Study of build rate in laser directed energy deposition

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Build Rate.

ABSTRACT

Laser directed energy deposition is an additive manufacturing process in which laser melted powder deposited at target spot. In the past few years, it has become more popular because it lets manufacturers make complex parts in small batches with a small number of post-processing steps. Fabrication of components in directed energy deposition takes lots of time. Therefore, it is necessary to study the build rate in laser directed energy deposition method. Optimum values of different powder feed rate, scan speed, and laser power on build rate are evaluated. It observed that the laser power is a significant process parameter in build rate followed by scan speed and powder feed rate for the printing of Inconel 718.

1. Introduction

Directed Energy Deposition, often known as DED, is a technique that is extensively utilized in the coating and repair industries. In DED, the powder is blown into the laser-initiated melt pool. Recently, this technique has been used in advanced technological industries for the fabrication of complex components. Heavy industries, those producing shipbuilding, and turbomachinery-based parts are seeking their interest in additive manufacturing (AM) (Dass & Moridi, 2019; Strickland, 2016). However poor deposition rate and high fabrication cycle durations of the DED technique may be difficult. But the parametric study can achieve a fast deposition rate while maintaining high quality and a high productivity level. In a DED operation, single-track deposition is the fundamental building block of the DED process. The main DED process parameters affecting the single-track characteristics are laser power, scan speed, and powder feed rate (PFR) for a particular laser beam diameter and laser beam profile. It is necessary to probe into the variation in the deposition rate and quality of the single tracks at different combinations of LDED process parameters. Thus, the selection of optimum process parameters and their values becomes essential for a high deposition rate.

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The ability to reach a high level of productivity is the primary benefit that comes from utilizing high-power inputs. Buchbinder et al. (2011) provided evidence that it was possible to manufacture aluminium components with inputs of a high-power level. According to the findings of their research, utilizing an input with a high-power level had the potential to increase the rate of output by up to four times. To use AISI 316 L particles in the selective laser melting to produce fully dense cubes. Sun et al. (2016) increased the laser energy to 380 watts. They showed that higher scan speed allows more power levels, which in turn increases in build rate by up to 70%. Spierings et al. (2014) performed a calculation to calculate the build rate. Based on what they found, the laser power should be kept at its highest level. Rao et al. (2016) studied the effects of process factors (Scan speed and Power) on the apparent density. The maximum density was achieved by optimizing the processing settings. Jinoop et al. (2021) examined the geometry by observing how laser energy per unit powder feed affected walls. Statistical techniques were used to examine the differences in built wall geometry over its length and cross-section. The highest deviations along the wall's height and width were found at 13.2 kJ/g and 8.2 kJ/g., respectively.

Nayak et al. (2020) developed a regression model to determine the relationship between the depth of the re-melted zone in the substrate

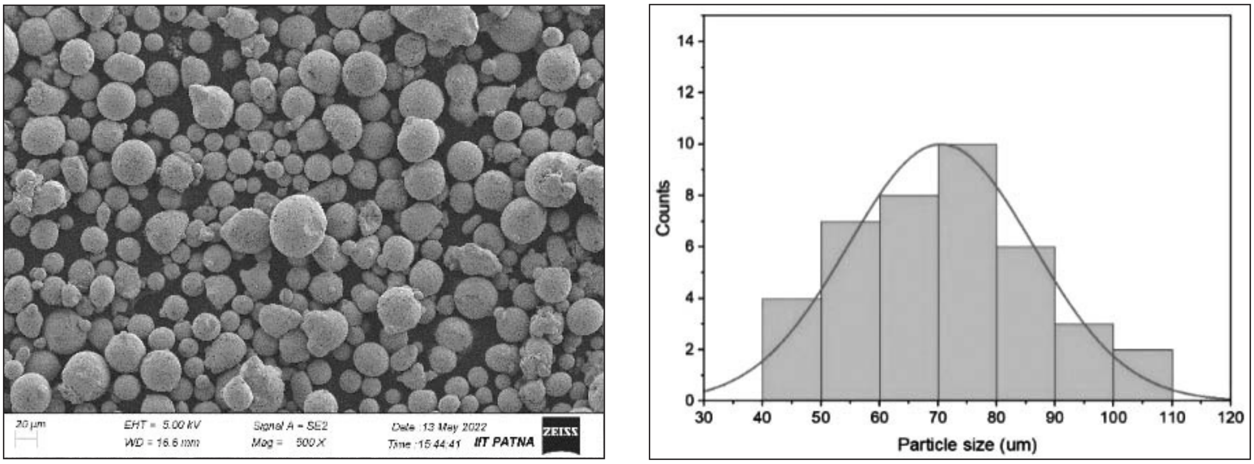

Fig. 1.(a) Powder morphology and (b) particle size distribution.

Table 1
Chemical composition of used Inconel 718.

Element	Ni	Cr	Nb	Mo	Ti	Al	Co	Cu	C	B	Fe
Weight (%) Nominal	50-55	17-21	4.75-5.5	2.8-3.3	0.65-1.15	0.2-0.8	≤1	≤0.3	≤0.08	≤0.006	Balance

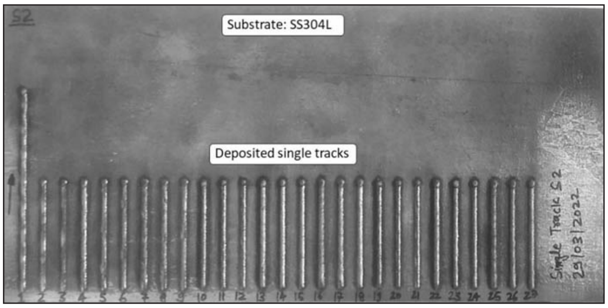

Fig. 2. Deposited single tracks.

Table 2
Process parameters used for LDED experiments.

Process parameter	Value
Laser power (P)	800 - 1200 W
Scan speed (V)	0.4 - 0.8 m/min
Powder feed rate (F)	6 - 12 g/min
Laser spot diameter	~ 2.0 mm
Argon gas flow rate	6 - 8 litres per minute

subsurface and the track area in terms of energy density during the building of a single track. They also built an analytical model for forecasting the aspect ratio. Within the process window, there were an average difference of 7.61% and 3.18% between experimental and projected values for the area and width of the track, respectively. To estimate the speed of the moving laser and the rate of powder feed for a given set of parameters, such as the power of the laser, the width of the beam, and the form of the powder stream, (Picasso et al., 1994) created a simple analytical model for the LDED process. Zhu et al. (2019) created a different analytical model to forecast the deposit's geometrical characteristics. Authors are unable to find work related to maximizing the build rate in DED by optimizing the process parameters. The goal of this study is to find out how different process parameters affect DED-built single tracks to achieve a higher build rate. Present work provide an experimental methodology for identifying the LDED process parameters that yield the higher build rate. This is done by varying the parameters: laser power, powder feed rate, and scan speed.

2. Experimental Procedure

The Inconel 718 is used to deposit the single tracks using laser-directed energy deposition techniques. Inconel 718 powder with a particle size distribution between 40 and 110µm (measured with ImageJ software through the SEM image) as shown in Fig. 1 (a), and (b) was used as the feed stock material. Fibre laser of nominal power 2 kW is used for the experiments. Argon gas is used as a carrier as well shielding gas. Table 1 presents the nominal composition of the Inconel 718 powder.

The three most crucial process variables affecting the deposition rate for a given laser spot diameter are the scan speed, laser power, and powder feed rate as given in Table 2. Hence, these three parameters are selected for the parametric investigation. The range of process parameters used for single-track formation is given in Table 2. The deposited single tracks are shown in Fig. 2.

3. Results and Discussion

3.1. Build rate analysis

Build rate is an essential factor as it governs the amount of time required for building a component. According to a full factorial design of experiments, the process parameters for material deposition are listed in Table 3, along with the relevant experimental findings. The experimental result matrix is analyzed using the combined parameters, laser energy per unit powder feed (LEPF), catchment efficiency (η), laser energy per unit length (LEL), powder feed per unit length (PFL), aspect ratio, track area, and build rate are presented in Equations (1-7), respectively. The area of the track is calculated by assuming the shape of the track geometry as a parabolic segment (Huang et al., 2019).

Laser energy per unit powder feed (LEPF) =

$$\frac{Laser\ power}{Powder\ Feed\ rate} = \frac{P}{F_R}\left(\frac{kJ}{g}\right) \quad \text{.................(1)}$$

Catchment efficiency (η) =

$$\frac{amount\ of\ material\ deposited}{amount\ of\ material\ fed\ to\ the\ melt-pool} \quad \text{.................(2)}$$

Laser energy per unit length (LEL) =

$$\frac{Laser\ Power\ in\ watt}{Scan\ speed\ (\frac{m}{min})} = \frac{P}{V}(J/m) \quad \text{.................(3)}$$

Powder feed per unit length (PFL) =

$$\frac{Powder\ feed\ rate\ (\frac{g}{min})}{Scan\ speed} = \frac{F}{V}(g/m) \quad \text{.................(4)}$$

Aspect ratio = $\frac{width}{height}\left(\frac{mm}{mm}\right)$ ....(5)

Track area (A_t)=2/3×track width×track height ....(6)

Build rate=A_t×V ....(7)

The build rate is directly related to the track area, track width, track height, and scan speed as per equations (6) and (7). Whereas track width and height dependupon laser power and powder feed rate, so it concludes that build rate is a combined effect of laser power, scan speed, and powder feed rate. As the laser energy per unit powder feed (LEPF) increases catchment efficiency increases resulting ingreater powder particles being melted and deposited. It is noted that the decrease in scan speed and increase in the laser power which leads to an increase in the track width and height results in a higher build rate. This is mainly caused by the fact that there is more energy available for deposition at higher laser powers and that there is more time for interaction between the laser beam and the material at slower scan speeds. The reason for the above can be explained with the help of a combined process parameter called "Laser Energy per unit Length (LEL)" shown in eq. (3).

The ratio between the beam diameter and scan speed defines interaction time. An increase in the interaction time increases the amount of powder captured by the melt pool and the availability of more energy in the melt pool, which increases the deposit height. The effect of PFL on aspect ratio and build rate is shown in Fig. 3(a), and (b), respectively. At the constant LEPF, as the PFL increases aspect ratio decreases, and the build rate increases slightly and then decreases. It was due to a decrease in the scan speed. As the scan speed reduces, the amount of powder fed per unit length of deposition increases, which increases the track height and finally reduces the aspect ratio. At the constant LEL, as shown in Fig. 3 (c-d), the PFL increases the aspect ratio decreases whereas the build rate increases because of higher track height. The PFL increases as the powder feed rate increases, indicating that more powder is available for deposition which increases the track height. However, the powder feed rate doesn't have much effect on track width. At the constant PFL, as shown in Fig. 3 (e-f), the aspect ratio decreases whereas the build rate increases. It was because higher laser power was available which increase the track height resulting lower aspect ratio and higher build rate. It is observed that the effect of laser power on the track width is maximum, followed by scan speed and the effect of powder feed rate is the least. This is because the availability of laser power and the interaction time are the major factors governing the melt-pool width/track width. The inverse relationship between scan speed and track area is due to the reduction in the interaction time between the laser energy and powder material with an increase in scan speedwhich results in a smaller track area.

Table 3
Process variables and related observations.

Track No.	P	V	F	LEPF	LEL	PFL	Width	Height	Aspect ratio	Track area	Build rate
	W	m/min	g/min	kJ/g	kJ/m	g/m	mm	mm		mm²	mm³/min
1	800	0.4	6	8	120	15	1.936	0.452	4.286	0.583	0.233
2	800	0.4	9	5.34	120	22.5	2.08	0.814	2.557	1.128	0.451
3	800	0.4	12	4	120	30	2.188	0.832	2.631	1.213	0.485
4	800	0.6	6	8	80	10	1.852	0.373	4.961	0.461	0.277
5	800	0.6	9	5.34	80	15	1.931	0.613	3.148	0.79	0.474
6	800	0.6	12	4	80	20	2.013	0.675	2.982	0.906	0.544
7	800	0.8	6	8	60	7.5	1.784	0.337	5.299	0.4	0.32
8	800	0.8	9	5.34	60	11.25	1.8	0.384	4.693	0.46	0.368
9	800	0.8	12	4	60	15	1.817	0.423	4.292	0.513	0.41
10	1000	0.4	6	10	150	15	2.258	0.823	2.743	1.239	0.496
11	1000	0.4	9	6.67	150	22.5	2.328	0.899	2.589	1.396	0.558
12	1000	0.4	12	5	150	30	2.403	0.923	2.603	1.479	0.592
13	1000	0.6	6	10	100	10	1.9	0.565	3.363	0.716	0.429
14	1000	0.6	9	6.67	100	15	2.054	0.694	2.962	0.95	0.57
15	1000	0.6	12	5	100	20	2.128	0.713	2.983	1.012	0.607
16	1000	0.8	6	10	75	7.5	1.832	0.401	4.565	0.49	0.392
17	1000	0.8	9	6.67	75	11.25	1.914	0.425	4.5	0.543	0.434
18	1000	0.8	12	5	75	15	2.012	0.458	4.39	0.615	0.492
19	1200	0.4	6	12	180	15	2.426	0.863	2.81	1.396	0.559
20	1200	0.4	9	8	180	22.5	2.534	0.913	2.775	1.543	0.617
21	1200	0.4	12	6	180	30	2.61	0.933	2.796	1.624	0.65
22	1200	0.6	6	12	120	10	2.322	0.693	3.349	1.073	0.644
23	1200	0.6	9	8	120	15	2.458	0.724	3.396	1.186	0.712
24	1200	0.6	12	6	120	20	2.53	0.754	3.357	1.271	0.763
25	1200	0.8	6	12	90	7.5	2.012	0.564	3.571	0.756	0.605
26	1200	0.8	9	8	90	11.25	2.336	0.663	3.522	1.033	0.826
27	1200	0.8	12	6	90	15	2.42	0.69	3.509	1.113	0.89

The aspect ratio is the ratio of track width to track height. The calculation of the aspect ratio will help to understand the relative variation of track width concerning track height when process parameters are changed. It can be observed that the aspect ratio increases with laser power and scan speed while decreasing with powder feed rate. As the laser power increases, the increase in the width of the meltpool is greater than the increase in the track height. This increases the aspect ratio. On the other hand, an increase in scan speed leads to more reduction in track height than a reduction in track width, which increases the aspect ratio. It can also be observed that the contribution of laser power to the aspect ratio is low as compared to scan speed and powder feed rate. As LEL increases, track width and track height increase mainly due to the significant effect of scan speed and laser power, respectively.

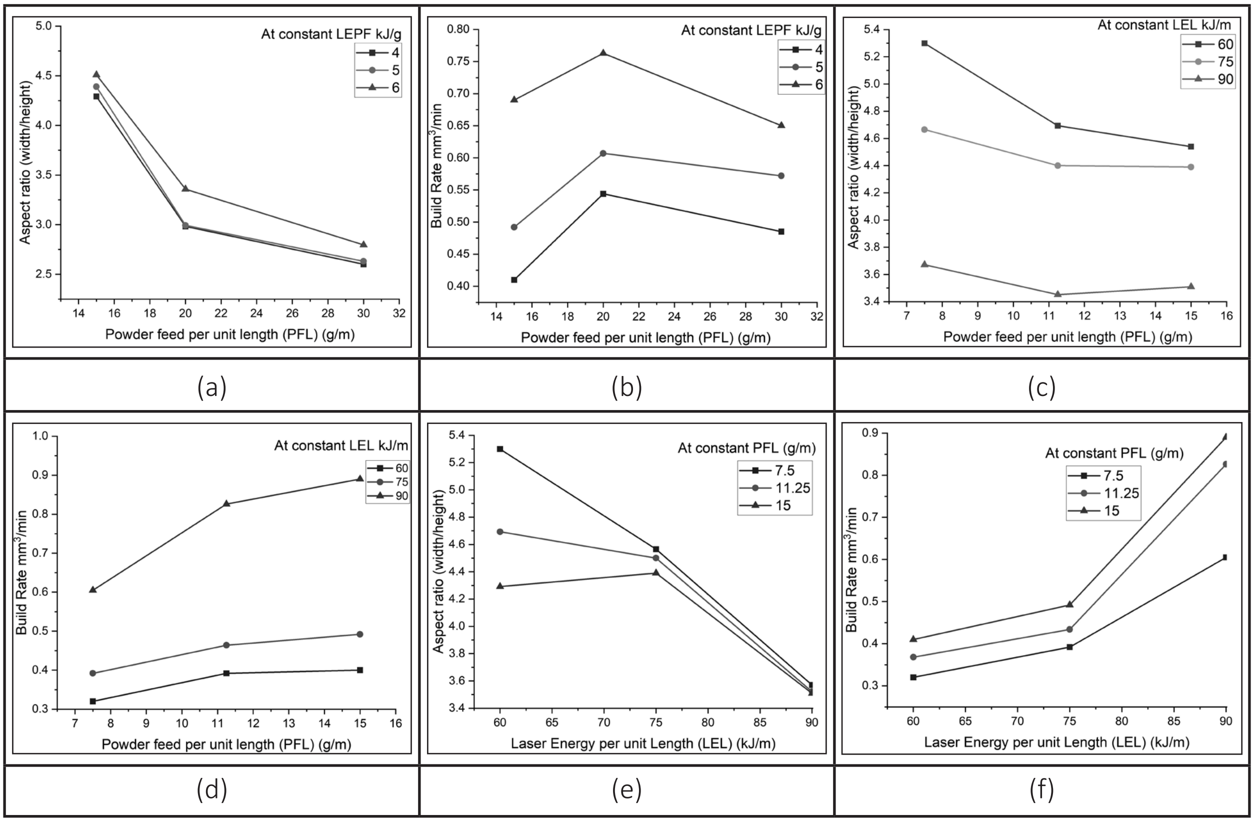

Fig. 3. Showing the effect of PFL, LEL, and LEPF on aspect ratio and build rate.

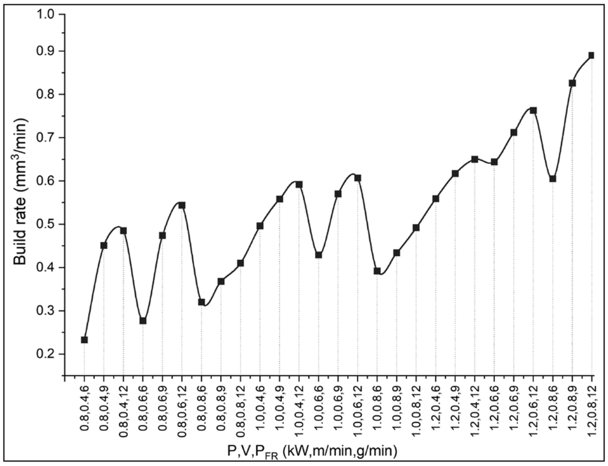

Fig. 4. Build rate at different process parameters.

The effect of process parameters on build rate is shown in Fig. 4. As the powder feed rate, scan speed, and laser power increases the build rate increase but the effect of laser power is found to significant process parameters in build rate followed by scan speed and powder feed rate for the printing of Inconel 718.

4. Summary

Laser-directed energy deposition is a cutting-edge additive manufacturing method frequently employed in the repair industry but it can be used for making thin-walled components. In this work Inconel, 718 single tracks have been built using the commercially available Inconel 718 powder by a directed energy deposition process. The tracks were built varying the process parameters namely powder feed rate, laser power, and scan speed. It found that the laser power is a significant process parameter in build rate followed by scan speed and powder feed rate for the printing of Inconel 718. The results of this study provide a better knowledge of how the various process parameters affect the build rate. Many engineering components require less time to build it. So, it was necessary to study the process parameters for a higher build rate.

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