Surface Roughness Analysis of Cold-Spray and Selective Laser Melted Manufactured 316L Stainless Steel Parts for Biomedical Applications

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Abstract-

Additive Manufacturing (AM) processes have emerged as the most preferred method for production of components for bio medical applications. Selective Laser Melting (SLM) is one of the AM processes used in producing metal components. In addition to the other mechanical and bio-mechanical properties the surface properties of the AM manufactured parts are very important for the human body to accept the parts and growth of ligaments in case of implants like knee and hip joints. Cold Spray (CS) is method,basically a metal spray technique, has also been used to manufacture components as in AM by spraying metal into mold. The present paper discusses the comparison of surface roughness of the 316L stainless steel samples manufactures using SLM and cold spray. To observe the difference in the output parameter i.e surface roughness, the material used for experimentation was same i.e. 316L stainless steel powder. It has been observed that the surface roughness the material used for both the in CS is better as compared to SLM process.

Keywords- Selective laser melting; Cold spray; 316L stainless steel; Surface roughness

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1. INTRODUCTION

In the current scenario of manufacturing advancements, additive manufacturing (AM) techniques have proved to be better compared to the traditional processes [1]. The AM processes play a vital role in overcoming the flaws during subtractive manufacturing [2]. With the development of processes and addition of more and more materials AM manufactured components have found application and have started replacing the subtractive manufacturing methods. With appropriate AM method coupled with the required material have made a big difference in the manufacturing environment, the biggest beneficiary being bio medical area.

One of the widely used AM technique is the laser-powder bed fusion process, also known as the selective laser melting (SLM) process [3]. SLM is used in the production of the metal components using the metallic powders where a very high-intensity laser source is used to melt the selective regions of the powder and fuse layer over layer. SLM process exposes the metal powder to very high temperature and results in phase changes which further results in change in the properties of the material.Cold spray method, on the other hand, is basically a metal coating technique under low temperature conditions and the component is made layer by layer.

Apart from using it as coating, several researchers are investigating the use of cold spray to print standalone parts by depositing thick layers over substrate [4]. In CS metal powder particles of size ranging between 5-100 microns are used to create deposits on the substrate with the help of high-velocity powder jet. The sudden impingement of jet results in the sticking of metal powder on the surface. The velocity of the gas stream used to carry powder is increased on the expense of its pressure energy using de Laval type nozzle. The powder particles, initially transported by a gas source, are pumped into the nozzle either at the inlet of the nozzle or a lower downstream pressure point. Upon entering the nozzle, the particles are then propelled by the nozzle gas flow and impacted upon a substrate. The powder particles which strike with the velocity more than critical velocity will result in the formation of bond with the substrate. As the process followed the particle continues to strike and results in the coating layer [5].

It is recognized fact rougher metal surfaces have comparatively higher corrosion potential. Metals like stainless steel [6,7], copper alloys[8] and titanium-based alloys[9] with low surface quality are more often susceptible to the pitting and consequently have high rate of corrosion.Process parameters of both CS and SLM techniques effect on surface quality owing to the alteration in process. In SLM, process parameters like laser power, scan strategies, powder morphology, scan speed, spot diameter, layer thickness and component orientation effect the surface quality [10].

2. Methodology

2.1 Metal Powder

In both selective laser melting (SLM) and high-pressure cold spray (CS) techniques material, spherical-shaped 316L grade stainless steel (PLM-316AA) powder with 99 % purity was used to print samples parts. Table 1 indicates the composition of the powder.

Table 1 Composition of 316L grade stainless steel feedstock powder used by selective laser melting (SLM) and cold spray (CS) processes for the fabrication of316L stainless steelparts.

Elements	Fe	Cr	Ni	Mo	Mn	Si	C	P	S
%age (by weight)	68.22	17.05	10.30	2.39	1.56	0.40	0.03	0.03	0.015

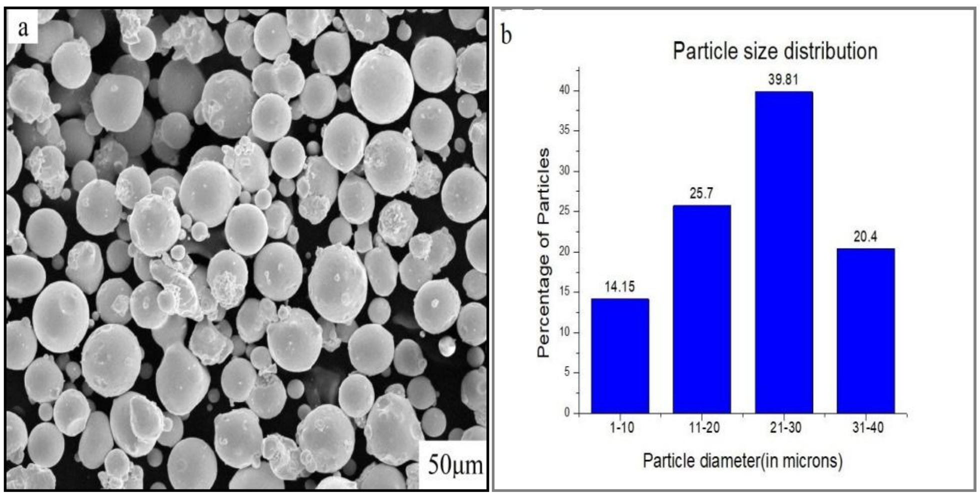

Fig.1. (a) Surface morphology and (b) particle size distribution of 316L grade stainless steel powder used to fabricateparts by selective laser melting (SLM) and cold spray(CS) techniques.

The metal powder was analyses using scanning electron microscope (JEOL, JSM-6610LV, Japan) confirmed the powder's shape to be spherical, shown in Fig 1(a) with presence of 86 % of particle diameter within 11-40 μm range.

2.2 Development of SS 316L Samples

A selective laser melting technique (EOS GmbH, EOSINT M 280, Germany) with a recommended process parameter (Table 2) and maximum 3d printing volume of 250 mm X 250 mm X 325 mm was used to produce 316L stainless steel specimen of dimensions measuring 20 mm X 60 mm X 5 mm (fig. 2).The sample was fabricated over the substrateof medium carbon steel grade C45.High-pressure cold spray system (Plasma Giken, PCS-100, Japan) was used to 3d print the other 316L stainless steel specimen with dimensions of 25mmX30mmX1mm(fig.

3).The process parameters used to print the CS specimen are given in Table 3.

Table 2 Process parameters used to print SS 316L part by selective laser melting technique.

Laser type	Laser wavelength	Spot diameter	Laser power	Layer thickness	Hatch distance	Scanning speed	Inert gas used
Yb-fiber laser	1100 nm	0.1mm	210W	0.04mm	0.09mm	900mm/s	Argon

Fig. 2. Photograph of fabricated selective laser melted 316L stainless steel specimen of 5 mm thicknessformed using recommended process parameters.

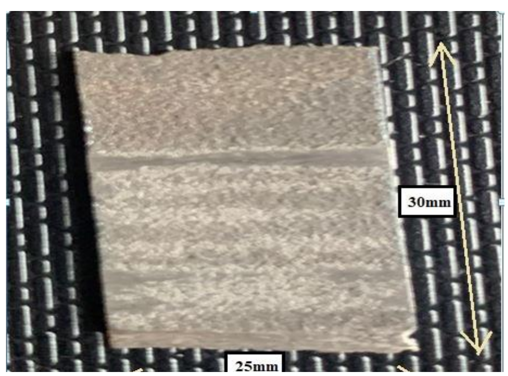

Fig. 3. Additive manufacturing (AM) of 316L stainless steel part of specified dimensions using cold spray (CS) technique at recommended process parameters.

Table 3 Process parameters used to print SS 316L part by cold spray technique.

Nozzle	Carrier gas	Gas pressure	Gas temperature	Stand-off distance	Gun transverse speed	Number of passes	Step size	Powder feed rate
Tungsten Convergent -Divergent	Nitrogen	50 bar	873 K	25 mm	0.3 m/s	15	1.5 mm	20 g/min

2.3Surface Roughness Measurement

The surface roughness of parts (CS and SLM manufactured) was measured using standard type surface roughness tester (Mitutoyo, SJ-210, Japan). The device evaluated quick and precise surface roughness results in terms of the mean value in micrometers. The measuring force of 0.75 mN was employed by a stylus with the tip diameter, corresponding to 2 µm at an angle of 60^o on the testing surface. Furthermore, stylus speed was set to 0.25 mm/s along with the returning speed of 1 mm/s. While quantifying the value, the device also detected the grooves and recessions as peaks and valleys on the cross-section. To comprehend the reason behind the values of surface roughness, the SEM micro-images were taken. The Mountains 8 image processing software analysis were done to analyse the roughness of the samples.

2.4Results and Discussion.

Diligent measurement of 10 readings using surface roughness tester for SLM and CS specimens with their respective average roughness (Ra) and root mean square roughness (Rq) are shown in Table 4. It was observed that, at recommended parameters for both processes, the surface roughness of CS part was 28 % lower than the corresponding SLM. It is pertinent to note that in both cases, surface roughness can be altered by varying the process parameters. The surface quality of the cold sprayed samples is significantly affected by technique's process variables like

Table 4. The surface roughness tester measured average surface roughness (Ra) and root mean square roughness (Rq) of 316L stainless steel fabricated part manufactured using cold spray (CS) and selective laser melting (SLM) technique.

Reading no.	**AF-CS**		**AF-SLM**	
	Ra (µm)	Rq (µm)	Ra (µm)	Rq (µm)
1	6.12	8.04	11.32	14.37
2	5.31	6.99	5.56	7.06
3	5.56	7.33	6.98	8.86
4	5.23	6.89	6.11	7.76
5	5.92	7.80	7.34	9.311
6	5.74	7.56	5.99	7.607
7	5.81	7.66	7.45	9.46
8	6.75	8.89	6.63	8.42
9	6.03	7.94	7.11	9.03
10	5.61	7.39	10.12	12.85
Average	5.81	7.65	7.46	9.47

powder characteristics, gas temperature, pressure, stand-off distance, type of carrier gas and substrate material[11-13]. Furthermore, the surface roughness in selective laser melted specimen is prone to the alteration of powder size, layer thickness, laser power and the orientation inside the building chamber [14,15]. Theroughness variation in 10 readings, being1.52 μm inCS and comparatively higher of 5.76 μm in SLM was noted by calculating difference of maximum and minimum readings from the table 4. In an attempt to establish the cause, this variation was studied using SEM micro-images and Mountains8 software results, as shown in Fig. 4.

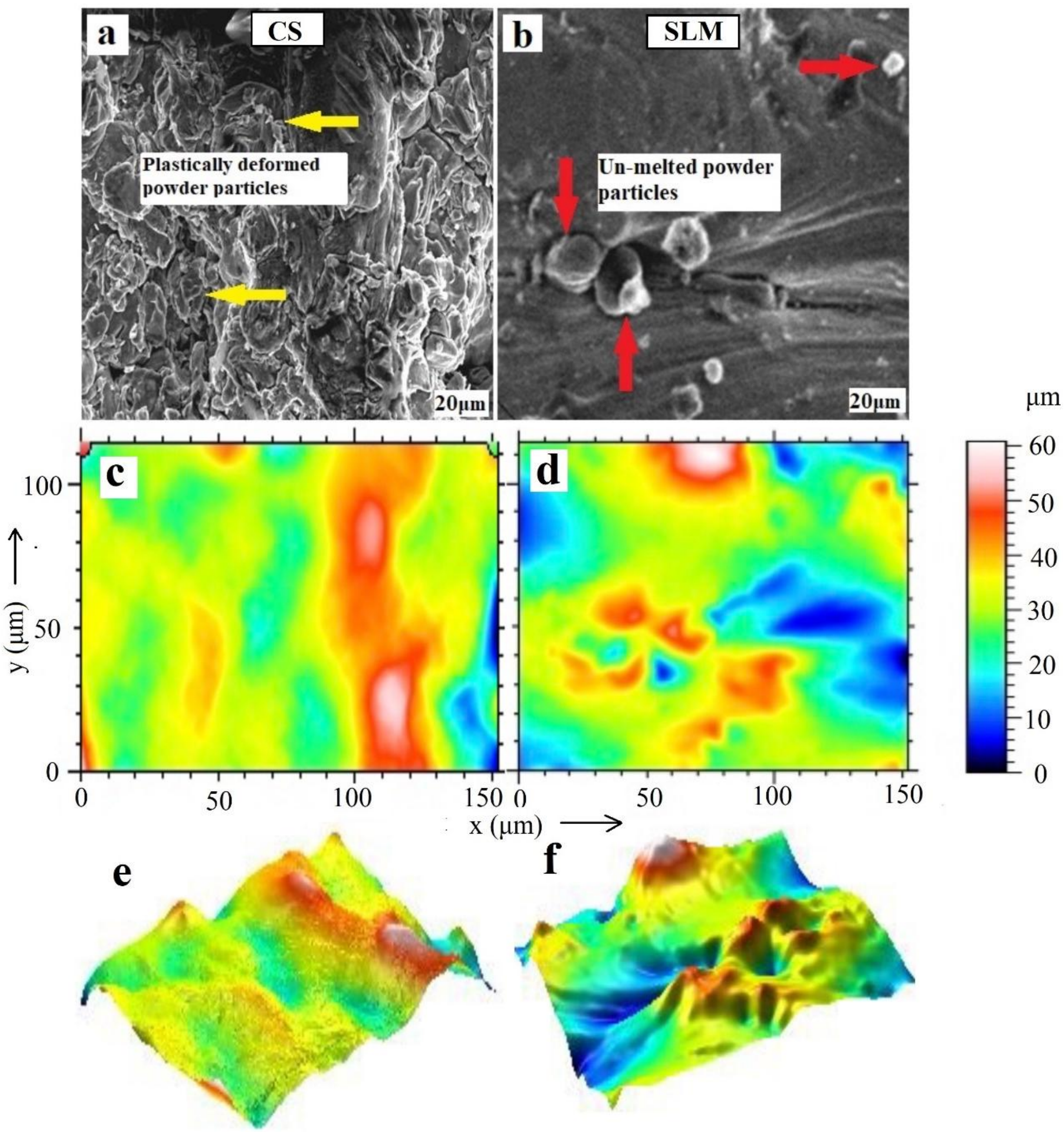

Fig. 4. Scanning electron microscopic (SEM) and mountains8 colour coded (2D and 3D form respectively) cross-sectional images of 316L stainless steel part developed using (a,c,e) cold spray (CS) and (b,d,f) selective laser melting (SLM) technique.

In CSmanufactured part, the high-velocity particle on striking the substrate results in plastic deformation and as an outcome gets adhered to it due to adiabatic shear instability. Owing to the gas pressure of 50 bar used in this study, the high particle velocity was achieved, resulting in the deformation of particles to a greater extent shown in Fig. 4(a).This high plastically deformed particles in CS then formed the surface of low average roughness (5.81 μm) as compared to SLM part. The negligible variation in the ten roughness readings of the cold sprayed sample can be attributed to the almost uniform particle plastic deformation throughout the specimen. Subsequently, the carrier gas temperature of 873 K has also substantially affected the surface roughness of the sample. By virtue of the previously mentioned temperature, the particles carried by gas must have raised to a temperature below their melting point. This heating results in thermal softening of particles, thereby easing the process of plastic deformation, resulting in low surface roughness [16].

In the case of SLM, the average value of Ra was measured as 7.46 μm. The concise information of this value being greater than CS includes the process of melting and solidification of laser affected powder. The area under the immediate effect of laser undergoes indentation of powder layer that collapses due to change in the velocity vector field of laser [17-19]. The indentation then results in the voids on the cross-section of the SLM surface contributing to the surface roughness. Also, on account of the high scanning speed of 900 mm/s, some particles present at a significant distance from laser spot left un-melted (Fig. 4 (a)) adding up to thevalue of roughness and sudden hike of some readings (Reading 1 and 10). The Mountains8 colour coding analysis (Fig. 4(c,d)) complements the discussion by providing the peaks on the surface relative to the ground level represented by blue colour. The range of values corresponding to 0-60 μm was similar in both CS (Fig. 4(c)) as well as SLM (fig. 4 (d)), with the maximum peak value at 60 μm shown by pink colour. The excess area shown in the graph presents the peaks of cold sprayed samples in the range of 20-40 μm, relative to blue colour (fig. 4 (e)), proving the uniformity of the aforementioned ten surface roughness readings. Similarly, the range of 0-40 μm was observed in the excess region of selective laser melted part along with the presence of voids and peaks, as shown in fig. 4 (f). Further, the surface texture graph of the CS and SLM is shown in fig. 5. The accentuated small peaks and valleys in the range of -10 to 10 μm can be seen in CS (Fig. 5 (a)) as compared to SLM (Fig. 5 (b)). Its presence can be attributed to the process of the adhesion of particles repetitively banged over others, resulting in the small grooves. Furthermore, in case of SLM the solidification of the meltpool resulted in the comparatively a smaller number of peaks and valleys owing to the smooth structure with peaks and valleys of greater size as discussed earlier.

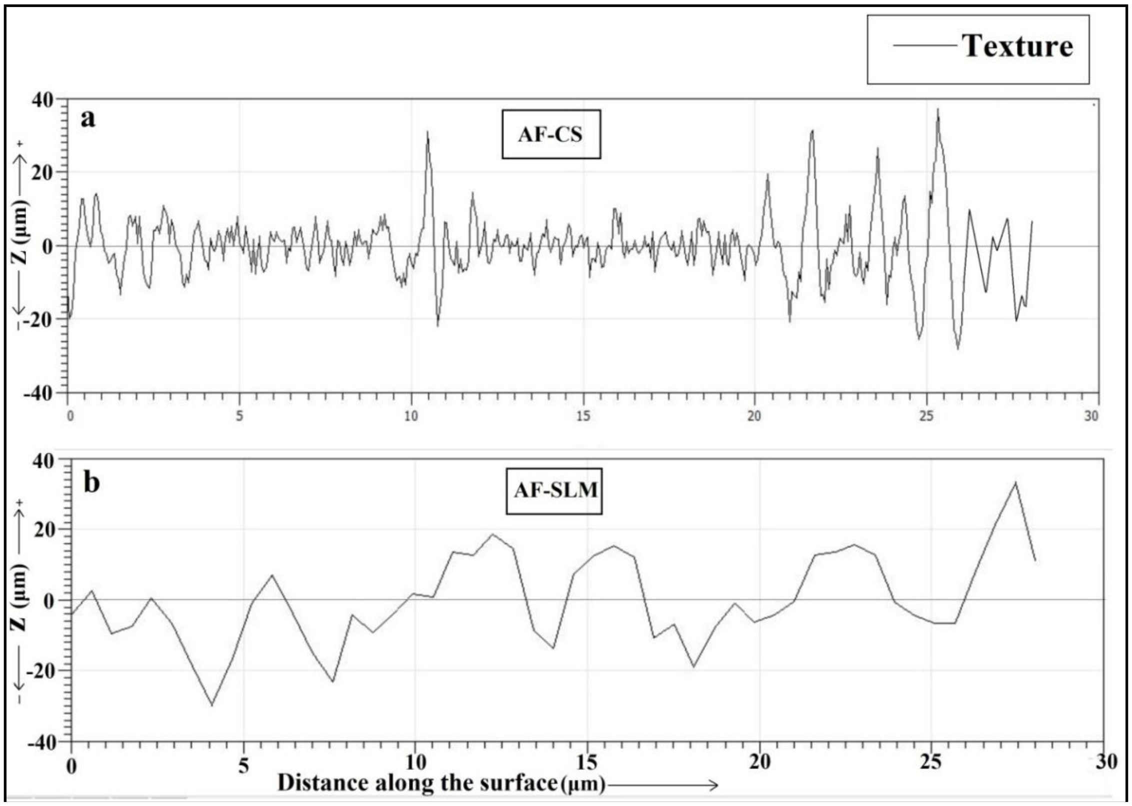

Fig. 5. Surface texture graph of 316L stainless steel part additively manufactured using (a) cold spray (CS) and (b) selective laser melting (SLM) technique.

2.5Conclusions.

From the discussion it can be concluded that surface roughness obtained in the SLM sample was 28 % higher, compared to CS. Besides the lousy surface quality of SLM, a sudden hike in roughness values was observed (Table 5.1), attributed to the presence of un-melted powderowing to high scanning speed of 900 mm/s. SEM image provides the evidence to support the previously mentioned claim (fig. 5.10). On the other hand, a CS sample with a comparatively low surface roughness value was developed using the CS system's recommended parameters. It is relevant to mention that the roughness can be tailored to lower values using optimized parameters of the CS technique.The minor variation in the 10 values of CS sample was confirmed and attributed to the uniform particle plastic deformation throughout the sample. The superior surface quality obtained in the CS technique will reduce the corrosion potential of the sample. Since the corrosion is an ample concern in biomedical applications affecting biocompatibility, the CS sample proves its suitability over SLM as a viable technique to develop bio-implants.

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