

Parametric Optimization of Biocompatible Ti6AL4V Alloy on Selective Laser Melting for Enhanced Structural Support and Reduced Stress Shielding

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Abstract

The Selective Laser Melting technique is widely employed in the production of complexly shaped end products for a range of industries, including biomedical, aerospace, automotive, and defence. SLM is a complicated manufacturing process since a lot of factors influence the characteristics of the items that are printed using it. The SLM printing of fully dense parts is becoming more and more popular for various high-end applications. Because of their biocompatibility following implantation, titanium alloy and stainless-steel alloy are the materials most frequently used in the fabrication of implants. The primary objective of this study is the parametric optimization of the Ti6AL4V alloy manufacturing process on the DMP Flex 350, utilizing SLM as a 3D printing technique. Response surface methodology (RSM), an optimization technique, and a genetic algorithm were employed to determine the optimal laser power, scan speed, and hatching distance in order to produce samples with the highest potential porosity and compressive strength.

Keywords: Parametric optimization, selective laser melting, Ti6AL4V alloy, Response surface Methodology, genetic algorithm.

INTRODUCTION

The tooling, automotive, medical, aerospace, and construction industries are among the areas seeing a rise in the use of metallic additive manufacturing. Figure 1 illustrates the six categories into which metal additive manufacturing can be further subdivided [1]. and the proportion of industrial adoption by 2020. This image illustrates how the VAT photopolymerization process uses composites of photopolymer and metal particles rather than directly producing metal components. Based on this data, it is possible to draw the conclusion that the powder bed fusion metal AM technique is extensively

utilized for the direct fabrication of metal parts across a variety of sectors, and that a deeper comprehension of these processes is necessary for a range of applications.

A layer of metal powder bed is utilized in the Powder Bed Fusion (PBF) procedure, wherein certain regions are melted or fused in accordance with the part's 3D model. PBF is primarily divided into two categories: laser and electron beam, depending on the energy source. Two popular PBF procedures that use laser and electron beam energy sources, respectively, are Selective Laser Melting (SLM) and Electron Beam Melting (EBM). Bhavar et al [2]. provided the main characteristics that distinguished the two PBF procedures. It may be concluded that SLM controls a great deal of the

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minimum feature sizes and geometric tolerances, even with EBM's rapid build speeds. Therefore, it would be simple to create intricately detailed parts with complex shape using the SLM technique.

SLM has the potential to be used to print complicated shaped parts with optimized design and reduced weight, based on the benefits of AM techniques. Any component's weight reduction strategy starts during the design stage.

There is a lack of effort in suggesting new parameters that can accurately predict the density of parts using input parameters, even though a significant amount of research in additive manufacturing is dedicated to optimizing the relative density of metal printed parts through the adjustment of various process parameters. Energy density is a frequently used parameter in SLM process optimization to achieve a high relative density. This parameter includes a number of SLM parameters, including laser power, scan speed, hatch distance, and layer thickness, but it ignores the scan strategy and build orientation. Energy density can be expressed as follows [3]:

$$\text{Energy density} = \frac{LP}{SS*hs*lt} \quad (1)$$

Where LP is the power of the laser chosen, SS is the applied scan speed, HS is the given hatch spacing and Lt is the thickness of each layer.

Researchers utilized this function to establish a connection between the density of SLM samples and the heat input, enabling the production of fully solid components. However, their common goal was to discover an optimal energy density level that corresponded to a low porosity content [4]. However, a number of research recommended using statistical analysis through the use of design of experiments (DoE) methods including the Analysis of Variance (ANOVA) and the Response Surface Method. The Central Composite Design (CCD) is widely acknowledged as a highly favored RSM design. The letter "k" represents the total number of components taken into account by this design. Included in the design are the two-level factorial, face points (sometimes called axial points), and center points (also called cube points). The statistical parameter known as α is utilized to regulate the axial points. Each factor in Central Composite Design is adjusted over 5 levels ($-\alpha$, -1 , 0 , 1 , and α) [5]. These methods were effectively used to examine how process variables, including scan speed, power of the laser and hatch spacing, affected the surface quality and percentage of porosity that were produced during the Selective Laser Sintering of Ti6Al4V alloy.

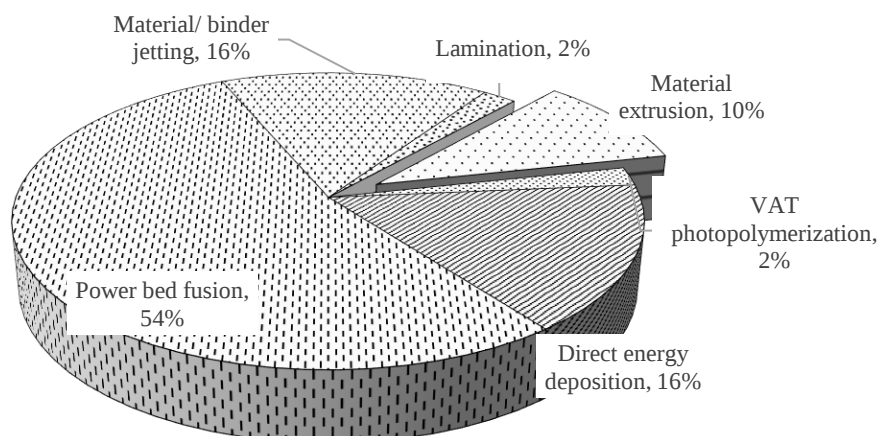


Figure 1. A summary of the applications of additive manufacturing for metal in 2020.

EXPERIMENTAL METHOD

Materials

Titanium alloys are of great importance in contemporary engineering because of their excellent combination of qualities, including strength, low density, and resistance to corrosion. Out of all these alloys, titanium alloy 6-4, which is also referred to as grade 5 titanium alloy, Ti-6Al-4V, or 6Al-4V titanium, is recognized as one of the most adaptable titanium alloys. Titanium alloy 6-4 is the predominant titanium alloy worldwide, constituting around 50% of the total titanium usage. 6Al-4V titanium is utilized in several industries for a wide range of applications, including automotive parts such as exhausts and springs, as well as medical components like joint implants. The composition of Ti-6Al-4V consists of 5.5–6.75% aluminum and 3.5–4.5% vanadium, with the remaining fraction being titanium. Titanium alloy 6-4 provides an excellent combination of superior strength and rigidity, resistance to corrosion, and low weight. This makes it ideal for applications that necessitate certain characteristics, such as the aerospace, automotive, or medical sectors. The SLM-produced Ti-6Al-4V sheet exhibits inferior corrosion resistance when contrasted with the commercial casting Ti-6Al-4V sheet, as evidenced by the pertinent results. The corrosive current density of SLM-produced Ti-6Al-4V in PBS solution is $1.78 \mu\text{A cm}^{-2}$ and $7.065 \mu\text{A cm}^{-2}$ in 15 wt [6]. Surfaces made of Ti-6Al-4V are susceptible to corrosion by SRB metabolites. Corrosion of Ti-6Al-4V alloys is mostly caused by the chemical interaction of aluminum, which ultimately results in a minor amount of TiS_2 and $\text{Al}(\text{OH})_3$ [7]. The application of this technology in these sectors, as well as others, has resulted in the development of numerous novel products that possess characteristics such as reduced weight, enhanced efficiency, and improved safety.

Utilizing Response Surface Methodology to Conduct Design of Experiment (DOE)

The goal of this study's RSM experiment design was to create an experimental plan with the fewest number of trials achievable. Using analysis of variance (ANOVA), we were able to isolate critical parameters, establish a relationship between the input and output parameters, and then find the ideal parameter configuration to accomplish the target function. Equation 2 demonstrates the utilization of a second order polynomial equation to represent the response surface "Y".

$$Y = c_0 + \sum c_i x_i + \sum c_{ii} x_i^2 + \sum c_{ij} x_i x_j \quad (2)$$

where x_i denotes the input parameters of the factor. Process parameter main and secondary effects are represented by the model coefficients, which are c_0 , c_i , c_{ii} , and c_{ij} . [8,9] The constant coefficients are determined through the application of the least squares method. Using Design-Expert Software, the experiment's design was employed.

The following protocol was used in this study:

1. Establishing the boundary limits for each of the crucial process parameters.
2. Selecting the reaction that is generated.
3. Developing the matrix for the experimental design.
4. Carrying out the trials in accordance with step3 and noting down the resulting reaction.
5. To develop a mathematical model for connecting responses with input parameters.
6. Use Genetic algorithm to improve response efficiency.

In the current study, three elements were considered: hatch spacing, scan speed, and laser power. For this study, the value of α was set at two in order to evenly adjust each element across five levels. The quantities of each factor in this study are presented in Table 1. Here, α and $-\alpha$ represent the maximum and minimum levels of each factor, respectively. Additionally, three center points were considered. The experimental error is evident in the use of the data points. Table 2 clearly shows that this resulted in the discovery of 14 different combinations for testing. Measurements were taken of various factors such as percentage of porosity, surface roughness, modulus of elasticity and Ultimate compressive strength (UCS) to gain a deeper understanding of the quality features of the produced samples.

Table 1. Building parameters and their values for CCD.

Parameter	Units	Levels chosen				
		- α	-1	0	1	α
LP	Watt	73	80	90	100	107
SS	mm/s	664	800	1000	1200	1336
HS	μm	26	40	60	80	94

Sample Build and Characterization

The DMP Flex 350 was used to produce SLM components. Layer thickness of 30 μm was chosen for building the specimen. Every step of the procedure was done in an argon environment with less than 0.1% oxygen. A circular coupon of 5 mm in diameter and 10 mm in height was created for every parametric condition. The samples were positioned on its base so that there is very minimum requirement of support structures and no overhanging layers.

Using a surface profilometer (Taylor Hobson Form Talysurf 120L), the surface roughness of the manufactured coupons was determined. In this work, the average surface roughness (R_a) served as the primary expression for the parts' surface quality. For every sample, two measurements were taken at the top surface and two at the side surfaces. The R_a was calculated across a 5mm diameter. Each sample's surface roughness was thought to be expressed by the average value of all the surface roughness values taken.

The samples were subjected to standard mechanical grinding and polishing using Silicon Carbide paper to achieve a 0.1 μm finish, which was necessary for microscopic analysis. An optical microscope, specifically the Zeiss Gemini1 model, was utilized to examine polished surfaces. The microscope was installed with AV 4 image analysis software to aid in the study. For every sample, eight frames measuring 800 μm by 600 μm were taken, and ImageJ image analysis software was used to calculate the area fraction of the pores. The compression tests were conducted using a universal testing device, with a constant loading speed of 3 mm/min. UCS and modulus of elasticity for each specimen were determined by analyzing the stress-strain curves that emerged from the compression test. The investigation's 14 parametric conditions and their accompanying quality attributes are displayed in Table2.

Table 2. Test Responses for Ti6AL4V Alloy Samples.

Run	A:Laser power (W)	B:Scan speed(mm/sec)	C:Hatching space(μm)	Surface roughness	Porosity %	Elastic modulus (GPa)	Ultimate compressive strength (MPa)
1	90	1000	26	9.97	19.74	23.72	484.82
2	80	1200	80	20.04	14.35	30.89	737.08
3	100	1200	80	15.80	5.21	62.98	1607.19
4	73	1000	60	16.74	9.77	46.12	1097.74
5	80	800	80	16.86	25.06	16.87	382.34
6	100	800	40	12.23	2.90	73.89	1723.46
7	80	1200	40	12.09	4.33	65.95	1640.69
8	100	800	80	20.03	2.59	70.53	1479.09
9	100	1200	40	14.93	7.54	53.68	1224.85
10	90	1336	60	14.72	22.75	20.51	460.18
11	90	1000	94	8.97	3.80	65.46	1612.11
12	90	664	60	14.37	7.69	48.22	1194.30
13	107	1000	60	14.37	21.38	21.31	420.77
14	80	800	40	16.27	6.09	58.32	1322.41

RESULTS AND DISCUSSIONS

Table 2 displays the measured values for UCS , percentage of induced porosity, surface roughness, and Modulus of Elasticity in addition to the parametric combinations.

Analysis of Variance Results

As a statistical metric, R^2 (or least square fitting) describes how well the model fits the data. Surface roughness (with an R^2 value of 89%) and modulus of elasticity (with an R^2 value of 91%) both fit linear models according to the RSM method. Furthermore, the content of porosity can be accurately represented by a quadratic model, which has a high R^2 value of 95%. On the other hand, the UCS (ultimate compressive strength) is best described by a two-factor interaction model, which also has a respectable R^2 value of 93%. The surface roughness, modulus of elasticity, porosity, and UCS plots for the Ti6AL4V were compared and analyzed are shown in Figures 2(a)–(d). The data points on each graph demonstrate that the actual values are always distributed closely around the line. As a result, it's possible that all of the models faithfully represented the relationship between the process parameters and the answer types studied here. The general empirical model can be defined using Equation 3. Functions of laser power (LP), scan speed (SS), and hatch spacing (HS) are used to describe the four models.

$$\text{Response} = c_0 + c_1(\text{LP}) + c_2(\text{SS}) + c_3(\text{hs}) + c_4(\text{LP}*\text{SS}) + c_5(\text{LP}*\text{hs}) + c_6(\text{SS}*\text{HS}) + c_7(\text{LP})^2 + c_8(\text{SS})^2 + c_9(\text{HS})^2 \quad (3)$$

The model coefficients, denoted as $c_1, c_2, \dots, c_9$, depend on the primary and secondary impacts of the process parameters. The coefficient c_0 represents the average response. The coefficients for the quality attributes are displayed in Table 3. The study analyzed the responses and process parameters. Equation 3 can be utilized to establish the comprehensive empirical model, which can be expressed as functions of LP, SS and HS for the four models.

Table 3. RSM coefficients for the four models for Ti6AL4V Alloy

Model coefficient	Surface roughness	Porosity	Modulus of elasticity	UCS
c0	+14.76	+7.17	-185.57	+1173.38
c1	-2.92	-2.20	+0.03	+179.93
c2	0.248	+5.04	0.2	-300.16
c3	-0.26	+4.44	0.14	-280.50
c4	0	-1.01	0	+26.03
c5	0	-0.42	0	-62.18
c6	0	+3.44	0	-191.22
c7	0	+0.30	0	0
c8	0	+1.54	0	0
c9	0	+1.15	0	0

In statistical significance testing, the value of p reflects the probability of obtaining a test statistic as extreme as the observed one, assuming the null hypothesis that parameters have no significant influence is true. Given a probability value below the predetermined significance level of 0.05 (95% confidence level), the null hypothesis is rejected. Accordingly, a model parameter is deemed significant if its p -value is less than 0.05. The p -values [10] for the Ti6AL4V alloy's parameters and interactions are shown in Table 4. Based on the analysis of variance results, the laser power was found to be the most relevant parameter influencing surface roughness across the range of parameters examined in this study. On the other hand, scan speed, hatch spacing, and laser power were the most important elements influencing modulus of elasticity. In the end, the three process factors, along with the synergy between scan speed and hatch spacing, greatly affected the percentage of porosity and UCS.

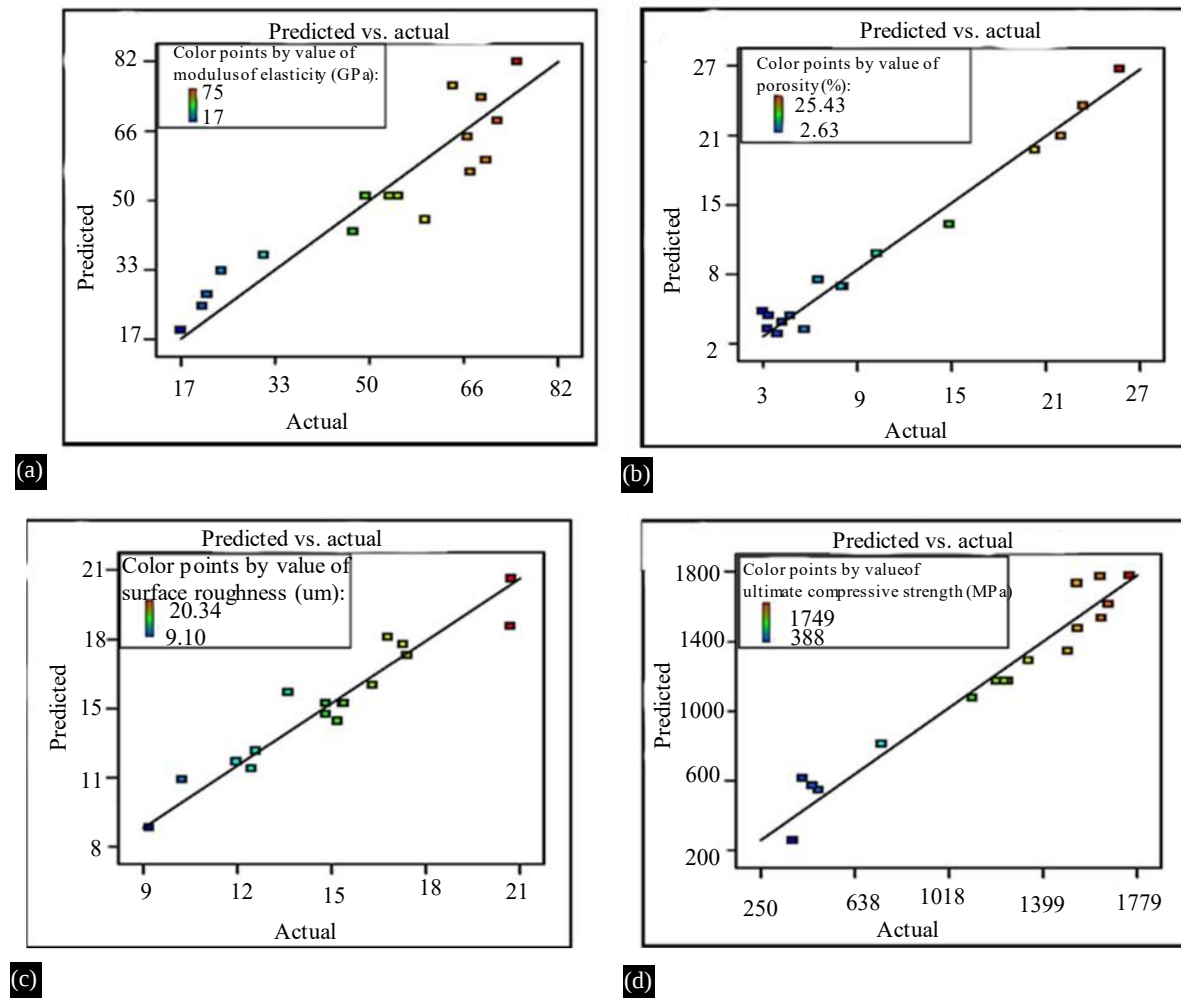


Figure 2. Comparing predicted and actual data for various properties of Ti6AL4V Part, (A) elasticity modulus, (b) percentage of porosity induced, (c) surface roughness and (d) ultimate compressive strength

Table 4. Probability values for the analysis of variance of each parameter for Ti6AL4V

Model parameter	Probability value			
	Surface roughness	Percentage of porosity	Modulus of elasticity	UCS
LP	0.00093	0.00151	0.00487	0.00052
SS	0.11496	0.00021	0.00089	0.00088
HS	0.29999	0.00083	0.00087	0.00089
LP*SS	-	0.22419	-	0.57669
LP*HS	-	0.54311	-	0.20826
SS*HS	-	0.00085	-	0.00326
LP ²	-	0.45658	-	-
SS ²	-	0.00563	-	-
HS ²	-	0.01879	-	-

Surface Roughness Analysis

As previously noted, a linear model depicts the relationship between the two variables and the power of the laser alone had a large impact on surface roughness. The impact of laser power on surface roughness for Ti6AL4V alloys is displayed in Figure. 3. It is evident that a considerable decrease in the R_a value from 21 to 18 μm occurred when the laser power was increased from 130W to 150W while

maintaining a constant scan speed and hatch spacing of 1300 mm/s and 40 μ m, respectively. This implies that the top surface and side surface of the printed pieces might both be considerably smoothed out by increasing the laser power. A flatter melt pool and better surface quality are the results of higher recoil pressures, which are produced by more powerful lasers [11].

Porosity Analysis

The use of high energy causes capillary forces and surface tension to close holes, increasing the density of SLM samples. Additionally, obtaining continuous tracks is ensured by low scan speed. Due to the increased overlapping area of nearby scanning lines, a short hatching spacing would result in the powder between scanning lines melting entirely. Due to the succeeding pool of melting accumulating on the previously formed layer and the solidified scanning lines, the scanning line would gradually transition from melt to solid [12,13]. As the distance between hatches increases, the impact of scan speed on porosity development also increases. The Ti6AL4V alloy exhibited the same behavioural pattern, as seen in Figure 4

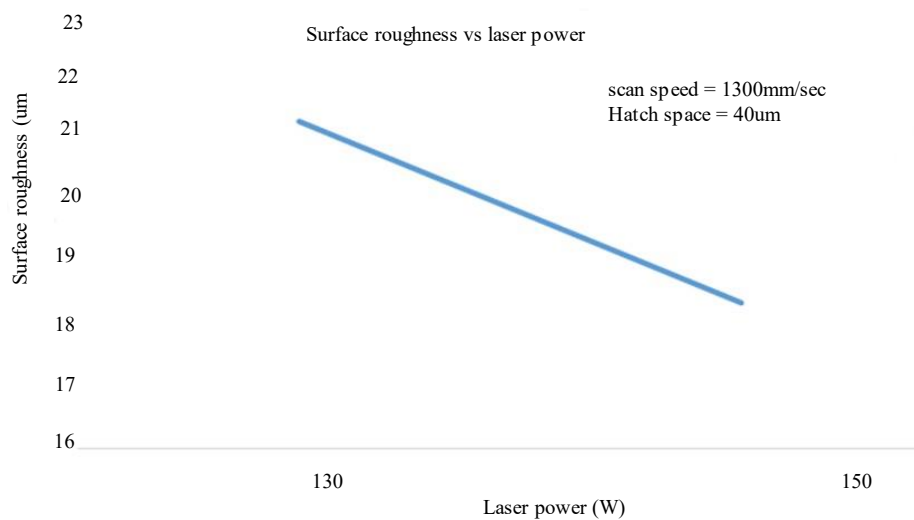
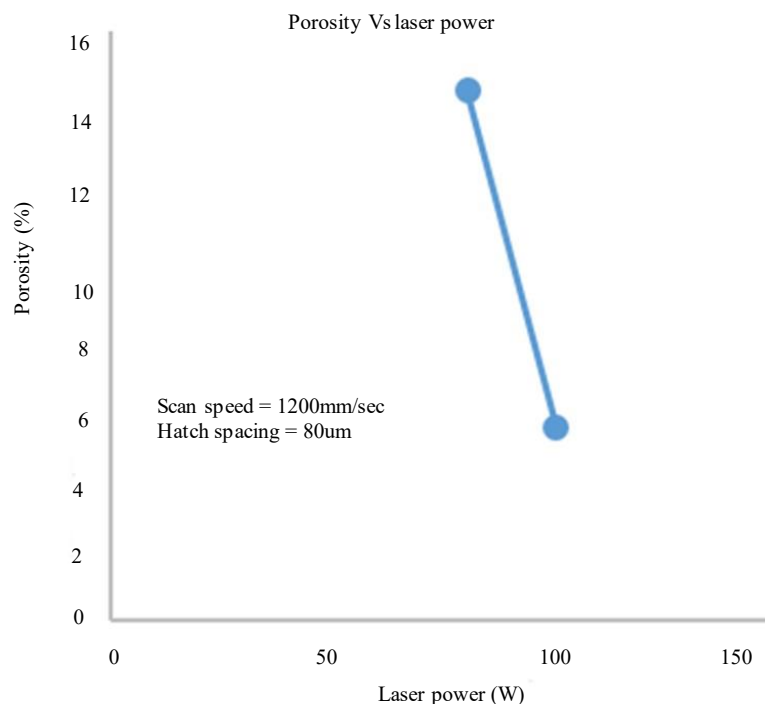


Figure 3. Analysis of the surface roughness as a function of laser power for Ti6AL4V.



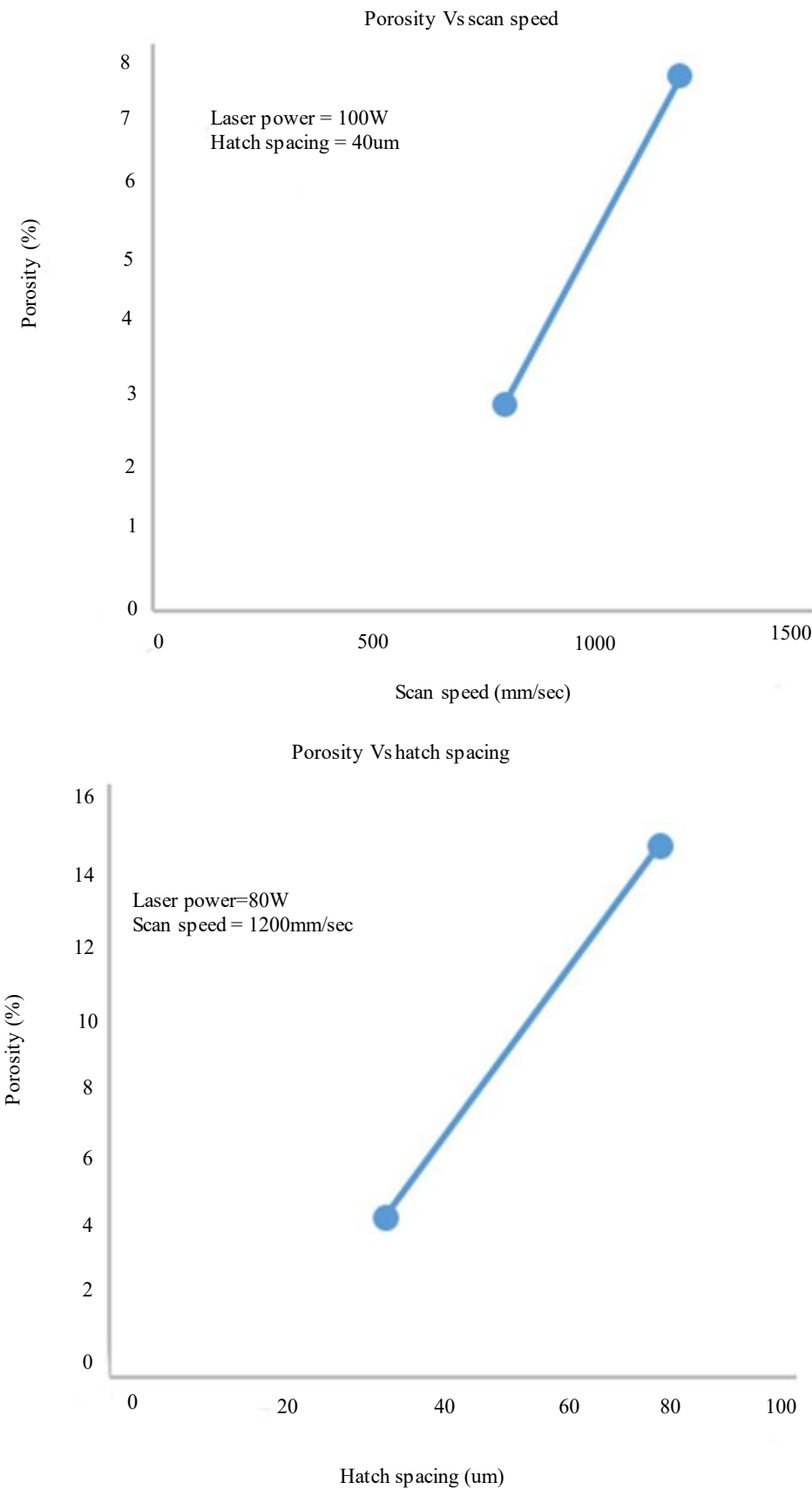


Figure 4. Impact of various parameters on porosity.

Microphotographs of samples 8 and 2, respectively, for the Ti6AL4V alloy are displayed in Figs. 5.20 and 5.21 (See Table 2). Samples 8 and 2 of Ti6AL4V had porosity contents of 2.59% and 14.35%, respectively. When using a slower scanning speed and higher laser power (sample 9), it was observed that the material displayed a notable increase in density, as illustrated in Figure 5. Alternatively, when the laser power is low and the scan speed is fast, the energy may not be sufficient to fully solidify the powder. This leads to the formation of structures with pores, as shown in Figure 6. Because of its low elastic modulus, an implant made of Titanium alloy with a structure like sample 2 is advised for use in biomedical applications. Furthermore, the pores will facilitate the easy growth and integration of tissues with the implant.

Analysis on Elastic Modulus

As seen in Figure 7 for Ti6AL4V Alloy, it was discovered that all three process factors had a considerable impact on the elastic modulus of the manufactured samples. The three parameters were found to be linear functions of elastic modulus. An increase in laser power was shown to increase the modulus of elasticity. Reducing the scan speed and/or hatch spacing could have the same effect on characteristics.

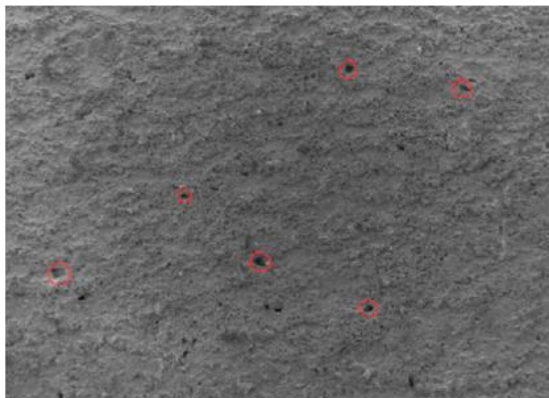


Figure 5. Micrograph of sample 8 of Ti Alloy.

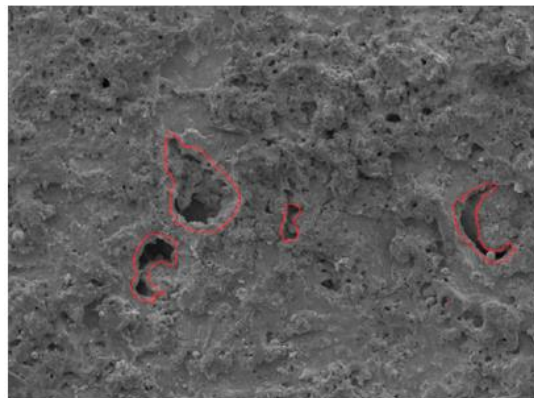
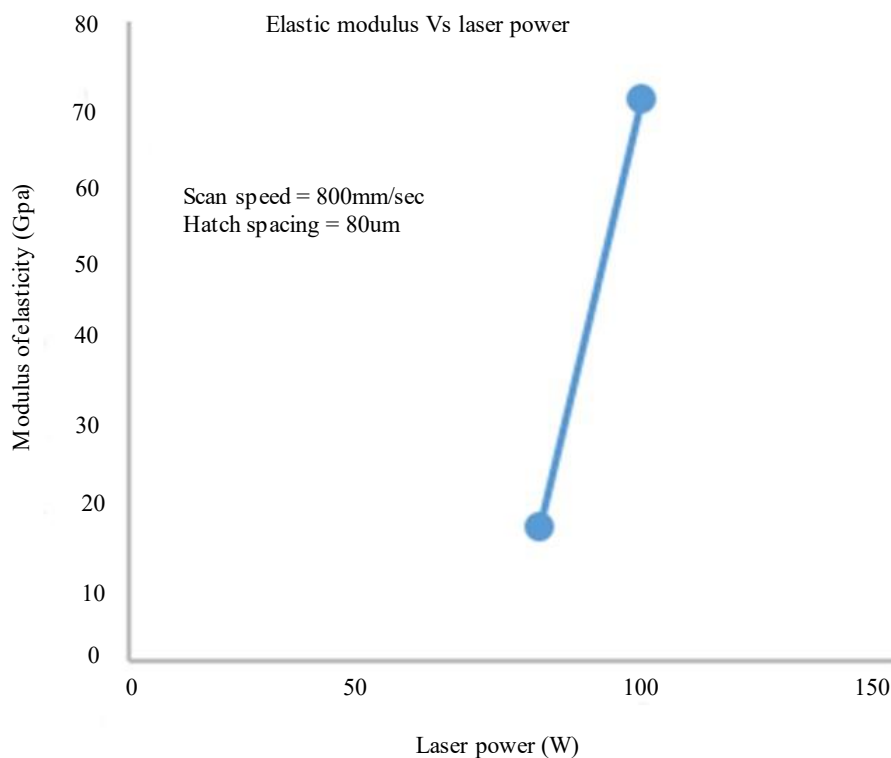


Figure 6. Micrograph of sample 2 of Ti Alloy



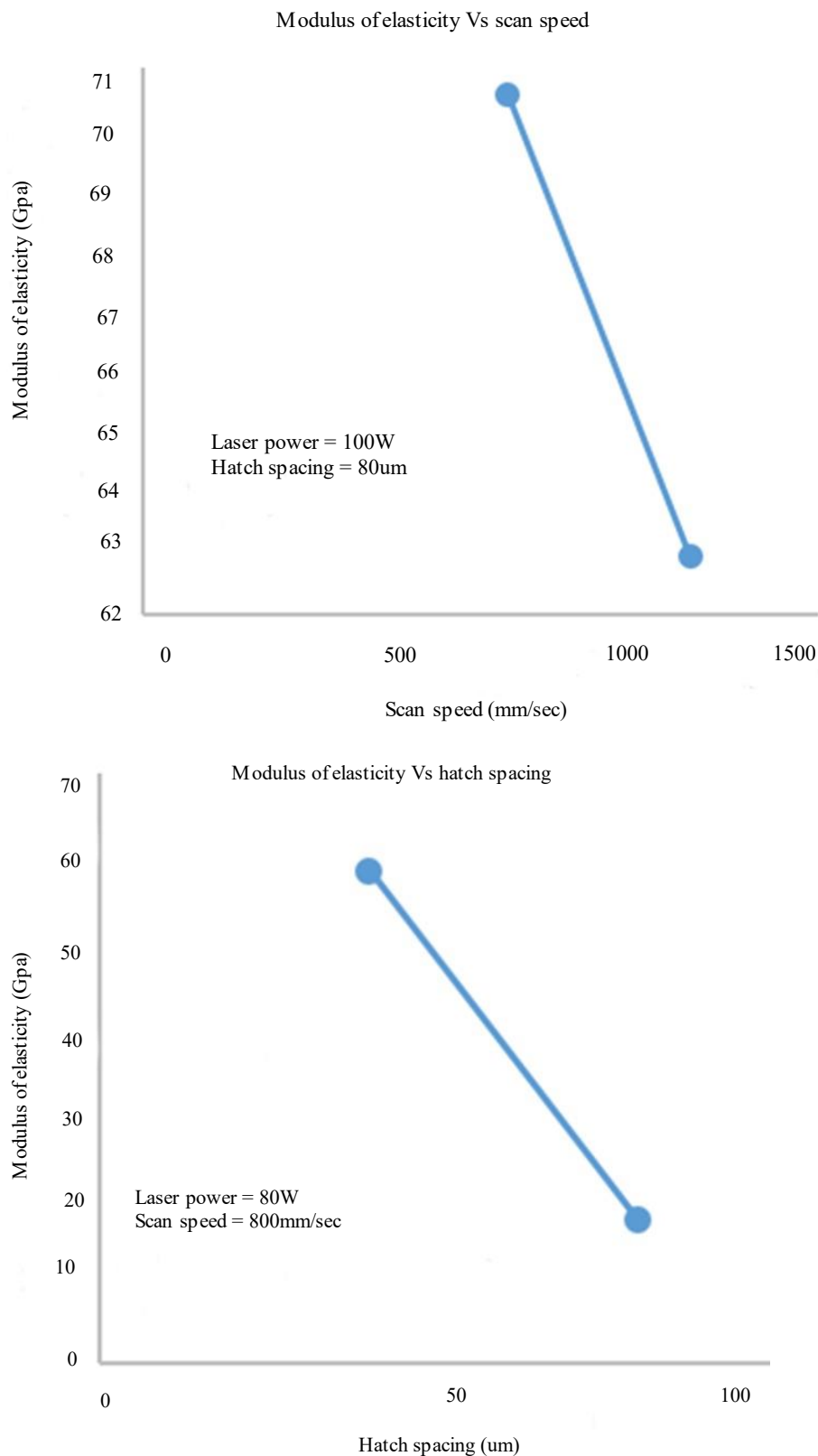
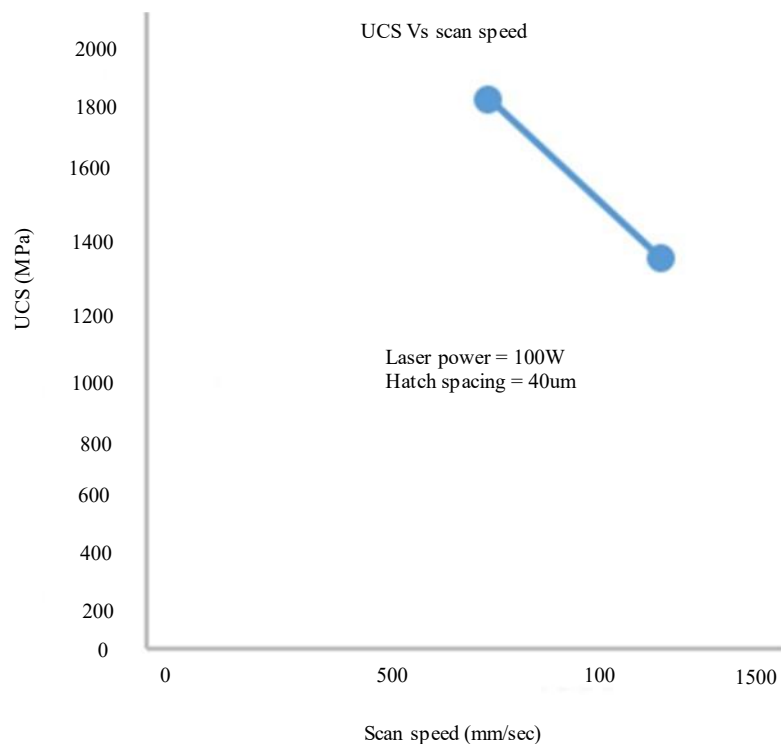
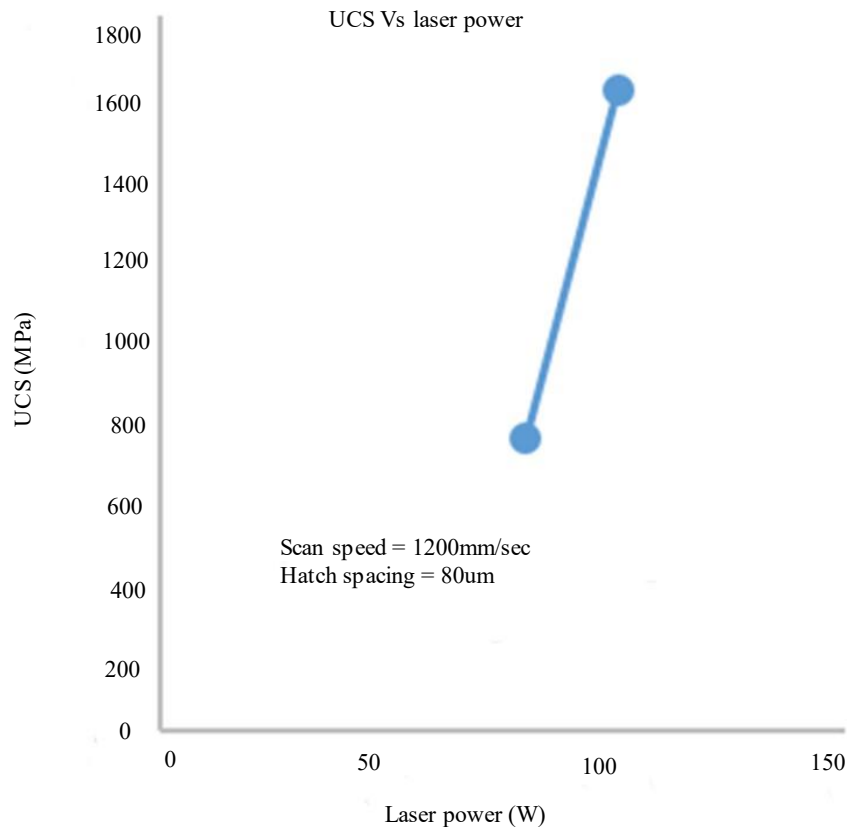


Figure 7. Impact of various factors on modulus of elasticity.

Analysis of Ultimate Compressive Strength

Like the elastic modulus, the model predicted that the UCS would be directly related to laser power and inversely related to scan speed and hatch spacing (See Figures 8 The UCS was also shown to be

significantly affected by the interaction between scan speed and hatch spacing [14]. Increasing the hatch spacing while maintaining the same laser power resulted in a steeper slope for the scan speed versus UCS relationship. Nonetheless, it was proposed that UCS be depicted as a 2FI model of the parameters involved in the SLM process.



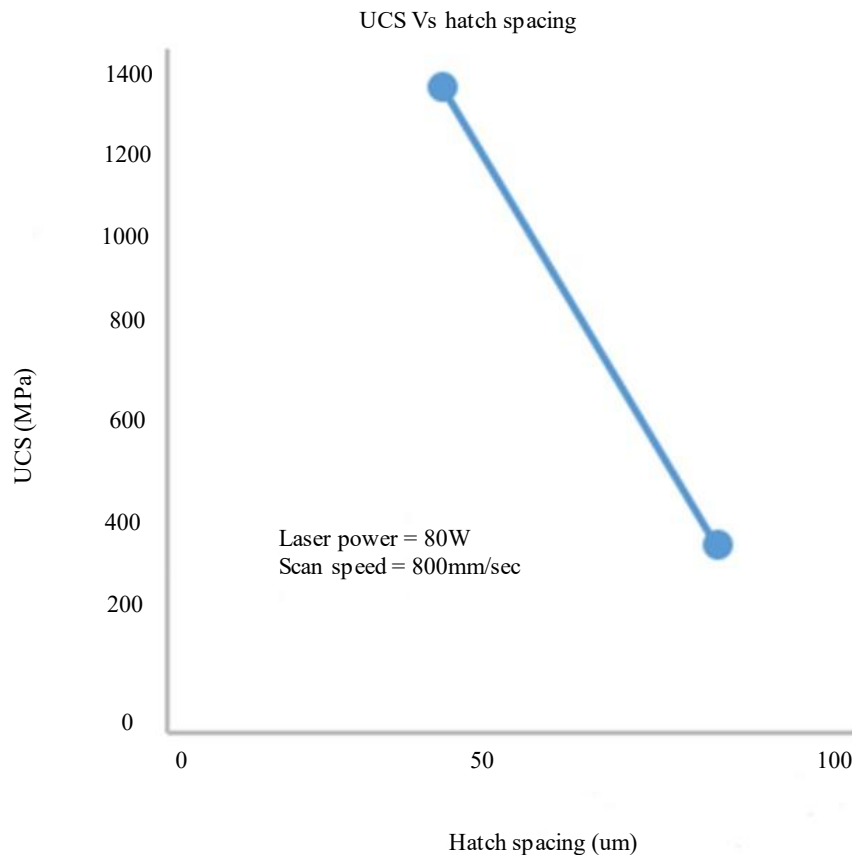


Figure 8. Impact various factors on Ultimate compressive strength.

Explaining The Formation of Porosity by Analysing the Energy Density

If the energy density is insufficient to achieve complete melting and even distribution of the powder, the final build may exhibit the formation of pores. There will be less melt pool and partial consolidation if the considered factors are increased [15]. Consequently, when the powder particles solidify, the spaces between them get trapped under the hatch lines. This leads to an increase in the porosity content, which in turn reduces the overall density of the SLM part. This is a crucial requirement for implants [16]. With the enhanced consolidation of the metal powder, the porosity content steadily decreases as the energy density rises, ultimately reaching a minimum value between 90 J/mm^3 and 130 J/mm^3 . Nevertheless, the porosity content scatters up to 180 J/mm^3 when the energy density increases further. Other defects, including keyhole development (caused by vaporization) within the SLM portion, may also occur in this area, raising the porosity level overall.

Optimization Towards Medical Applications

To determine the ideal processing parameter setting required for SLM of an Ti6AL4V component with properties appropriate for orthopaedic surgery, an optimization research was conducted. The goal function was to get the maximum matching UCS and porosity percentage while obtaining a modulus of elasticity in the limits of 10 to 30 GPa and a surface roughness between $1 \mu\text{m}$ and $10 \mu\text{m}$ [17,18]. The Design-Expert program examined the experimental data, and the genetic algorithm was utilized to forecast the process parameters that meet the objective function. Simultaneous solutions were found for the response equations that describe the responses considered in terms of the important process parameters. A 1000 mm/s scan speed, a 78 W laser output, and an $97 \mu\text{m}$ hatch spacing would be the model's recommended optimal values for the process parameters for Ti6AL4V. An energy density of 26.804 J/mm^3 is corresponding to this. For an SLM part, the estimated surface roughness, porosity, modulus of elasticity, and UCS at these process parameter values would be $9.78 \mu\text{m}$, 23.62%, 29.93 GPa, and 522 MPa, in that order.

CONCLUSIONS

The effects of the SLM process parameters on the quality attributes of Ti6Al4V SLM parts were examined. The most important factors were determined and an experimental plan was created using the RSM and ANOVA. The best process parameter setting to yield parts with qualities appropriate for orthopedic structure was determined using the generic method. The findings acquired allow for the conclusion of the following points:

1. When the laser power was increased, a noticeable decrease in surface roughness was observed for the SLM component. It is probable that the melt pool flattened during the process, leading to a decrease in surface roughness and the elimination of balling. These changes are anticipated to enhance the overall quality of the side surfaces of the SLM parts.
2. Through improved consolidation of the metallic powder, adjustments such as increasing the laser power or reducing the scan speed and hatch spacing (within a certain range) resulted in a decrease in porosity level for the SLM part. As a result, the part's UCS and modulus of elasticity were increased. In addition, the mechanical properties of an SLM component demonstrated a significant relationship with the amount of pores present. This indicates that the porosity level of the SLM part can be precisely adjusted to alter its characteristics.
3. A 1000 mm/s scan speed, a 78 W laser output, and an 97 μm hatch spacing would be the model's recommended optimal values for the process parameters for Ti6Al4V. An energy density of 26.804 J/mm³ is corresponding to this. For an SLM part, the estimated surface roughness, porosity, modulus of elasticity, and UCS at these process parameter values would be 9.78 μm , 23.62%, 29.93 GPa, and 522 MPa, in that order.

REFERENCES

1. Stavropoulos, P.; Foteinopoulos, P.; Papacharalampopoulos, A.; Bikas, H. Addressing the challenges for the industrial application of additive manufacturing: Towards a hybrid solution. *Int. J. Light. Mater. Manuf.* 2018, 1, 157–168
2. Bhavar, V., Kattire, P., Patil, V., Khot, S., Gujar, K., and Singh, R, *A review on powder bed fusion technology of metal additive manufacturing*, *Additive manufacturing handbook*, CRC Press.2107, p. 251-253.
3. Read N, Wang W, Essa K, Attallah MM , Selective laser melting of AlSi10Mg alloy : Process optimisation and mechanical properties development. *Materials and Design* (2015) 65:417-424.
4. Olakanmi EO, Cochrane RF, Dalgarno KW , Densification mechanism and microstructural evolution in selective laser sintering of Al–12Si powders.*Journal of Materials Processing Technology* , (2011) , 211(1):113-121.
5. El-Sayed MA, Parametric analysis of SLM process for fabricating 316L stainless steel samples by response surface method, *Journal of engineering technology*, 2018,emerging trends in engineering and technology.
6. Xuedan Chen,Qilong Liao ,Min Gong ,Qingshan Fu, Corrosion Performances of Selective Laser Melting Ti6Al4V Alloy in Different Solutions, *Journal of metals*, (2023), Volume 13(2), 192.
7. Xingwei Zheng ,Xin Zhuang,Yanhua Lei et. al., Corrosion Behavior of the Ti–6Al–4V Alloy in Sulfate-Reducing Bacteria Solution, *Journal of coatings*, (2020), Volume 10(1),24.
8. Elsayed, M., Ghazy, M., Youssef, Y., & Essa, K. Optimization of SLM process parameters for Ti6Al4V medical implants. *Rapid Prototyping Journal*. (2018).
9. Carter LN, Essa K, Attallah MM Optimisation of selective laser melting for a high temperature Ni-superalloy. *Rapid Prototyping Journal* (2015), 21 (4):423-432
10. Morgan R, Sutcliffe CJ, O'Neill W, Density analysis of direct metal laser re-melted 316L stainless steel cubic primitives. *Journal of Materials Science*, (2004), 39 (4):1195-1205.
11. Sun J, Yang Y, Wang D, Parametric optimization of selective laser melting for forming Ti6Al4V samples by Taguchi method. *Optics & Laser Technology*, (2013), 49:118-124.
12. Hassanin H, Modica F, El-Sayed MA, Liu J, Essa K Manufacturing of Ti–6Al– 4V Micro-Implantable Parts Using Hybrid Selective Laser Melting and Micro-Electrical Discharge Machining. *Advanced Engineering Materials* ,2016, 18 (9):1544-1549

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13. Weißmann V, Wieding J, Hansmann H, Laufer N, et. al , Specific Yielding of Selective Laser-Melted Ti6Al4V Open-Porous Scaffolds as a Function of Unit Cell Design and Dimensions. *Metals* (2016), 6 (7):166
 14. Kurgan N Effect of porosity and density on the mechanical and microstructural properties of sintered 316L stainless steel implant materials. *Materials & Design* (2014) ,55:235-241.
 15. Dewidar MM, Khalil KA, Lim JK Processing and mechanical properties of porous 316L stainless steel for biomedical applications. *Transactions of Nonferrous Metals Society of China* (2007), 17 (3):468-473.
 16. Bender S, Chalivendra V, Rahbar N, El Wakil S Mechanical characterization and modeling of graded porous stainless steel specimens for possible bone implant applications. *International Journal of Engineering Science*, (2012) , 53:67-73.
 17. Song B, Dong S, Zhang B, Liao H, Coddet C, Effects of processing parameters on microstructure and mechanical property of selective laser melted Ti6Al4V. *Materials & Design* ,2012 , 35:120-125.
 18. Strano G, Hao L, Everson RM, Evans KE Surface roughness analysis , modelling and prediction in selective laser melting. *Journal of Materials Processing Tech* ,(2013) , 213 (4):589-597.