Experimental investigation of additive manufacturing of SS 316L using laser direct metal deposition

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Deposition Rate,
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ABSTRACT

Laser direct metal deposition (LDMD) is a rapidly emerging additive manufacturing technique offering attractive characteristics like high deposition rates, component repair, and deposition of functionally graded materials. Experimental investigations have been carried out to deposit SS 316L structures at higher deposition rates using LDMD. A continuous fiber laser operating at a wavelength of 1070 nm is used to deposit the structures under different processing parameters like power, scanning speed, and powder feed rate. A power range of 600 W to 1200 W is found to be optimal with speed varying in the range between 10 mm/sec and 25 mm/sec. At low power with higher velocities, a low layer thickness is obtained and vice-versa. With an increase in the power and the decrease in the speed, deposition rates are increased. The findings will help to develop pre-processing, online-processing, and post-processing strategies for LDMD.

1. Introduction

Owing to the remarkable characteristics of using laser as a power source, laser-based methods have achieved prominence among the currently available additive manufacturing (AM) techniques. Laser beams can generate extremely high-power densities with high spatial and temporal coherence because of which they can be focused on a spot with a diameter close to the diffraction limit. Because of this, with minimal thermal and thermomechanical collateral damage, specific transformations can be induced in materials in a short period with high temporal and spatial accuracy. Laser-based methods also don't require vacuum, unlike electron beam methods. Microstructure refinement, dissolving inclusions and precipitates, and forming nonequilibrium supersaturated solutions often with improved properties is possible with laser heating and Solidification (Steen, 2003). With such remarkable properties, laser-based methods have rightly elicited a lot of interest both from academia and industry and are being extensively studied.

Based on the way material is fed, laser-based additive manufacturing can be classified into powder bed fusion (PBF) and Laser direct metal deposition processes (Jinoop et al., 2019). In PBF technology, metal powder is spread uniformly over the build plate or the substrate, and a wiper is used to level the powder. The laser beam follows the trajectory obtained from the computer-aided design (CAD) model for melting and consolidating the powder thereby forming a single layer. The bed or the substrate moves down and the laser scans again forming another layer over the previously deposited layer. This process continues to form the desired 3D component (Sames et al., 2016). LDMD is an AM technology derived from the laser cladding process. In LDMD, powder or wire feed is added into the molten pool created by a focussed laser beam. Once the laser beam moves away, deposited powder in a molten state cools down rapidly due to heat transfer to the surroundings, causing solidification to progress, thereby forming a solidified material track bonded strongly to the substrate or the previously deposited layers. A wide range of materials, including most metallic alloys and metal-matrix composites (MMCs), as well as some cermets (a composite of ceramic and metallic materials) and ceramic materials themselves, can be deposited, similar to laser cladding, allowing functional parts for a wide range of applications to be manufactured (Costa & Vilar, 2009).

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When compared to the PBF technique, LDMD has many advantages, including unlimited building size, a faster deposition rate, and the ability to produce functionally graded compositions and multi-material structures. LDMD can repair high-value components that have worn out or been damaged and reduce the need for the support structure (Svetlizky et al., 2021).

In recent years, AM technologies are used widely to process Stainless Steels which because of their superior mechanical properties, finds a lot of applications across the automotive, aerospace, and petrochemical industries. Among the Stainless steels, AISI 316L is the most processed steel because of its welding, corrosive and mechanical characteristics (Zadi et al., 2018). 316L is primarily austenitic stainless steel, in particular, a chromium-nickel alloy and is used across bio-medical, automotive, defence, marine, oil and gas, petrochemical, and nuclear industries (Sasikumar et al., 2022).

The current work aims to study and investigate the effects of various process parameters on the Laser Direct deposited SS 316L part features like width, height, roughness, and powder deposition rates. Accordingly, experimental investigations of LDMD were conducted by depositing single metallic layers followed by their characterization. Thickness, layer height, powder deposition rate, and powder deposition efficiency were calculated experimentally and were studied to find their variation with various process parameters.

2. Experimental Setup and Methodology

The deposition experiments were performed on an LDMD system. The system consists of a 2KW IPG YLR 2000U Laser power source (IPG Photonics, Oxford, MA, USA) and a brass nozzle mounted on a 3-axis CNC gantry. The Laser source is a continuous-wave Ytterbium fiber laser make of 1070 nm wavelength with a fiber diameter of 200 µm and a spot diameter of 1.3 mm. The laser system is equipped with dual powder hoppers to supply the powder, and a three-channel brass nozzle to deliver the powder coaxially with the laser beam. The brass nozzle is a coaxial continuous nozzle with the laser beam traveling through the central hole and the carrier gas which is carrying the powder being delivered through the slit holes. N_2 is used as a carrier gas to deliver the powder from the hoopers to the bed. SS 316L powder is obtained from INDO-MIM PVT LTD and has a size range of 15-53 µm which is given by

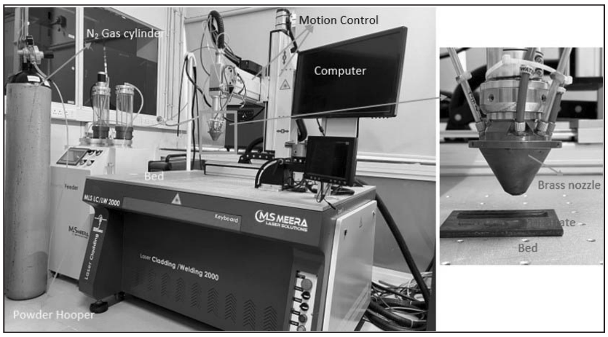

Fig. 1. Experimental setup of the LDMD.

Table 1
Experimental parameters.

Parameter	Value	Remarks
Power (W)	600-1400	Varying
Scanning speed (mm/sec)	5-30	Varying
Feed rate (LPM)	10-15	Varying
Pressure (KPa)	320	Fixed
Focal length (mm)	14	Fixed
Acceleration (mm/sec^2)	45	Fixed
Feeder disc speed (mm/sec)	8	Fixed
Shielding Gas	-	N_2
Carrier Gas	-	N_2

the light scattering technique (ASTM B822 / ISO 13320-1). The experimental setup can be seen in Fig.1.

All the samples were fabricated by depositing a single layer on the AISI 1020 baseplates of dimensions 120 x 50 x 6 mm. Laser Power, Scanning Speed, and Powder feed rate are the variable input parameters considered in this study Preliminary experiments were conducted to determine the range of the input process parameters. In the present study, power is varied at a regular interval of 200 W from 600 W to 1400 W, scanning speed in the range of 5 mm/sec to 30 mm/sec at a regular interval of 5 mm/sec, and powder feed rates of 10 and 15 Litres per minute (LPM) are considered. All the depositions were carried out at a pressure of 320 KPa. The deposition parameters are summarized in Table 1.

Dimensional characterization of the deposited samples for obtaining thickness and height was carried out using Macsope-Z at a magnification of 6.2 ×. For each sample, thickness and height are determined at four locations and the average

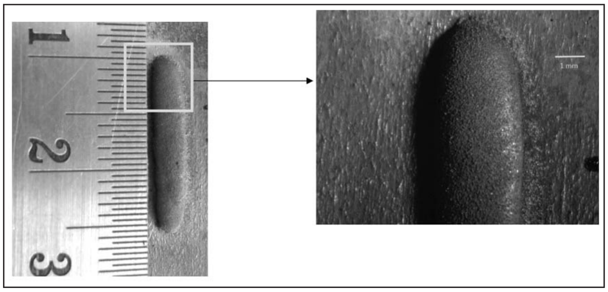

Fig. 2. Image of the single-layer deposited at 1200W, 5mm/sec, and 15 LPM and its microscopic image.

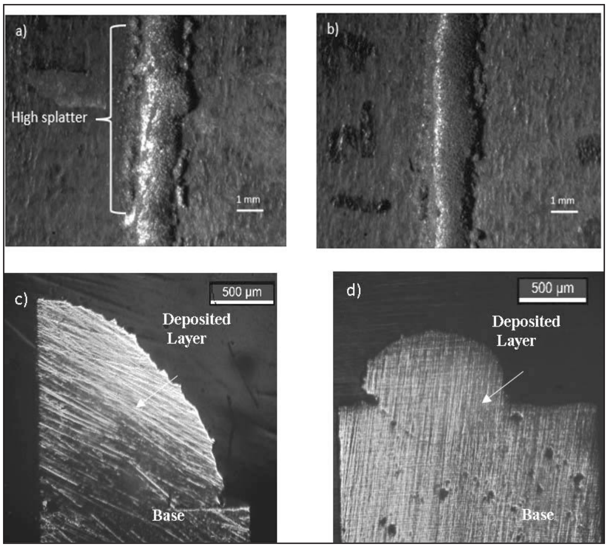

Fig. 3. Top view of the deposited surface at 800 W, 15 mm/sec, (a) 10 LPM, (b) 15 LPM and cross section view of the deposited surface at (c) 15 LPM, 5 mm/sec and (d) 15 LPM; 15 mm/sec.

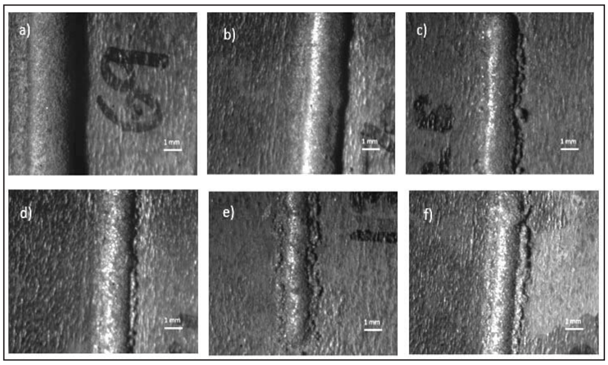

Fig. 4. LDMD images at 1000 W, 15 LPM and speeds of (a) 5 mm/sec (b) 10mm/sec (c) 15mm/sec (d) 20 mm/sec (e) 25 mm/sec (f) 30 mm/sec.

of those four measurements was taken for calculations to be precise.

3. Results and Discussion

In this section, experimental results from depositing samples at various parameters were

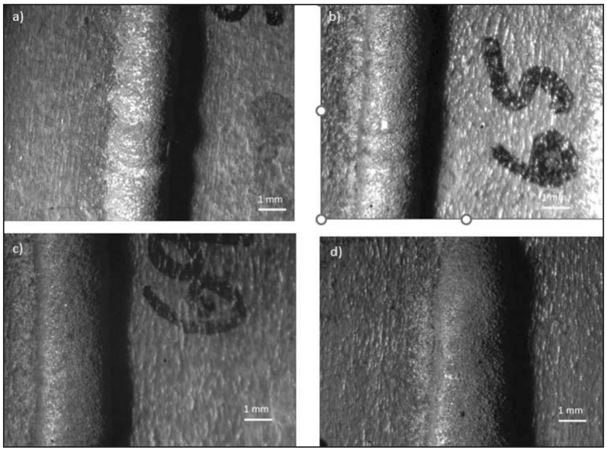

Fig. 5. Samples deposited at a) 600 W b) 800 W c) 1000 W d) 1200 W for a speed of 5 mm/sec and 15 LPM feed rate.

discussed. An image of the sample deposited at P=1200 W, 5 mm/sec, and 15 LPM, along with its microscopic image is shown in Fig.2.

Some initial observations were made from the microscopic images. It was observed that the deposits made at a feed rate of 15 LPM are relatively smooth and with less splatter when compared to the deposits made at a feed rate of 10 LPM. In Fig.3., both the deposits are made at a power of 800 Watts and a scanning speed of 15 mm/sec. But the deposit in Fig. 3 (a) is deposited at a feed rate of 10 LPM While that of Fig. 3 (b) is at a feed rate of 15 LPM. Relatively high splatter observed at 10 LPM is marked in the figure. The same trend is observed for the majority of the other deposits. Therefore, a powder feed rate of 15 LPM is considered optimal in the present investigation.

It can also be observed that with the same feed rate of 15 LPM, the height of the deposited layer decreases with increased in scan speed from 5 mm/sec to 15 mm/sec from Fig.4 (c) and Fig.4 (c). Further, it was observed that for the same power and same feed rate, the thickness of the layer deposited decreased with the speed. This can be observed in Figure 4, where samples are deposited at a power of 1000 W and a feed rate of 15 LPM. From Fig.4 a) to f), the scanning speed is increased from 5 mm/sec to 30 mm/sec. A decrease in the thickness with the speed can be observed from a) to f) in Fig.4. This decrease is more prominent at lower speeds than at higher speeds.

It was also observed that for the same speed and powder feed rate, thickness increased with an increase in power. This is shown in Fig.5 where all the samples are deposited at a feed rate of 15 LPM and a scanning speed of 5 mm/sec but with varying powers.

Further thickness and height data obtained from the microscope and roughness data measured are all plotted. The variation of thickness with the scanning speed at different powers can be seen in Fig.6. Samples in Fig. 6 (a) are deposited at 10 LPM while that in Fig.6 (b) are deposited at 15 LPM. In both the figures thickness generally decreased with the scanning speed for different powers. But this trend is marginally more uniform at 10 LPM when compared to 15 LPM. This downward trend is observed because with the increase in the scanning speed at the same power, the time that the laser head remains at a spot decrease thereby depositing less material. Also, for the same scanning speed, thickness increased with the power as observed earlier. This happens because for the same scanning speed and feed rate, as the power increases, more energy is available per unit length thereby melting and depositing more powder causing an increasing trend in the thickness. Also, there is no significant difference in the thickness obtained between samples deposited at 10 LPM and that of 15 LPM. This is because of the more sputter (i.e., spitting of powder from the melt pool) caused at higher feed rates as reported earlier in the research (Takemura et al., 2019).

Similar to the way thickness data has been plotted, data of layer heights at different parameters obtained are plotted in Fig.7. A downward trend is observed for height with scanning speed for both the feed rates of 10 and 15 LPM. This may have been caused because of the decrease in the time, a laser beam is at a given spot with an increase in scanning speed. For both the feed rates, the decrease in height with the scanning speed is more prominent from 5 mm/sec to 10 mm/sec than at other speeds. Here too, at both the feed rates nearly the same values of height are observed just like that of thickness plots. As discussed earlier, this may be again due to more sputter generation at higher feed rates. For both the feed rates, at lower speeds (5mm/sec and 10 mm/sec) there has been an increase in layer height with the power. But for higher speeds (15 mm/sec to 30 mm/sec), there has been no significant change in the height along with the power. This is because an increase in laser power increases the catchment efficiency (catchment efficiency can be estimated by the number of powder particles that imping the molten pool area at a given time) because of the increased molten pool surface

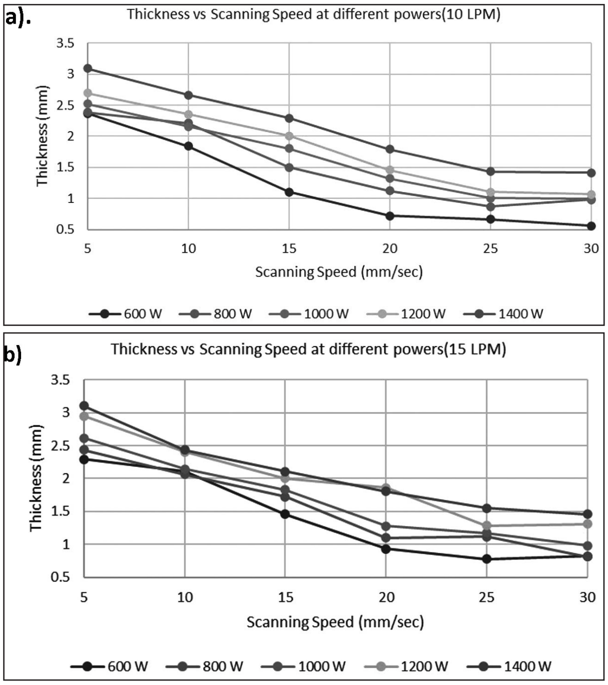

Fig. 6. Variation of thickness with scanning speed at different powers for a feed rate of a) 10 LPM b) 15 LPM.

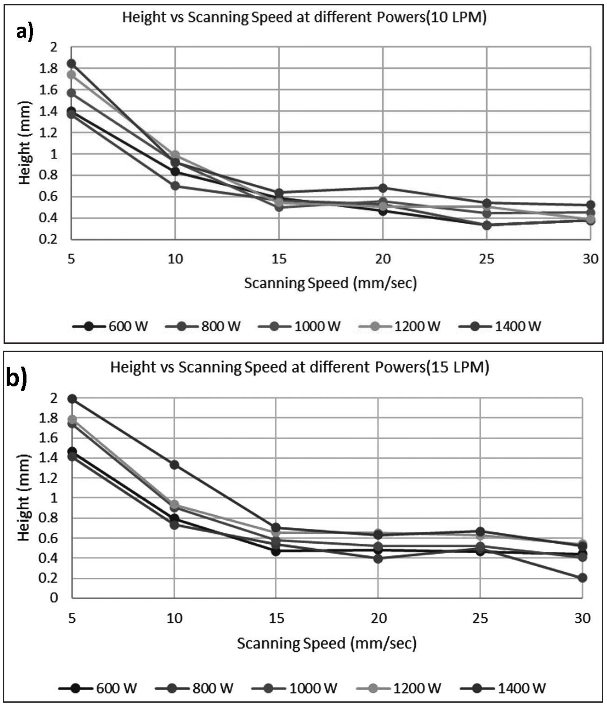

Fig. 7. Variation of height with scanning speed at different powers for a feed rate of a) 10 LPM b) 15 LPM.

area. This is in accordance with the earlier work reported by (Svetlizky et al., 2021). So, as the increased powder mass is deposited over a larger melt pool, layer width and depth of penetration increase, causing a minor effort on the deposit height.

Table 2
Powder deposition efficiency calculations.

Power (W)	Speed (mm/s)	Feed rate (LPM)	Mass of the powder deposited (g)	Mass of the powder not deposited (g)	Efficiency
1000	10	15	4	12.6004	24.0958
800	10	15	47	10.9785	21.616

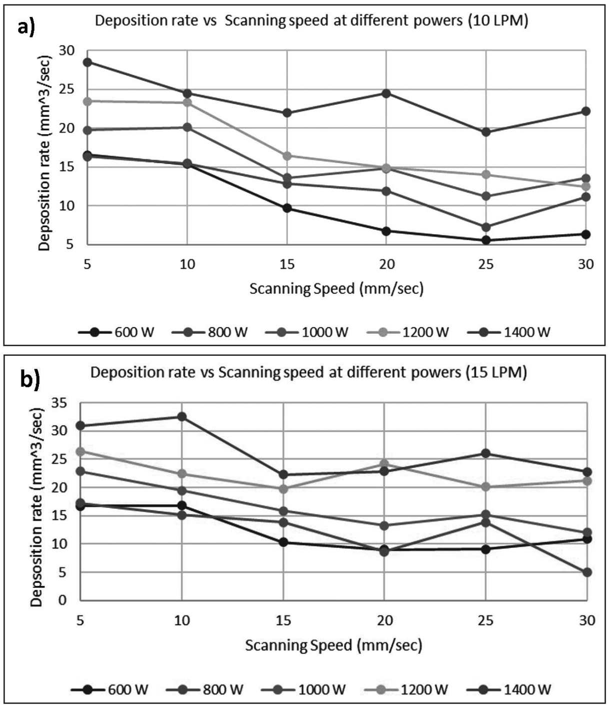

Fig. 8. Plot of deposition rate vs scanning speed at different powers for a feed rate of a) 10 LPM b) 15 LPM.

The deposition rate is calculated by multiplying thickness, height, and scanning speed. And the graphs plotted for the same at different power are shown in Fig.8 at 10 LPM and 15 LPM. It can be seen that the deposition rate is largely the same for various deposits made at 10 LPM and 15 LPM. As discussed earlier, this can be explained by the fact that at higher feed rates, the extra powder is largely sputtered instead of getting deposited. It can be observed that the deposition rate increased with an increase in power for both 10 LPM and 15 LPM feed rates at almost all the scanning speeds. This can be attributed to more energy being available per unit length thereby melting more powder and leading to an increase in the deposition rate. At the same power, for varying scanning speeds, the deposition rate is generally found to decrease with an increase in speed. This can be attributed to the fact that the time for which the laser beam has been positioned at a spot decrease with an increase in scanning speed. Because of this, the laser intensity at a particular spot decrease with an increase in speed, causing a decreasing trend of deposition rate for the same power with increasing scanning speeds. After 15 mm/sec, it appears that the deposition rate more or less seems to be saturated at a given power for different speeds thereafter at both 10 LPM and 15 LPM feed rates.

Powder deposition efficiency is calculated to understand how much of the powder feed given is being deposited and how much of the powder is being wasted. Experiments have been conducted on depositing a single layer at 1000 W, 10 mm/sec and at a feed rate of 15 LPM and 800 W, 10 mm/sec, and at a feed rate of 15 mm/sec for different structures. For 1000 W, the total duration laser is operated for is 19.5 seconds. Whereas at 800 W, the laser is operated for 16 seconds. Mass of the substrate before and after the deposition is calculated along with the powder collected in the tray for both the samples. At 1000 W, deposited powder amounted to 4 grams while the powder collected from the tray (non-deposited powder) was 12.6004 grams. And efficiency was calculated to be 24.09 % which is in agreement with the results reported in the literature (Syed et al., 2005). At 800 W, deposited powder amounted to 3 grams while the undeposited power was 10.8785 grams. This gave an efficiency of 21.61 %. With more power as expected more amount of powder is deposited increasing the efficiency. A table detailing the parameters and results obtained while calculating deposition efficiency is presented in Table 2. From this, it is evident, how important the role of collection and reuse of undeposited powder plays in LDMD.

4. Conclusion

Laser direct metal deposition of SS 316L was investigated experimentally in this work. Experiments were carried out to investigate geometrical obtained under various parameters.

The thickness of the deposits increased with an increase in the power and it decreased with an increase in the scanning speed. There is no significant difference between the thickness obtained at high and low feed rates as the extra powder fed at high feed rates is sputtered rather than being deposited. Layer height deposited for the samples decreased with an increase in the height similar to that of thickness. But at high speeds, there has been no significant variation in the height with power. The deposition rate at both low and high feed is nearly the same, and this is explained by the extra powder being sputtered instead of getting deposited. It is found to generally increase with an increase in the power and decrease with an increase in the scanning speed. At lower feeds, the surfaces of single-layered beads tend to have more spatter. This may be due to a shortage of powder to be deposited at the melt pool thereby increasing the energy available per unit powder mass. This excessive energy may have caused the spatter, degrading the surface. Powder deposition efficiency for LDMD was calculated and it was found to vary between 20-25 %.

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