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Analysis of Ti6Al4V Alloy Prototype Fabricated via Selective Laser Melting

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Abstract: During laser-based additive manufacturing, powder is selectively fused layer by layer to achieve the desired shape. Powder also serves as an integrated support framework, allowing for a wide range of material alternatives. Selecting suitable material whether it should be pure material powder or composite material powder such as titanium-based alloy which have wider application in biomedical industries to make surgical implants and orthodontic appliances, which requires good fatigue strength. The purpose of this analysis is to obtain a better understanding of the laser-based additive manufacturing process with the help of finite element simulations. The effect of variation in laser power, scan speed and layer thickness are considered the essential parameters for thermal and mechanical analysis of a part. One by one varying the process parameters such as laser power, layer thickness, beam radius, and scan velocity to generate the stress distribution, total distortion, and solid fraction of the part. Comparing the results and evaluating the most appropriate result from this. Keeping records of these results and validating these results with the results of fabricated part.

Keywords: selective laser melting (SLM), Power, Titanium, alloy, Layer, Thickness, Simulation

1. Introduction

Powder bed fusion is a group of AM technologies commonly known as 3D printing that are used to realize metallic or ceramic parts on a bed lying on a horizontal plate. It is basically the transformation from “design for manufacturing to manufacturing for design”. Powder bed fusion methods require the help of a high-intensity beam to melt and fuse material powder together [1-4]. Some of the commonly used printing technologies include selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting. In SLM, a thin layer of metal powder is spread over a platform, and a high-power laser beam is used to selectively fuse the metal powder in an inert gas environment. After scanning one layer, the main platform is lowered by one layer thickness and powder is again distributed on a platform using a roller, the process is continuously followed until the final layer is finished [4-6]. SLM is faster in which complex parts can easily be made with improved mechanical properties, especially high specific strength of the part, and are widely used to create biomedical components and aerospace spare parts. The most important process parameters of PBF printers are laser power, laser spot, number of heat sources, laser beam wavelength, scan velocity, working volume, layer thickness, material used, build envelope capacity and inert gas consumption [6, 7]. Laser power is the primary parameter of a PBF machine in which the power of a laser beam can range from 100 to 1000 watts [8]. Laser spot varies from 50μm to 500μm. Nd:YAG and fiber laser is adopted in almost all SLM printers which has wavelength of 1060 nm and Scan velocity in PBF machine is a variable parameter depending upon the consumer's choice to get accurate results in the part. Working volume depends on the chamber volume as per the size of the part to be created. Layer thickness is a variable parameter ranging from 20μm to 200μm. The range of the materials that is possible to treat as per the requirement. Build envelope capacity is inversely related to the resolution of accuracy and directly proportional to scan velocity, and varies from 5 to 50 cm^3/h in most circumstances. In SLM machines, the printing process is performed in an isolated chamber filled with an inert gas, in general Argon. The gas consumption ranges from 30 to 300l/h [8-10]. As shown in Fig.1, Generic Powder bed fusion printer consists of following chambers, one is the powder delivery and recoating system which helps in spreading metal powder by a recoater blade, another one is Build platform chamber and scanning system, where the final part is built by the application of high-energy laser [9, 12]

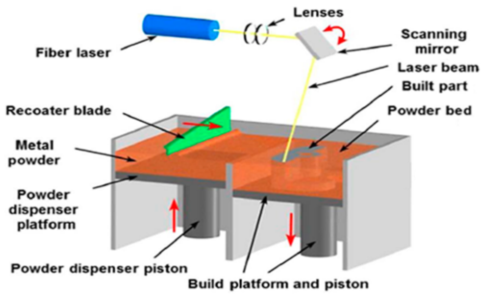


Figure 1: Components of generic Powder bed Fusion Printer [9].

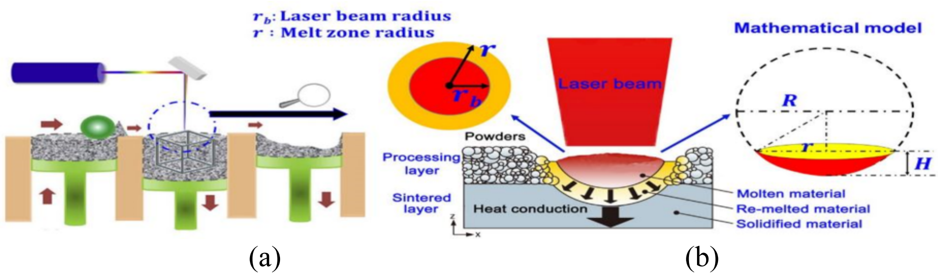


Figure 2: (a) Schematic diagram of the SLM process (b) The heat transfer in molten pool [10].

The metal powder is spread from the delivery system by a powder spreader blade, while the build platform is lowered to a height as per the layer thickness taken during application as shown in Figure 2(a). High temperature gradients cause residual stresses, which can have a considerable impact on mechanical properties [12]. The melting and solidification of powder material which is also called as melt pool analysis as shown in Figure 2(b). The generation of melt pool is typically thermo-fluid dynamic problem [12, 13]. Here selected a titanium-based alloy, i.e., Ti-6Al-4V, with varying iron and oxygen concentration rates. Composites having a low oxygen concentration, such as

TiGr23, increase the ductility of the part but may reduce its strength. The properties of titanium Ti-6Al-4V as shown in Table 1. In the titanium business, titanium is one of the most popular alloys, which is also known as Ti 6-5. The chemical makeup of this material is about 89%titanium, 6% aluminum, 4%vanadium, 0.25% iron, and 0.2% oxygen. The addition of aluminum and vanadium to the alloy matrix increases the material's hardness, which improves its physical and mechanical qualities [11]. Due to the high specific strength of the titanium alloy parts created using SLM, they are widely used in biomedical applications as shown in Figure 3 [6].

Table 1: Properties of Ti-6Al-4V [19]

Mechanical Properties	**Values**
Hardness, Brinell	375-379 HB
Tensile strength, Ultimate	1170 MPa
Tensile strength, Yield	1100 MPa
Modulus of elasticity	114 GPa
Poisson's ratio	0.33
Shear strength	760 MPa
Elongation at break	10%
Thermal Properties	**Values**
Melting Point	1660ºC
Solidus Temperature	1605ºC
Liquidus Temperature	1660ºC

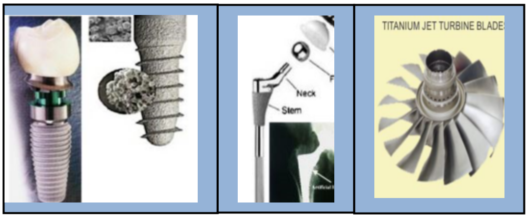


Figure 3: Applications [21]

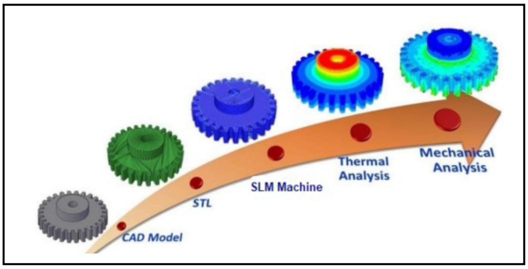
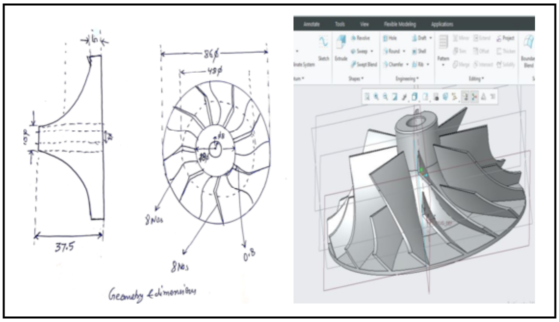


Figure 4: General framework adopted for SLM process simulation

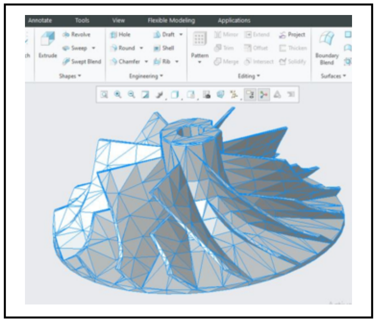
2. Materials and methods

2.1 Experimental Design

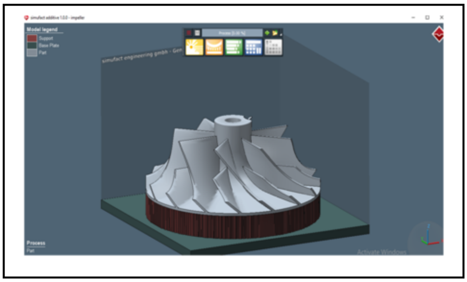
This research used the complex geometry of a pump impeller for the mechanical analysis using the most powerful simulation software, i.e., Simufact Additive [5], which is specially created for powder bed fusion based additive manufacturing, in which there is a option to select a SLM high-speed laser-based machine as per the build envelope size [14] . Then developed a finite element framework as shown in Figure 4 to simulate the PBF process at the component scale level, i.e., continuum level simulation. First, a 3D model of a part is created using CAD software, here Creo-Parametric is used to create 3D geometry shown in Figure 5(a), that created part is saved in STL file format as shown in Figure 5(b). This file is then imported to simulation software, i.e. Simufact additive as shown in figure 5(c) to perform analysis.



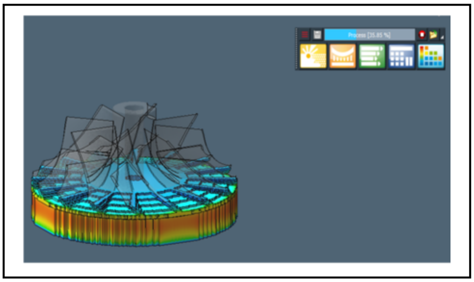
(a)



(b)



(c)



(d)

Figure 5: (a) CAD model (impeller) (b) STL file format (c) STL file import in simufact additive (d) Simulation process

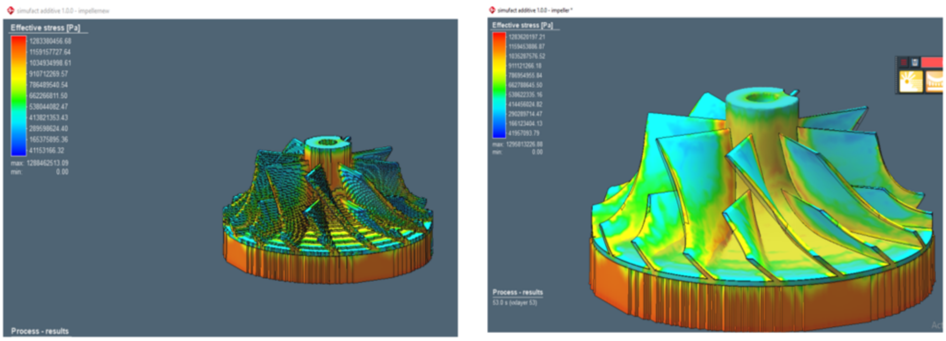
After importing the .stl file, it is required to select essential parameters such as Ti6Al4V Powder Material, selection of a SLM 280 HL machine (envelope size of 280*280*365 mm^3), laser power ranging from 100 W to 400W, layer thickness of 20 µm to 80µm, scan velocity of 1m/s to 8m/s and argon inert gas build atmosphere of the scanning chamber. The major objectives include the effect of variation of processing parameters such as laser power, layer thickness and scan velocity on Ti-6Al-4V alloy for which simulation software as shown in Figure 5(d) is used for thermal and mechanical analysis to evaluate stress distribution and deformations. Now considering laser power, layer thickness and scan velocity of 100W, 20µm, 1m/s and 200W, 30µm, 1m/s respectively to predict the stress distribution and displacement.

3. Results and discussion

Ti-6Al-4V alloy powder is selected while performing simulation in Simufact additive, which is one of the most powerful simulation software, especially for SLM under powder bed fusion additive manufacturing. Variation in characteristics was explored using main process parameters such as laser power, laser spot, scan velocity, and layer thickness. Stress distribution and total displacement are obtained after analysis as shown in Figure 6 and Figure7 at two different conditions, Figure 6(a) shows the stress distribution at 100W laser power, 20µm layer thickness and 1m/s scan velocity. Figure 6(b) shows the stress distribution at 200W laser power, 30µm layer thickness and 1m/s scan velocity. Total displacement at 100W, 20µm, 1m/s is shown in Figure 7(a) and displacement at 200W, 30µm, 1m/s represented in Figure 7(b) and the results obtained as shown in the Table2 below.

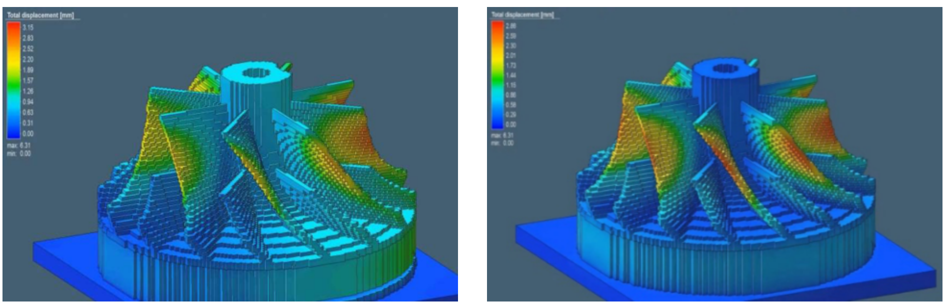
Table 2: Results obtained at two different cases

Experiment No.	Parameters	Results obtained
Case 1	Laser power= 100W Layer thickness= 20µm Scan velocity = 1m/s	Tensile strength, ultimate = 1288MPa Tensile Strength, Yield = 1165MPa Total Displacement =3.15mm
Case 2	Laser power= 200W Layer thickness= 30µm Scan velocity = 1m/s	Tensile strength, ultimate = 1295MPa Tensile Strength, yield = 1157MPa Total Displacement = 2.88mm



(a) (b)

Figure 6: Stress distribution at Laser power, Layer Thickness and scan velocity (a) 100W, 20µm, 1m/s and (b) 200W, 30µm, 1m/s



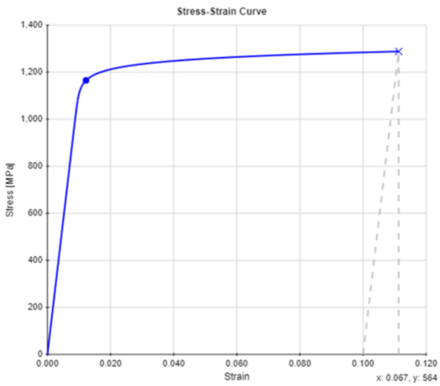
(a) (b)

Figure 7:(a) Total displacement at 100W, 20µm, 1m/s (b) Total displacement at 200W, 30µm, 1m/s

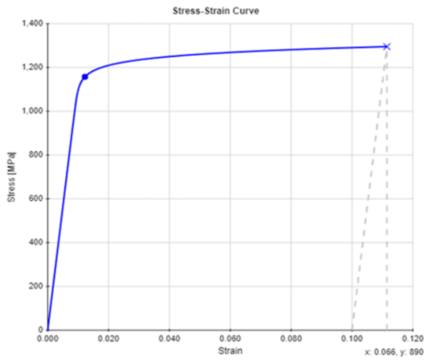
In these obtained results, we got ultimate tensile strength and yield tensilestrength. Ramberg-Osgood equation can be used to calculate the total strain as a function of stress:

$$\mathcal{E} = \sigma/E + 0.002\ (\sigma/S_{yt})^{1/n}$$

Where, $\mathcal{E}$ is strain, σ is stress, S_{yt} is Yield stress, E is young's modulus and n is the strain hardening exponent (n=0.0057)
Taking the reference values of stress, we calculated Strain and then we use these data points to generate Curves in MATLAB as shown in Figure 8(a) and Figure 8(b) below.



(a)



(b)

Figure 8: (a) Stress-strain curve at ultimate tensile strength of 1288 MPa (b) Stress-strain curve at ultimate tensile strength of 1295 MPa

Laser power of 200W, layer thickness of 30µm and scan velocity of 1m/s shows more tensile strength than laser power of 100W, layer thickness of 20µm and scan velocity of 1m/s. it was found that higher laser power and less than 50µm layer thickness provides more tensile strength to the part.

4. Conclusion

The present paper includes the analysis as per component level simulation of a complex part and it was found that for Ti-6Al-4V material the maximum tensile strength of a part is obtained for taking large laser power and minimum layer thickness. The main concept behind larger laser power is to melt the material by considering the melting point of the material which is 1660 ºC. It was found that laser power of 200 W is capable to melt the material powder. To obtain this result we took two cases in such a way that both laser power and layer thickness is considered along with scan velocity. In first case 100W laser power and 20µm layer thickness was taken and in 2nd case we took 200W and 30µm. obtained more tensile strength in 2nd case and less deformation of material particles. After comparing these results with properties obtained in wrought part of same material, it is found that method of additive manufacturing provides good improvement in mechanical properties especially specific strength of the part.

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