



Morphologies, microstructures, and mechanical properties of samples produced using laser metal deposition with 316 L stainless steel wire



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ARTICLE INFO

Keywords:

Laser metal deposition
316 L stainless wire
Microstructure
Mechanical properties

ABSTRACT

Laser metal deposition (LMD) with a filler has been demonstrated to be an effective method for additive manufacturing because of its high material deposition efficiency, improved surface quality, reduced material wastage, and cleaner process environment without metal dust pollution. In this study, single beads and samples with ten layers were successfully deposited on a 316 L stainless steel surface under optimized conditions using a 4000 W continuous wave fibre laser and an arc welding machine. The results showed that satisfactory layered samples with a large deposition height and smooth side surface could be achieved under appropriate parameters. The uniform structures had fine cellular and network austenite grains with good metallurgical bonding between layers, showing an austenite solidification mode. Precipitated ferrite at the grain boundaries showed a subgrain structure with fine uniform grain size. A higher microhardness (205–226 HV) was detected in the middle of the deposition area, while the tensile strength of the 50 layer sample reached 669 MPa. In addition, ductile fracturing was proven by the emergence of obvious dimples at the fracture surface.

1. Introduction

Laser processing, like laser beam welding and laser surface treatment, has been widely applied in the aerospace, petrochemical, automotive, and power generation industries, with its development continuing since the last century, especially for the joining of advanced materials [1]. Laser metal deposition (LMD) has been demonstrated to be an effective method for additive manufacturing in numerous manufacturing and repair applications [2]. Thus far, several LMD methods such as direct metal deposition [3], laser engineered net shaping [4,5], and selective laser melting have been reported as common and efficient methods for rapid laser prototyping and manufacturing [6,7]. In these methods, powder is delivered to a laser generated melt pool and solidifies [8,9]. Traditionally, powder-based processes have been widely applied for manufacturing parts with small and complex geometries because of its high laser absorption rate, good dimensional accuracy, and ability to produce a high surface finish. However, for large structures with moderate complexity, wire-based processes have significant advantages in relation to their deposition speed and efficiency, with the ability to produce smooth surfaces with limited porosity, fewer defects, and better material quality at a higher deposition rate [10]. Laser metal deposition using wire as the filler

material has been widely applied in the aerospace industry in recent years [11–13]. With the help of a robotic and automatic wire feed system, a laser is used to melt wire, which is fed into the weld pool. As the laser moves relative to the substrate with the melting wire, the deposited metal is formed layer-upon-layer.

Compared with other additive manufacturing methods, laser metal-wire deposition has been widely used in surface protection [14,15], surface treatment, and repair [16] because of its higher material deposition efficiency, improved surface quality, reduced material wastage, and cleaner process environment, without metal dust pollution. Real-time monitoring and feedback technology has also been applied to the laser metal-wire deposition process, significantly improving the deposition quality and efficiency [17].

In comparisons of the powder and wire-feed laser metal deposition methods, researchers have found that the wire-feed method has been widely applied because of its high efficiency and satisfactory process stability [18,19]. In laser metal-wire deposition, the wire position and orientation, deposition direction and angle, and detailed parameters for different materials have been investigated by many researchers [20,21] to obtain defect-free beads and achieve good process stability for multi-layer deposition. To realize a higher build rate and higher deposition accuracy, several researchers focused on height-control and real-time

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monitoring techniques. Signals based on the plasma, such as the emission intensity, chemical composition, and electron temperature, could be utilized to control the process in real time [22,23]. However, only a few researchers focused on microstructure homogenization and phase distribution rules during multi-layer deposition. The relationships among the parameters, microstructures, and properties should be established for further research.

In this work, single beads and multiple layers of 316 L stainless wire were successfully deposited on a 316 L stainless steel surface under optimized conditions employing a high-power fibre laser. The macro-morphologies, microstructures, grain morphology transformations, and mechanical properties of the multi-layer deposition samples were investigated in detail.

2. Experimental

2.1. Materials

Austenitic stainless steel (AISI 316 L) was utilized as the substrate material. Plates (200 mm × 100 mm × 10 mm) were prepared and then ground with a scouring wheel and degreased with acetone before the deposition process so as to improve the laser absorptivity of the surface. The chemical composition of the stainless steel, as received, is given in Table 1. The additive material was 316 L stainless steel wire with a diameter of 0.8 mm, the chemical composition of which is also provided in Table 1.

2.2. Experimental procedure

Fig. 1 shows the experimental arrangement for the laser deposition system employed in this study. A 4000 W continuous wave (CW) fibre laser with a wavelength of 1070 nm and circular beam shape was used in the deposition process. An arc welding machine was employed as the wire feeder machine. The 316 L wire was “front fed” at an angle of 35–45° to the horizontal to aim the wire tip at the centre of the melt pool. Argon gas (99.99%) was “back blown” through a gas nozzle at an angle of 45° to the horizontal to protect against oxidation. The laser head, wire feeder, and Ar gas nozzle were all fixed on an industrial robot (ABB).

The details of three preliminary groups of experimental settings with a single factor changed are listed in Table 2. Based on preliminary experiments, a process frame was found in which single beads could be manufactured stably and repeatedly. Further, the heat input was found to be an important factor. The heat input for each set of parameters was determined using the following equation:

$$Q = \frac{P(W)}{V(m/min)} \quad (1)$$

where Q is the heat input, P is the laser power, and V is the scanning speed. A total of 15 single beads and nine samples with ten layers each (shown in Fig. 2a–b) were obtained under different parameter conditions chosen from those used in the preliminary single factor experiments. The heat input and wire feed rate values were evaluated and compared. Table 3 lists the processing details for four typical layered samples selected for further measurements. All of the samples were obtained using a protective gas at 10 L/min and a spot size of 3 mm. A total of 50 layered samples (Fig. 2c) were finally deposited with the same appropriate parameters for each layer to measure the technical

stability and perform further mechanical performance testing. The whole deposition process was interrupted every five layers to confirm the surface condition and total height. Z-direction offsets between the five-layer sets were applied, with an extra 1 s of deposition time at the end of each five-layer deposition if necessary to unify the Z-direction height.

All of the samples were longitudinally cross-sectioned, sanded using sandpaper of up to 1500 grit, and polished using a diamond polishing paste. Later, the samples were further chemically rinsed for 40 s in a solution of 50% aqua regia (HCl: HNO₃:H₂O = 3:1:4). The macro-morphology, composition, and microstructure of each sample were investigated using an optical microscopy and a scanning electron microscope (SEM). Electron back-scattered diffraction (EBSD) was employed to study the grain size distributions, grain boundary types, and crystallographic textures of the studied samples. X-ray diffraction (XRD) was also used to identify the phases present in the layered samples. A Vickers hardness tester with a load of 0.3 kg was used to measure the microhardness along the depth in the transverse cross-sections of typical layered samples. The measurements were made along the middle of the deposition cross-sections, with a spacing of 0.25 mm between successive points. Tension testing was performed on a layered sample with 50 layers using a tensile test machine to examine the tensile strength, yield strength, and elongation of the deposition samples. Tensile samples were extracted along and perpendicular to the deposition direction, with samples sectioned from the substrate selected as a contrast (the sample designations are shown in Fig. 3). A fracture morphology analysis was also conducted using the SEM.

3. Results and discussion

3.1. Macro-morphologies of deposited samples

Fig. 4 presents typical samples of the beads deposited using deposition processes characterized by the dripping of a wire (wire dripping) and the smooth transfer of a wire (smooth wire deposition). The ideal transfer of the wire into the melt pool with a smooth and flat surface could be obtained using the ideal process conditions of a low heat input and large wire feed rate (Fig. 4a illustrates a deposition using 2000 W of laser power, a 0.36 m/min scanning speed, and a 2.4 m/min wire feed rate, along with one using 2400 W of laser power, a 0.36 m/min scanning speed, and a 2.8 m/min wire feed rate). These sample showed a large aspect ratio (0.41), small track width (3.29 mm), and appropriate wetting angle (70°) [24], which indicated the potential for large-height and high-quality additive manufacturing. However, when the wire feed rate was extremely small for a high heat input, intermittent dripping of wire was observed, which caused a discontinuous deposition (Fig. 4b illustrates a deposition using 3200 W of laser power, a 0.36 m/min scanning speed, and a 2.4 m/min wire feed rate, along with one using 2400 W of laser power, a 0.36 m/min scanning speed, and a 1.6 m/min wire feed rate). The track width also increased during this unstable process.

Typical 10 layer samples fabricated using different parameters are compared in Fig. 5, with the parameter details given in Table 3. As shown in Fig. 5a, samples L2 (deposited with a low heat input and medium wire feed rate) and L1 (deposited with a low heat input and large wire feed rate) both exhibited large deposition heights (10–11 mm). In addition, relatively smooth side surfaces (with no obvious defects like humps or pits) were also detected in sample L1. Hierarchical

Table 1
Chemical composition of 316 L stainless steel substrate and wire (wt%).

Element	Cr	Ni	Mo	Mn	Si	C	P	S	Fe
Wire	18.57	11.72	2.57	1.72	0.54	0.015	0.024	0.008	Bal.
Substrate	16.0–18.0	10.0–14.0	2.0–3.0	≤2.0	≤0.75	≤0.03	≤0.045	≤0.030	Bal.

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