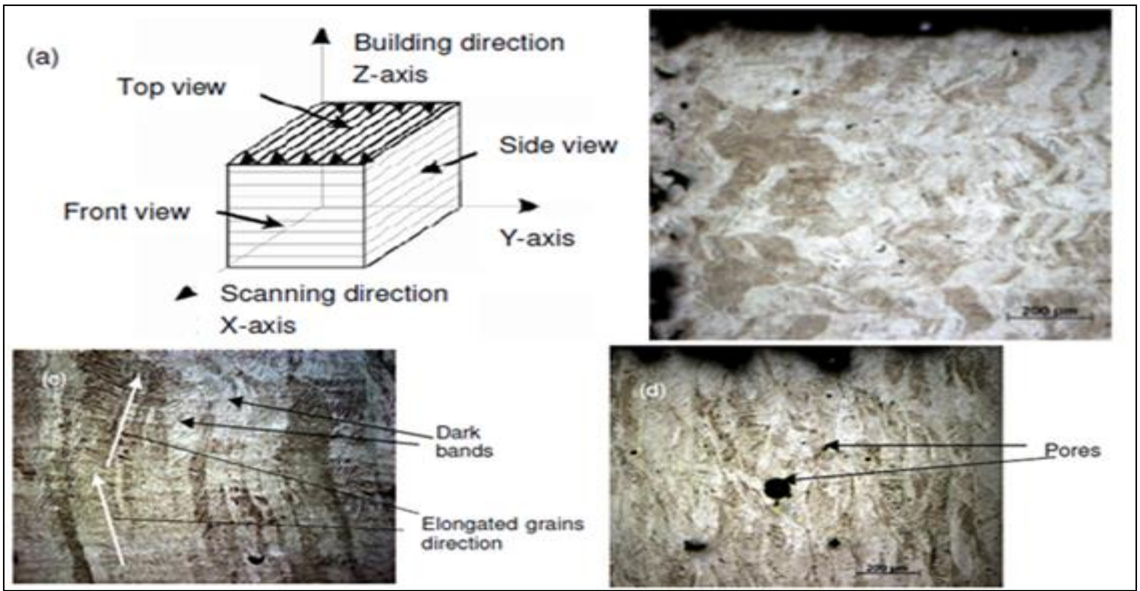

Fig. 5: *View of Ti6Al4V Sample[16].*

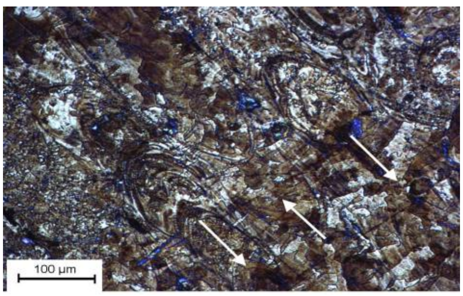

Fig. 6: *Top Surface of a SLM Part from AISI 316L Stainless Steel.*

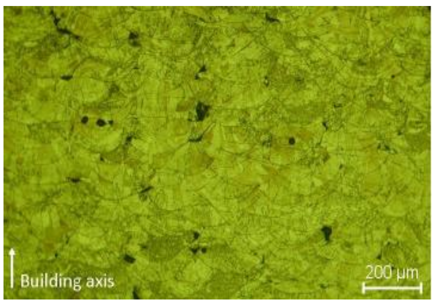

Fig. 7: *Frontal Section of Part from AISI 316L Stainless Steel.*

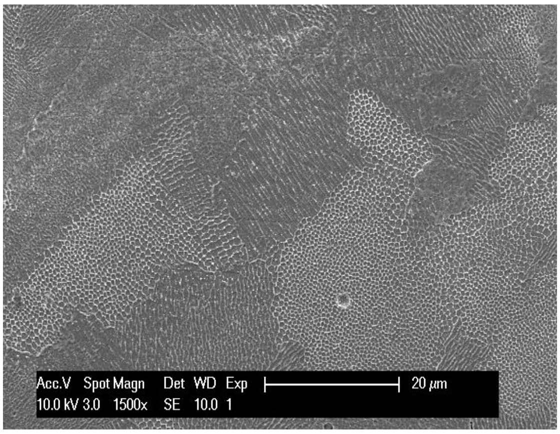

Fig. 8: *SEM Image of the Cross-Section of an AISI 316l Part Produced by SLM without Remelting.*

Laser- Powder Interaction

Both material properties of the processed powder and process parameters like scanning strategy, laser power, layer thickness, energy distribution etc. influence the appearance of thermal stresses in the part. In order to optimize the scanning strategy (scanning pattern) a closer look is taken to the different mechanisms involved during laser melting.

Temperature Gradient Mechanism

The temperature gradient mechanism (TGM) is the mechanism, which is commonly used for laser bending of sheets along straight lines. Albeit, this mechanism is applicable in SLM only where it acts on previously solidified layers lying underneath the processed layer. Due to rapid heating of the upper surface by laser beam and very slow heat conduction, a very steep temperature gradient develops. The material strength is reduced simultaneously due to a rise in temperature. Expansion of the heated top layer is converted into plastic and elastic compressive strains because the surrounding material is restricted to a free expansion. When the material's yield stress is reached, the top layer is plastically compressed. When mechanical constraints are absent, a counter bending away from the laser beam is perceived. When cooling and shrinkage occurs, plastically compressed upper layers become shorter and the bottom layers compress less compared to the upper layers. A bending angle towards the laser beam is also developed due to former condition. A link between SLM process and TGM used for laser bending can also be investigated. The already solidified layers in an SLM part are exposed to a comparable temperature gradient as mentioned in the TGM earlier each time a new powder layer is melted. In this way, the stress which is generated tries to bend the consolidated layers towards the laser beam and it can cause distortion and part failure by cracking and/or delamination. Moreover, shrinkage of the molten layers during cooling leads to generation of additional tensile stresses on top layers.

Binding Mechanism

The structural material should generally have higher melting point than the binder material. Binder particles are usually smaller than the structural ones, in order to facilitate their preferential melting. In some cases, even reverse melting occurs, in which the structural particles will melt prior to the binder grains. The combination of small binder particles and large structural particles has the additional benefit of better packing with small pores, favoring fast spreading of the molten binder by capillary forces and fast rearrangement of the particles[17].

$$M_a = \left(\left[\frac{d\gamma}{dx}\right]\left[\frac{w}{\eta}\right] / \frac{k}{w}\right)$$

Thermal Analysis

Figure 9 is a schematic representation of heat transfer in SLM. The laser scans the top of the powder bed following a prescribed scan pattern. The heat transfer process consists of powder bed radiation, convection between the powder bed and environment, and heat conduction inside the powder bed and between the powder bed and substrate. The latent heat of fusion is large in SLM. The complexity brought about by the powder phase change and the corresponding variation of the thermal properties during SLM complicates the heat transfer problem.

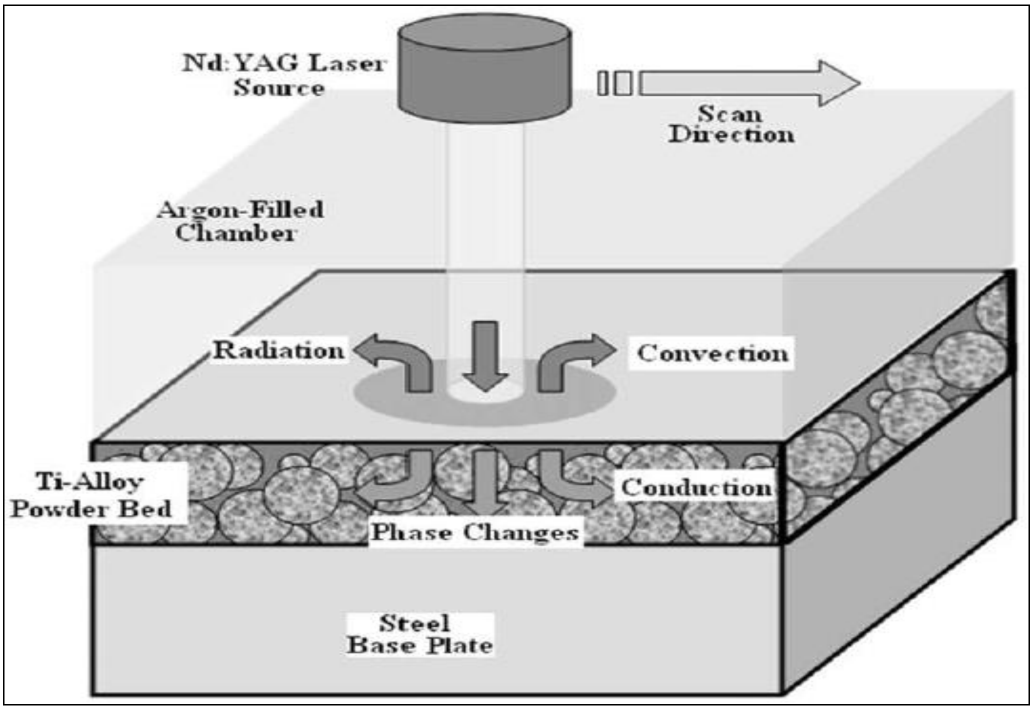

Fig. 9: *Heat Transfer in SLM*

The most common formulation considers SLM thermal evolution as a heat transfer process utilizing Fourier heat conduction theory. Carslaw and Jaeger used an equation to describe the governing heat conduction in the moving medium[13].

$$\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+q=\rho c\frac{\partial T}{\partial t}$$

Initial Condition:
Initial temperature: $T(x,y,z,0) = T_o$
Boundary conditions:
Surface convection and radiation: $-\lambda\frac{\partial T}{\partial x}=\varepsilon\sigma(T^4-T_e^4)+h(T-T_e)$

No heat loss at the bottom: $-\lambda\frac{\partial T}{\partial z}=0$ at z = 0

Understanding of the interaction between the powder bed and laser beam is key to the laser penetration and powder bed absorption. Since the absorption parameters were unknown accurately, a constant absorption ratio of pure titanium powder at the Nd-YAG laser wavelength (1.06 mm) was assumed[18]. The laser energy absorptance of a material is dependent on a number of factors such as the nature of the surface, level of oxidation, the wavelength of the incident laser beam, surface temperature, etc.

However, in the case of metallic powders, the absorption ratio varies from the in-coupling absorption as proposed by Kruth[16,21] to within a few percent of the molten metal absorption ratio.

Residual Stress

Residual stresses are the ones that remain inside the material, when it has reached equilibrium with its environment. We have included only one type of residual stresses[19], which vary over large distances, namely the dimensions of the part, which results in large deformations of the part (Figure 10).

Other types of stresses include stresses, which occur due to different phases in materials, due to dislocations at atomic scale and residual stress, large thermal gradients that are already present in the processes.

Owing to the rapid heating of the upper surface by the laser beam and the rather slow heat conduction, steep temperature gradient develops. Due to the temperature rise, material strength also reduces. Since the expansion of heated top layer is restricted by the underlying material, elastic compressive strains are induced. When the material's yield strength is reached, the top layer will be plastically compressed.

In absence of mechanical constraints, a counter bending away from the laser beam is observed. Another mechanism that induces residual stresses is the cool-down phase of the molten top layers. The latter tend to shrink due to the thermal contraction.

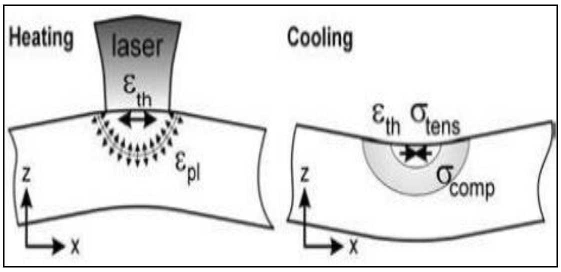

Fig. 10: *Residual Stress.*

DRAWBACKS

Full melting has the main advantage to produce almost full dense products in one-step, but it also has drawbacks that require careful process control:

1. The high temperature gradients and densification ratio during the process yield high internal stresses or part distortion range from 50% powder porosity to 100% density in single step.
2. The risk of balling and dross formation in the melt pool may result in bad surface finish.
3. Controlling the flow might be the problem during consolidation. The pool of molten metal must wet the previously processed metal below it. In addition, when it solidifies, its upper surface must be flat enough to enable a next layer of powder to be spread over it.
4. Contamination, usually by oxygen, oxide, impurities within the powder or trapped gas in the powder bed is a main cause of consolidation problems.
5. When temperature gradient is created in a melt pool, there is the potential for convective motions in the pool to reduce those gradients.

Temperature gradients through the depth of the pool, causing density gradients, and hence buoyancy forces, are probably of no importance to the millimeter or less melt pool sizes of SLM. However, temperature gradients in the surface, coupled with a temperature dependent surface tension, can cause rapid motions known as thermo-capillary or Marangoni flow (Figure 11).

The equation below defines the dimensionless Marangoni number Ma.

$$Ma = -\frac{d\gamma}{dT}\frac{L\Delta T}{\eta\alpha}$$

γ: surface tension; L: characteristic length;
α: thermal diffusivity;
η:dynamic viscosity; T
temperature difference

Balling

During the SLM process, the laser molten track possesses a shrinking tendency to decrease the surface energy under the action of surface tension.

Thus, the balling phenomenon is easily observed during SLM process, which determines the quality of SLM processed part and hinder the further development of SLM technology.

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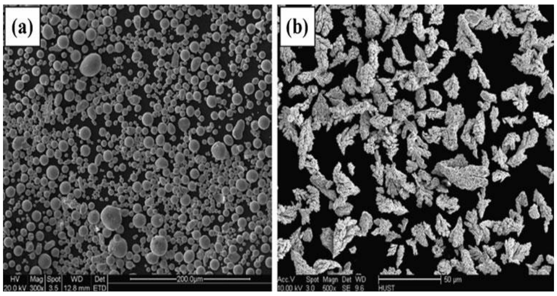

Fig. 11: *SEM Images Showing Characteristic Morphologies of Starting Powders:[20] a) Gas Atomized 316L Stainless Steel b) Electrolytic.*

The disadvantages of balling phenomenon on quality of SLM technology can be summarized as follows[21,22]:

1. The balling phenomenon could increase the surface roughness; thus, the SLM component needs polishing treatment.
2. A large number of pores in SLM component tend to be formed between many discontinuous metallic balls.
3. When the severe balling phenomenon occurs, the bellied metal balls tend to hinder movement of paving roller; thus, the unfinished part can be scratched by paving roller or the powder-paving step is stopped immediately.

Balling Characterization

Figure 12 illustrates the surface morphologies of SLM specimen, which reflects the typical balling characteristics. In low magnification, it can be seen that the processing surface is separated by a large number of big-sized metallic balls; thus, the surface is discontinuous, as shown in Figure 12a. [16]

In general, the SLM balling effect can be classified into two types:

(1) Ellipsoidal balls: the size is about 500 μm;
(2) Spherical balls: the size is about 10 μm.

The above balling classification could contribute to understand the balling mechanisms and obtain effective balling controlling method.

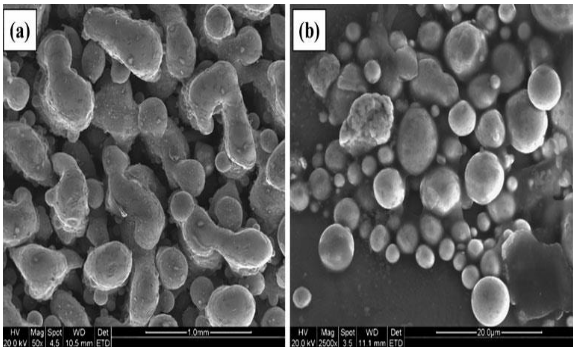

Fig. 12: *SEM Images Showing Typical Balling Phenomenon: a) Big-Sized Balls, 500 μm; b) Small-Sized Balls, 10 μm[20].*

CONCLUSIONS

SLM allows the better product development meaning reduced time to design test and more time for iterative design evolution. Low-volume fabrication is possible due to the removal of expensive tooling. Functionally graded structures can be developed allowing new possible design routes for components; this enables combination low cost parts with high wear resistance. The fast cooling rate in SLM gives rise to a martensitic phase. Due to partial re-melting of the previous layers, elongated grains of several hundred micrometers grow.

In short, we can conclude that SLM enables the ability to manufacture for design and reduces design for manufacture.

Benefits of SLM

1. Optimize material usage, saving cost.
2. Improves production development cycle.
3. Allows complex geometry to be made.
4. Ideal process for low-volume production.
5. Improve buy-to-fly ratio.
6. Functionally graded parts can be produced.
7. Allows completely customized parts to suit the individual.

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