Effect of Process Parameters on Surface Roughness of Laser Processed Inconel Superalloy

Sateesh.N.H, Mohankumar.G.C, Prasad Krishna

Abstract — Direct metal laser sintering (DMLS) is an additive manufacturing technology that uses a high power laser to produce three dimensional parts by sintering metal powders spread on the substrate under protective inert gas environment. This paper focuses on direct metal laser sintering of Inconel-625 super alloy and its surface roughness studies. Inconel-625 material was sintered on steel substrate by varying the laser scan speed from 2.5 to 10 mm/s in steps of 2.5, hatch spacing from 0.2 to 0.4 mm in steps of 0.1, while laser power, hatch width and layer thickness were maintained constant at 240 W, 5 mm, 50 μm respectively with laser beam diameter of 0.4 mm. The build orientation during sintering was such that the axis of the cylindrical specimens was parallel to the build direction. Nitrogen atmosphere was maintained in the build chamber. The Surface roughness studies clearly reveal that with increase in laser scan speed and hatch spacing there was an increase in surface roughness of the sintered parts.

Index Terms - Additive manufacturing (AM), Direct metal laser sintering (DMLS), Inconel-625, Characterization and Surface roughness.

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1 INTRODUCTION

Aeronautic, nuclear, marine, chemical, and petrochemical industries now-a-days demand highly advanced engineering materials having superior mechanical properties [8]. Inconel-625 is one such super-alloy widely used in such industries because of its attractive properties at high temperatures such as excellent resistance to corrosion and oxidation, resistance to strain age cracking, and outstanding creep resistance at high temperatures. Inconel-625 is a non-magnetic, nickel-base alloy with outstanding strength and toughness in the temperature range cryogenic to 1093^{0}C are derived primarily from the strengthening effects of the refractory metals, niobium and molybdenum, in a nickel–chromium matrix. Nickel and chromium provide resistance to oxidizing environment, while nickel and molybdenum to non-oxidizing environment. Pitting and crevice corrosion are prevented by molybdenum. Niobium stabilizes the alloy against sensitization during welding. Its resistance to chloride stress- corrosion cracking is excellent. Some typical applications for Inconel-625 are heat shields, furnace hardware, gas turbine engine ducting, chemical plant hardware and nuclear reactor control rods [7]. The material possesses a high degree of formability and shows better weldability than many highly alloyed nickel-base alloys. It is also used in functional prototypes and high temperature turbine parts [4].

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Lot of researchers studied about the surface roughness of different materials processed using laser sintering process. The effect of different laser parameters, i.e., laser beam power, spot size, scanning speed, and hatching distance; on various properties of a laser sintered CuSn-made parts for surface roughness was investigated [10]. The surface roughness, density, and porosity for Cu, Fe, and Ni-based laser-sintered material processed by using DMLS process were investigated [14]. While measuring the surface roughness, they concluded that the building direction had a coarser topography than the surface parallel to the building direction. The effect of bronze infiltration into two different metallic powders with two different SLS machines was compared [3]. The surface roughness, bending strength density, and hardness have been measured to determine the characteristics of sintered parts. The surface roughness of laser sintered metallic parts was investigated taking laser power, scan speed, scan spacing, and layer thickness as process parameters [9]. They found that the parameters of the top surface are around Rz 35–45 μm and Ra 10–12 μm, respectively, but after post-sintering treatment, the surface quality improved and the Rz and Ra parameters were reduced to around 30 to 8 μm, respectively. The effect of laser power and scanning speed on silica sand for surface roughness was investigated using self developed high-temperature laser sintering equipment [12]. It was observed in the study that the increase in laser power tends to increase surface roughness and the increase in scanning speed tends to decrease the surface roughness. The numerical method to optimize part orientation for selective laser sintering by taking build time, part strength, and surface finish into account was developed [13]. A process planning approach to improve the efficiency in layered manufacturing process and surface quality of a product was proposed [11]. They presented an algorithm to determine the successive layer area difference for layer deposition. A generic algorithm to

determine the best part orientation for creating rapid prototyping parts with a higher level of accuracy and surface finish was presented [5]. The revised average weighted surface roughness, which considered stair-stepping effect and build time, was taken from the convex hull model, and the best orientation was chosen using the simple additive weighting method [1]. A feed forward neural network with back-propagation learning algorithm to improve mechanical properties, surface roughness, accuracy, and processing time for DMLS process was developed [6]. This also helps in determining the most suitable parameter setting, according to different process requirements, the different process parameters and resulting properties can also be estimated from the database. Surface roughness is a primary concern in rapid prototyping and it is highly related to the shape and size of the sintered particles, packing direction, and packing density.

The literature available clearly gives information about surface roughness studies on different engineering materials that are used to produce complex parts by direct metal laser sintering (DMLS) process with different process parameters. With the vast literature review, very less information is available about the study of surface roughness of super alloy materials by laser sintering. In the light of the above, present investigation is aimed at studying the influence of different process parameters on surface roughness of Inconel-625 sintered parts.

2 EXPERIMENTAL DETAILS

Inconel-625 in powder form was chosen as sintering material and its chemical composition is shown in Table 1. Figure 1 shows the scanning electron micrograph of Inconel-625 powder particles used in this study. It can be seen from the figure that the powder particles are spherical in shape. Particle size analysis was carried out using laser based particle size analyser of make: HRLD, USA and model: 8000A. 20 mg of Inconel-625 powder was mixed with hydraulic oil. The powder-oil mixture after mixing is passed through particle size counter. The particle size analysis revealed that the size distribution varies between 30-60 µm. Table 2 gives the information about particle size distribution of Inconel-625 powder. Stainless steel rectangular bar of higher hardness is used as the substrate material to sinter the Inconel-625 powder on it.
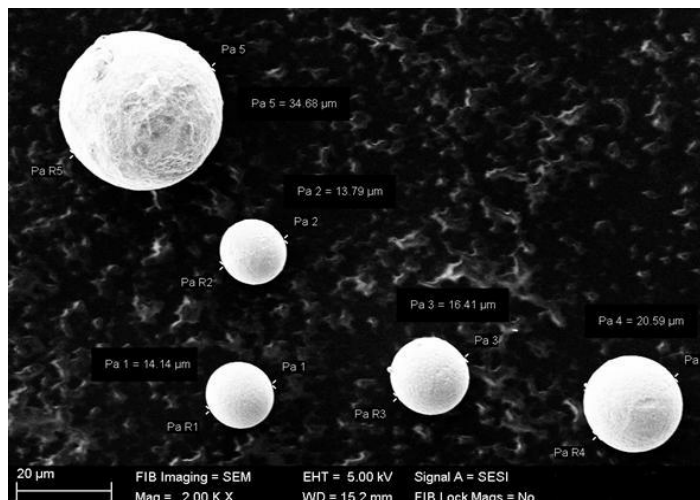
Table 1
Chemical composition (in wt. %) of Inconel-625 (Powder alloy corporation, USA)

Ni	C	Fe	Mn	Si	Cr	Mo
58.0	0.1 max	5.0 max	0.5 max	0.5 max	20-23	8-10
Nb+Ta	Al	P	S	Co	Ti	
3.15-4.15	0.4 max	0.015 max	0.015 max	1 max	0.4 max	

Fig.1 Scanning electron micrograph of Inconel-625 powder

Table 2

Particle size distribution of Inconel-625

Particle size (µm)	10	20	30	40	50	60	70	80	90
Percentage (%)	2	2	54	20	15	3	2	1	0

The energy density calculations were done initially by varying the scan speed from 2.5 to 10 mm/sec in steps of 2.5 and hatch spacing from 0.2 to 0.4 in steps of 0.1 at constant laser power of 240 watts and beam diameter of 0.4 mm. The laser energy density for different scan speeds and hatch spacing were calculated using the Andrew number equation (1) as shown:

$E = P / V \delta$ ………. (1) [2] Where,
E=Energy density in J/mm^2,
P=Laser power in watts,
V=Scan speed in mm/sec and δ= Hatch spacing in mm.

EOSINT M250 Xtended RP machine was used for laser sintering of Inconel-625 with CO_2 laser as the heat source. Laser sintering of Inconel-625 is tried as per the parameters mentioned in the table 3. The laser sintering is done in inert atmosphere to avoid oxidation. The sintered specimens on the substrate were cut using wire electrical discharge machine of make charmilles technologies and model ROBOFIL 290 and deburred for measuring surface roughness. The surface roughness of the sintered specimens was measured using confocal microscope of make: OLYMPUS, JAPAN and model: OLS4000.

Table 3

Process parameters used for laser sintering of Inconel-625

Power (P) (Watts)	Scan Speed (V) (mm/s)	Beam Dia. (mm)	Hatch Spacing (δ) (mm)
240	2.5	0.4	0.2
	5		
	7.5		
	10		
240	2.5	0.4	0.3
	5		
	7.5		
	10		
240	2.5	0.4	0.4
	5		
	7.5		
	10		

Fig.2 Laser sintered Inconel-625 specimens

3 RESULTS AND DISCUSSION

3.1 Analysis of sintered specimens

Fig.2 shows the photograph of Inconel-625 specimens sintered using the parameters mentioned in the Table 3. It can be observed from the figure that only part of the specimens was built for hatch spacing of 0.2 mm for all four laser scan speeds. The sintering process cannot be continued further because of jamming of the recoater blade due to severe balling effect. Then the sintering is tried with 0.3 mm hatch spacing, there was no jamming of the recoater blade and specimens were built almost to the required height 7 mm and diameter 12 mm, for all four laser scan speeds. Then the specimens were successfully sintered also for hatch spacing of 0.4 mm, but with lesser efficiency in dimensions compared to 0.3 mm hatch spacing. So, from the fig. 2 it is evident that hatch spacing of 0.3 mm yields better results compared to hatch spacing of 0.4 mm.
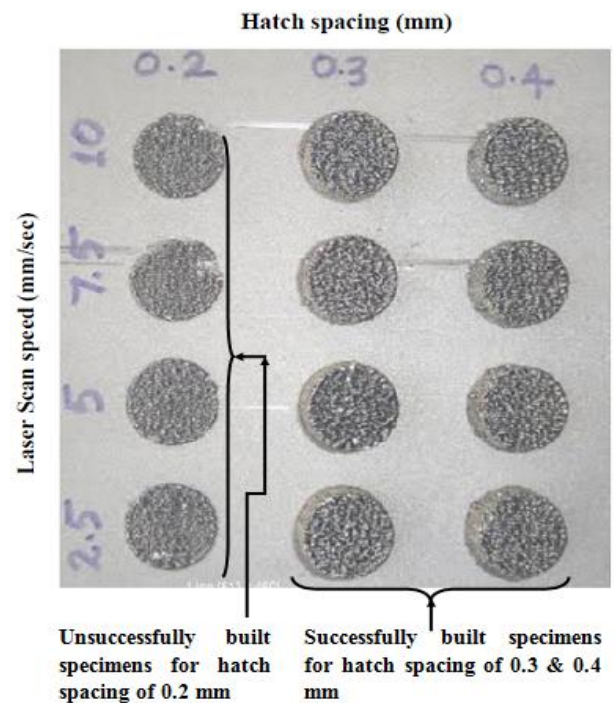
3.2 Surface roughness

The surface roughness measured along the sintered surface of the sintered Inconel-625 in inert atmosphere. The effect of the laser scan speed on the surface roughness of the laser sintered Inconel-625 is shown in the Fig.3.It is evident from the figure that the surface roughness increases with the increase in the laser scan speed. It is also clear from the figure that Inconel-625 sintered at a laser scan speed of 2.5 mm/s are smooth compared to those sintered at 10 mm/s.

The surface topographies taken from the confocal microscope shown in Fig. 4 also confirms the presence of the variable sharp peaks for the higher scan speed and moderate peaks for lower scan speed. The variation of the surface finish with laser scan speed can be explained in terms of the laser energy density. When the scan speed is low, the laser energy density is high, as laser density is inversely proportional to the laser scan speed. Literature also confirms that the surface roughness is a function of laser power density and line spacing [10]. The powders will be fully melted at lower scan speed, resulting in reduced melt viscosity, balling effect and increased melt cylinder diameter, leading to better connectivity and reduction in the inter pore size.
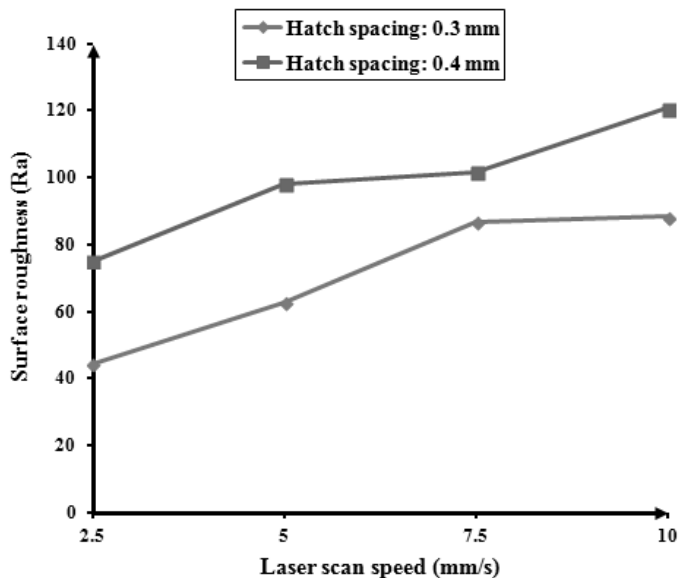
Fig. 3 Variation of Surface roughness with laser scan speed
of laser sintered Inconel-625

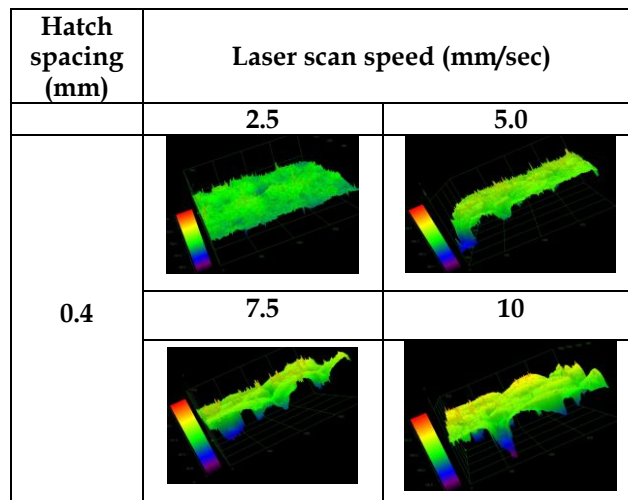| Hatch spacing (mm)	Laser scan speed (mm/sec)	
	2.5	5.0
0.4		
	7.5	10

Fig. 4 Surface roughness measurement of laser sintered

Inconel-625 from confocal microscope

At lower scan speeds, higher heat energy is induced into the powder bed, resulting in increase of melt temperature with less viscosity, lower contact angle and higher marangoni flow and capillary force, resulting in full densification and good surface finish with lower surface roughness values. At higher laser power increased heat affected zone will increase the percentage of unmelt powder sticking to the surface of the built parts resulting in increased surface roughness. At higher laser scan speed lower energy density results in partial melting and viscosity is high leading to balling effect. The balling effect results in poor surface finish with higher surface roughness values. It is also evident from the confocal pictures and the graph that surface roughness of the sintered specimens for the hatch spacing of 0.3 mm is better than the sintered specimens with hatch spacing of 0.4 mm.

4 CONCLUSIONS

Inconel-625 has been successfully sintered at different processing conditions by DMLS process. Surface roughness of the sintered Inconel-625 parts increases with increase in laser scan speed under constant laser power, beam diameter and hatch thickness. This study also revealed the fact that the hatch spacing of 0.3 mm gives better results with respect to surface roughness compared to hatch spacing of 0.4 mm while processing Inconel-625 using DMLS process.

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Hatch spacing (mm)	Laser scan speed (mm/sec)	
	2.5	5.0
0.3		
	7.5	10

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