Influence of process variables on surface roughness of 316L stainless steel parts fabricated via selective laser melting process

Meena Pant[1*], Leeladhar Nagdeve[1], Girija Moona[2,3], Harish Kumar[1], J. Ramkumar[4]

[1]National Institute of Technology Delhi, India
[2]CSIR–National Physical Laboratory, New Delhi, India
[3]Academy of Scientific and Innovative Research (AcSIR), CSIR-HRDC Campus, Ghaziabad, India
[4]Indian Institute of Technology Kanpur, Kanpur, India

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316L SS,
Surface Roughness.

ABSTRACT

Selective laser melting process (SLM) is a metal additive manufacturing technique with excellent design freedom and feasibility. In SLM, a high-energy source is used to melt powder particles into a pattern of successive layers. However, the major challenge associated with the SLM process is that the parts have a high surface roughness (R_a) compared to forming, machining, and rolling processes. In this paper, the core parameters, including scan speed, hatch distance, laser power, and energy density effects discussed as the roughness parameters. The experimental runs were designed based on Taguchi L_9 orthogonal array. The results displayed that R_a of samples was largely affected by laser power as compared to scanning speed and hatching spacing. The R_a of samples achieved less at high energy density. In contrast to other surface finishing operations, the polished sample showed the average R_a value of 0.049 µm manufactured at an energy density of 58.83 J/mm^3.

1. Introduction

Over the past few decades, additive manufacturing techniques have fundamentally altered the production standard in both industry and academia. The American Society for Testing and Materials (ASTM) classified AM processes into seven categories: material extrusion, binder jetting, Vat Photopolymerization, sheet lamination, powder bed fusion, and directed energy deposition. SLM is a powder-based technology in which a strong laser beam melts powder particles. After the first layer is constructed, the build platform descends, and a second layer of powder is placed on top of the first. This process is repeated until the final finishing of parts. It has become a good choice to create components with interior design and/or complex geometries in the biomedical, aerospace, automotive, and petrochemical industries (AlMangour et al., 2017; Brytan, 2017). The SLM process manufactures various ranges of metals and their alloys. Among all, 316L stainless steel (SS) is the main focus of this study. It has excellent corrosion resistance, high strength, and good biocompatibility; due to this, it has been used for making stents, dental dentures, and the petrochemical industry (Thijs et al., 2010; Pant et al., 2022). In the SLM process, powder characteristics, process parameters, and energy density affect the final quality components. The influence of core parameters, including hatch distance (h), layer thickness (l), laser power (P), scan speed (v), and scanning strategy, has already been reported on the mechanical properties and quality in the literature (Yakout et al., 2018; Sun et al., 2018). It was reported that the surface roughness (R_a) of SLM parts by focusing on signal track characteristics. They found that R_a was 50 percent greater than the theoretical value. They concluded that the powder layer thickness, width track, and hatch distance influenced the R_a. value. The energy density has a major influence on the R_a value, and laser surface re-melting can reduce R_a value (Wang et al., 2016). It was reported that the average R_a 316L SS parts were affected by the scan speed, laser power, and hatch distance. The significant parameter has

*Corresponding author E-mail: meenapant95@gmail.com

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Table 1
DMP flex 350 metal printer specifications.

Laser power	500 W/ Fiber Laser (Adjustable according to metal powder)
Laser wavelength	1070 nm
Layer thickness	Adjustable, minimum 5µm, Typical Values 30, 60, 90 µm
Build volume	10.82 x 10.82 x 16.54 in X, Y, and Z directions
Materials	Laserform Titanium and its grade, Laserform Stainless steel 316L, Laserform 17-4PH, Laserform aluminum and its grade, Laserform Nickel and its grade, Laserform CoCrF75, Laserform maraging Steel
Material deposition type	Soft blade Recoater
Compressed air requirement	6-10 bar
Software tool	3DXpert all-in-one software

been predicted using analysis of variance (ANOVA). They have reported that laser power is the most important parameter. The shot peening technique has been suggested for enhancing the surface finish of parts (Aqilah et al., 2018). The authors examined the R_a of aluminum parts using a direct metal laser sintering process. ANOVA has been used to predict the most significant parameters. The analysis showed that scan speed was a highly significant parameter, followed by hatch spacing (Calignano et al., 2013). Some researchers examined the impact of process factors on the densification, surface roughness, microstructure, and microhardness of Ti-6Al-4V alloy manufactured by SLM. Ti-6Al-4V alloy denser component was produced using a 110 W laser power and a 400 mm/s scanning speed. They have reported that continuous melting provides high hardness and a smooth surface finish (Song, et al., 2012). The laser surface re-melting mechanism was evaluated to predict the R_a value of 316L SS parts. In this study, four variables have been identified: laser power (P), layer shell thickness (T), laser exposure duration (E), and point distance (D). Among the four parameters, E and P are the most affecting parameters for the R_a of the inclined surface (Ghorbani et al., 2020). Normally, components made using traditional methods like grinding and milling have an average roughness value of less than 1-2 µm. One major drawback of SLM-made parts, especially for high-performance functional components, is their worse surface quality. It has been reported that the part fabricated via SLM has a surface roughness range of 10 to 30 µm (Cherry et al., 2015). It was reported that laser power is one of the input variables which has a significant effect on the surface quality. It was also reported that the scan speed and hatch spacing, which control how much energy is used during melting, impacted the surface quality (Strano et al., 2022; Prashanth et al., 2017). This study focused on the surface roughness evaluation of selective laser-melted 316l stainless steel parts. The core parameters, including laser power, scan speed, hatch spacing, and energy density, have been identified to understand the effect on average R_a. However, the poor surface finish of parts deteriorates the mechanical properties, leading to crack initiation in the components. It is essential to evaluate the surface roughness of parts before being used for industrial application.

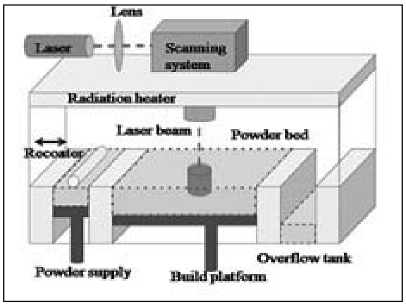

Fig. 1. Schematic of selective laser melting process.

2. Methodology

2.1. Equipment and materials

Samples were prepared via SLM-based commercially available DMP flex 350 metal printers. The machine specifications are listed in Table 1.

In Fig. 1, the SLM process was depicted schematically. Fig. 2 shows the SEM image of powder particles with a rounded shape morphology and some associated satellite particles. The powder particle size ranges from 10 µm to 50 µm. The chemical composition of

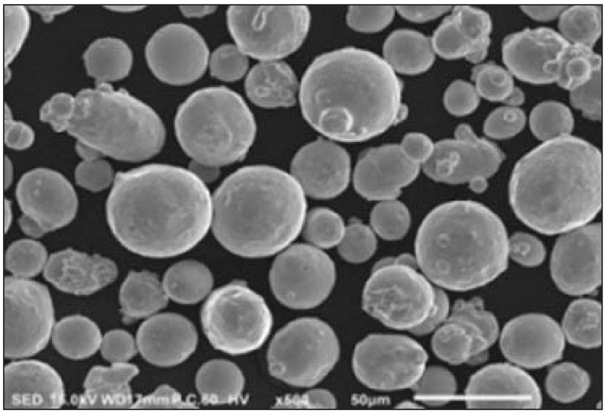

Fig. 2. SEM image of powder particles.

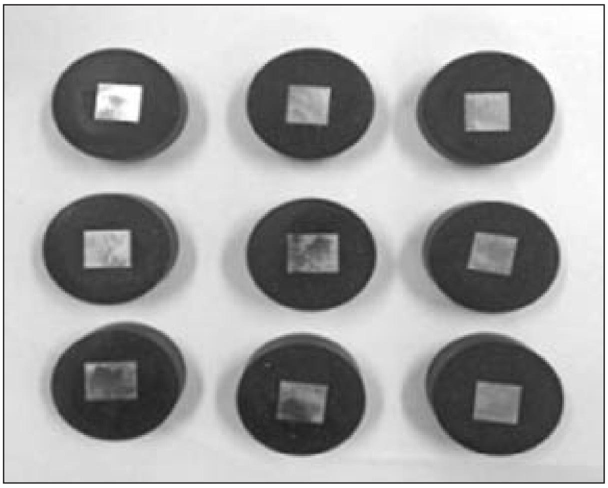

Fig. 3. Samples for roughness measurement.

Table 2
Chemical composition of 316L SS powder.

Elements	Mo	Si	Cr	Mn	Fe	Ni
Weight	2.66	0.15	18.07	1.07	64.72	12.52
Atomic weight	2.5	1	18.5	2	64	12.5

powder particles was determined by Energy Dispersive X-Ray Spectroscopy (shown in Table 2). A total of nine samples were fabricated using Taguchi L9 orthogonal array (OA), as shown in fig.3. The goal of employing OA is to decrease the number of experimental runs by managing proper parameter selection. Using the OA, the 27 total experiments for three factors and three levels can be reduced to nine, saving both machine hours and cost. For all experimental runs, the layer thickness of 0.06 mm and the scanning approach using stripes remained fixed. Table 3 displays the selected parameters for fabrication. Their combined effect has been calculated using the following equation (Kurzynowski et al., 2018).

Table 3
L_9 orthogonal array of process parameters for fabrication.

Sample No.	V (mm/s)	P (W)	h (μm)
S1	700	250	80
S2	700	300	90
S3	700	350	100
S4	900	250	90
S5	900	300	100
S6	900	350	80
S7	1100	250	100
S8	1100	300	80
S9	1100	350	90

$$E = {}^{P}/_{(v * l * h)} \qquad \text{.............(1)}$$

Where E is the energy density J/mm^3, l is the thickness of the powder layer, h is the hatch distance, V is the scan speed, and P is the laser power.

2.2 Surface roughness measurement

The surface roughness of samples was measured through Bruker Nano GmbH optical profilometers. The machine has a resolution of less than 0.01 nm and a maximum scan range of up to 10 mm. The surface tester measures four roughness parameters: average roughness (R_a), root-mean-square roughness (Rq), peak and valley heights (R_p, R_V), and maximum peak-to-valley height (R_t).

3. Results & Discussion

Table 4 shows the surface roughness parameter values for 316L SS samples at different energy densities. The roughness parameters such as R_a, R_q, R_p, $R_{t,}$ and R_v values have been extracted from the optical profilometers and shown in fig.4(a-c). The result showed the minimum R_a value obtained at high energy density. Here, the R_a value of SLM fabricated samples varies from 6 μm to 10 μm

Many researchers have reported that after applying the shot peening, the R_a can be achieved up to 1 μm. The R_a value has been seen as high for sample 7, as shown in fig.4 (a), at low energy density. Improper melting has occurred, and pores are formed at low energy density. If the

Table 4
Surface roughness parameters values obtained for samples.

Sample No.	E (J/mm³)	R_a (µm)	R_q (µm)	R_p (µm)	R_v (µm)	Rt (µm)	S/N ratios (R_a)
S1	74.33	7.16	10.95	42.77	-79.39	122.16	-17.09
S2	79.33	6.65	9.73	47.88	-73.35	121.23	-16.46
S3	83.33	7.27	10.59	39.97	-78.51	118.54	-17.23
S4	51.33	9.53	12.09	46.76	-79.80	126.67	-19.58
S5	55.50	10.91	14.53	51.45	-79.83	131.29	-20.75
S6	81.0	7.69	10.82	47.18	-85.83	135.64	-17.72
S7	45.33	10.44	13.66	65.92	-76.36	142.60	-20.37
S8	56.66	8.53	10.76	52.33	-75.82	128.15	-18.62
S9	58.83	10.70	14.22	46.46	-79.57	126.04	-20.59

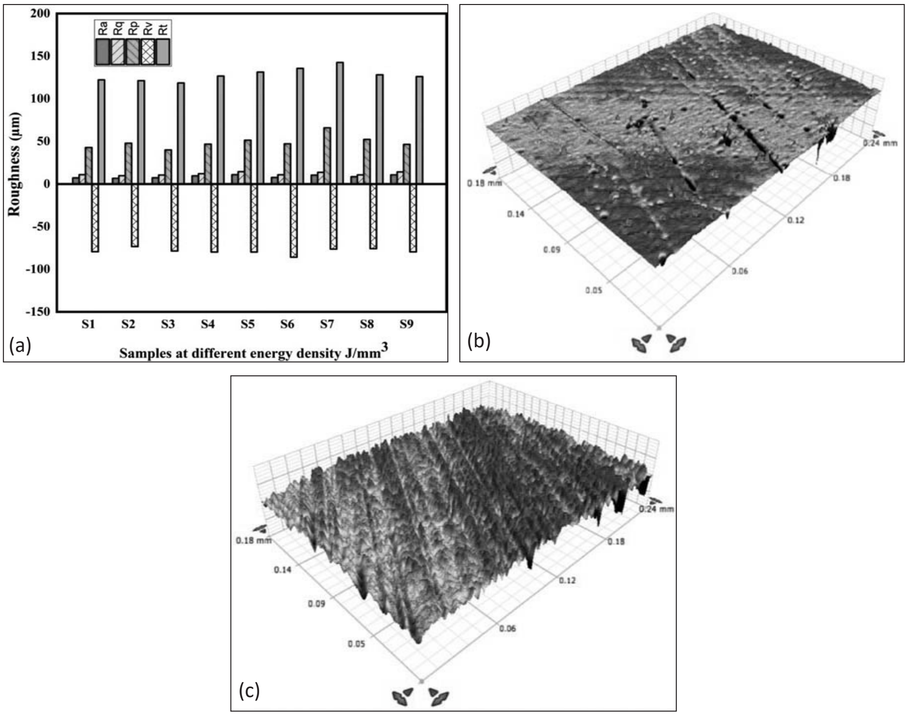

Fig. 4. (a) Surface roughness parameters correlation with energy density (b) 3D profile of polished sample 7 at low energy density (c) 3D profile of polished sample 9 at high energy density.

melting track's depth is insufficient, its wettability on a solid substrate is also insufficient. The interfacial tension effect causes the melting tracks to shrink into a ball, and some tiny metal balls make up the scanning line. The roughness of the polished samples was measured at both low and high energy densities. However, after polishing the surface, the roughness can be reduced to 0.022 µm for sample 7. Some pores were visible at low energy density, as seen in fig. 4(b). Fig.4 (c) shows the R_a value of the polished sample. It can be seen that no pores are visible at high energy density. In the present study, for the selected range process variable, the R_a value can be achieved up to 0.049 µm after grinding and polishing. Fig. 5 illustrates the average R_a correlation against energy density. With an energy density of 79.33 J/mm3, sample 2 yields the lowest R_a value. The high laser power, slow scanning speed, and optimal hatch spacing, therefore, decrease

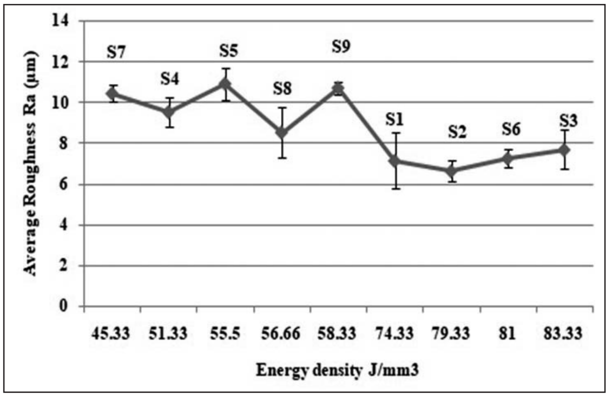

Fig. 5. Average roughness correlation with increasing energy density.

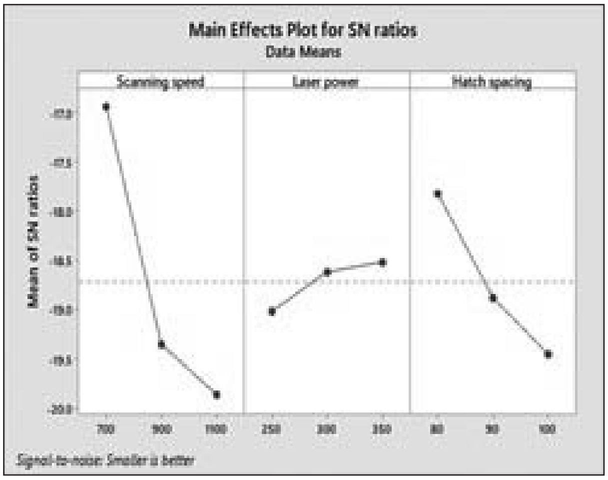

Fig. 6. Main effects plot for data means.

the surface roughness. It has been observed Ra value is high at low energy density. As the energy density increases to a certain level, the Ra decreases, then further, and its value increases at high energy density. The MINITAB software has been used to determine the signal-to-noise (S/N) ratio using the "smaller is better" method. All roughness variables showed a similar pattern; hence the S/N plot was only reported for average surface roughness. Fig. 6 displays the S/N plot for the data means of R_a value The S/N plot shows that the optimum R_a was obtained when the scanning speed was 350 mm/s, followed by laser power of 350 W and hatch distance of 0.08 mm.

4. Conclusions

The surface roughness of 316L SS components fabricated by SLM was examined about process parameters. Three process variables, including scanning speed, hatching distance, and laser power, were examined for their effects on surface roughness. The laser energy density significantly impacts the SLM fabrication quality. Different laser energy densities are correlated with various fabrication properties.

- The results show that the minimum value of R_a for as-built parts of 6.65 μm is obtained at high energy density. The R_a is increasing at an energy density below 45.33 J/mm^3.
- The high laser power, low scanning speed, and hatch spacing are the preferable parameters to obtain a low R_a value. The S/N plot showed the R_a achieved low at the laser of power 350 W, scanning speed of 700 mm/s, and hatch spacing of 0.08 mm.
- The roughness of the polished samples was determined at both high and low energy densities. The average roughness of samples can be reduced by increasing the energy density to a specific value. The roughness of the polished sample can be achieved at 0.049 μm at an energy density of 58.83 J/mm^3 after the polishing and grinding operation.

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Meena Pant is a Ph.D Scholar in the Department of Mechanical Engineering at the National Institute of Technology Delhi. She has completed a Master of Technology in Computer-Aided Design & Computer Aided Manufacturing (CAD/CAM) from the Department of Mechanical Engineering, National Institute of Technology, Delhi, in 2019. She has published four journal papers and two conferences in additive manufacturing.

Dr. Leeladhar Nagdeve is currently working as an Assistant Professor in the Department of Mechanical Engineering at the National Institute of Technology Delhi. He has received his Ph.D from the Department of Mechanical Engineering, Indian Institute of Technology (IIT) Kanpur, India. His research interests are the Nano-finishing of freeform/sculptured surfaces, Advanced Machining Processes, Magnetic and non-magnetic based nano-finishing processes, and Nano-Finishing of Bio-materials. He has published more than 20 journal papers also book chapters, and attended conferences at the National and International levels.
(E-mail: ldnagdeve@nitdelhi.ac.in)

Dr. Girija Moona is currently a Senior Scientist at CSIR-National Physical Laboratory, India. She has received her Ph.D from the Department of Mechanical Engineering at Delhi Technical University. Her specialization includes dimensional metrology, composite materials, mechanical testing, and advanced manufacturing process. She has published many research papers in National and International journals, also reviewed articles and book chapters, and attended conferences at the National and International levels. (E-mail: girijamoona1@gmail.com)

Dr. Harish Kumar is currently working as an Associate Professor in the Department of Mechanical Engineering at the National Institute of Technology Delhi. He received his Ph.D from the Department of Mechanical Engineering at Guru Gobind Singh Indraprastha University. Previously, He had ten years of experience as a scientist at National Physical Laboratory India. His research interest is Force transducer, metrology, additive manufacturing, and metal matrix composite. He has published more than 151 research papers in reputed journals and also book chapters, review articles, and conferences. (E-mail: harishkumar@nitdelhi.ac.in)

Dr. J. Ramkumar, Professor in the Department of Mechanical Engineering and Design Program at the Indian Institute of Technology Kanpur, has over 20 years of experience in the industry, research, and academia. He joined as an Assistant Professor in the Department of Mechanical Engineering in Dec 2003. He has published over 330 articles in peer-reviewed international journals and has delivered over 100 lectures at international conferences. He has 4000+ citations for his publications & an h-index of 33, which endorses his high research productivity. Five of his patents are commercialized, a total number of patents in his name being 88. He has procured funding of over US $ 5 million so far at IIT Kanpur. He is a reviewer of 27 technical journals from Elsevier, Blackwell Publishing Inc., Wiley, Springer, Hindawi, Highwire, MRS India/INSA, ACS Publications, Institution of Civil Engineers and American Society of Metals.
(E-mail: jrkumar@iitk.ac.in)