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Study on microstructure, mechanical properties and machinability of efficiently additive manufactured AISI 316L stainless steel by high-power direct laser deposition

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ABSTRACT

High-power direct laser deposition (HP DLD) was utilized to fast generate AISI 316L stainless steel parts with large size and excellent mechanical properties. In order to efficiently manufacture the stainless steel parts with high surface quality and dimensional accuracy, a dry milling finish was applied. During the DLD process, heat retaining powder was employed to prevent buckling deformation. The effect of building direction on the microstructure, mechanical properties and machinability of the stainless steel was investigated. It was found that the microstructure was homogeneous, at the building direction of 0°, while a number of larger dendritic grains were present in the microstructure, at the building direction of 90°. The tensile properties and hardness values at the building direction of 0° were higher than those at the building direction of 90°. For both building directions, the decrement in surface roughness and the increment in cutting force and tool wear, were observed with the increase in cutting speed. The cutting force, tool wear and surface roughness of the additive manufactured stainless steel at the building direction of 0° were relatively higher, which implies that the anisotropy in the machinability could be utilized to increase efficiency and reduce production cost.

1. Introduction

Direct laser deposition (DLD) is one of the laser-based additive manufacturing (LBAM) processes, which can be utilized to generate end products or prototypes (Thompson et al., 2015), by creating successive cross-sectional layers, directly from computer aided design (CAD) data, 3D scanning systems data, or other geometrical representations (Yasa and Kruth, 2011). In recent years, there has been an increasing interest in the process as it provides an opportunity to fabricate complex-shaped, functional graded or customized parts that can be widely used in various industries (Thompson et al., 2015), such as automobile, aerospace and medicine (Yan et al., 2014). Near net shape parts can be generated in a timely manner, at a reduced production cycle with minimum waste of material (Zhang et al., 2013). The factors that influence the microstructure and mechanical properties of the alloy parts, generated by LBAM, have been investigated in many studies. Considering that the stability of the geometrical characteristics of each single track and the good metallurgical bonding between two adjacent melt pool tracks or layers are essential in order to obtain a high-quality three dimensional object, Yadroitsev et al. (2013) focused on the effects of preheating temperature and laser scanning speed on the microstructure and geometrical features of single tracks. The key processing parameters, such as laser power, scanning speed and powder flow rate, were also investigated by observations of the geometrical shape and surface smoothness of the cladding (Zhang et al., 2014). In addition, Guan et al. (2013) studied the effects of slicing thickness, building direction, overlapping rate and hatch angle on the tensile properties of selective laser melted stainless steel in details. All of these studies contributed significantly to the understanding of the effect of the processing parameters on the microstructure and mechanical properties of as-fabricated samples. Also, some researchers investigated the effect of energy input by employing the volume energy density E_v, which is a function of laser power, hatch spacing, layer thickness and scanning velocity (Wei et al., 2014). Moreover, the ratio G/V_s, where G is the temperature gradient at the solid/liquid interface and V_s the solidification

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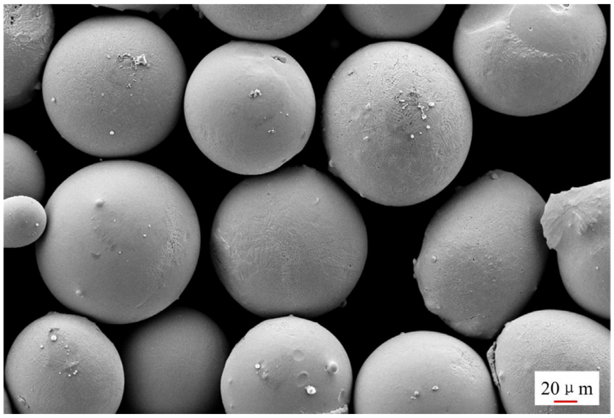

Fig. 1. SEM micrograph of the AISI 316L stainless steel powders.

velocity, could be utilized to predict the final morphology of the solidified microstructure (Hunt, 1984). In addition, *G* had a significant contribution to the oriented growth of dendrites (Song et al., 2015), which may affect the mechanical properties of the samples. For example, surveys performed in other studies revealed that the micro-hardness of the samples, fabricated by high-power selective laser melting, was directional dependent, which was attributed to the anisotropy of the microstructure (Ma et al., 2015), and the building direction affected the tensile properties by influencing the continuity of microstructure (Guan et al., 2013). Furthermore, it is widely acknowledged that the parts fabricated by additive manufacturing processes have a low dimensional accuracy and surface quality, and a post additive manufacturing machining process may be required before they are acceptable for use. As a result, some researchers have proposed a hybrid rapid prototyping system (Hur et al., 2002) and a metal direct prototyping system (Xiong et al., 2009), using both deposition and machining, and the chip morphology, cutting force and machining vibration of laser cladding layer, were studied (Zhao et al., 2015). However, among most of the studies carried out on LBAM processes, the building rate was relatively low due to the relatively small laser spot size (usually smaller than 0.5 mm), low laser power (usually lower than 500 W) and thin powder layer (usually thinner than 0.5 mm), and, up to now, there is no detailed report on the machinability of stainless steel manufactured by DLD.

In the present study, a high-power laser source with a large spot size was utilized to fast fabricate AISI 316L stainless steel parts with large size, excellent mechanical properties and no buckling deformation. The microstructure of the fabricated stainless steel was examined and the mechanical properties were measured and evaluated. In order to meet the demands of efficient manufacturing of the parts, including high surface quality and dimensional accuracy, the parts were finished by dry milling and the machinability was assessed. Taking into consideration the anisotropy of the parts, the effects of building direction on the microstructure, mechanical properties and machinability of the stainless steel were investigated in details. This study helped to lay the foundations for the integration of additive and subtractive processes to increase efficiency and reduce cost during production.

2. Experimental procedure

In this work, gas atomized AISI 316L stainless steel powders, with a particle size below 150 μm and a mean particle size at approximately 120 μm, were utilized as the starting material of the HP DLD experiments. Fig. 1 shows an SEM micrograph of the powder and the corresponding chemical composition is listed in Table 1. It can be observed that the chemical composition of the powders used in the experiments is similar to that of the 316 stainless steel powders used in previous studies (Zhang et al., 2014). The stainless steel samples were fabricated using a prototype coaxial powder-feeding HP DLD machine. The machine was equipped with a LDF 6000-100 (Laserline, Germany) fiber-coupled diode laser. The experiments were carried out at fixed values of laser power (2 KW), spot diameter (5 mm), hatch spacing (3 mm), laser scanning speed (0.5 m/min) and layer thickness (1 mm). During the process of HP DLD, a standard alternating *x*/*y*-raster scanning pattern was adopted, which means that the scanning direction of a layer was forming is 90° angle with the scanning direction of previous layer. During solidification, the stainless steel parts were embedded in heat retaining powder to prevent buckling deformation, with the top surface of the heat retaining powder being constantly 3 mm lower than the top surface of the parts, as illustrated in Fig. 2. Additionally, on completion of the HP DLD process, the parts were put into an electric furnace, which was pre-heated to 200 °C, followed by furnace cooling to room temperature. The building direction, which is defined as the acute angle between the longer axis of the fabricated sample and the horizontal plane, will have a significant effect on the microstructure, mechanical properties and machinability of the stainless steel parts, generated by HP DLD. The building directions of 0° and 90° were selected to manufacture the stainless steel parts, as shown in the schematic of Fig. 3.

Table 1
Chemical compositions of the stainless steel powders (wt.%).

Material	Chemical composition (wt.%)						
	S	C	Si	Mo	Ni	Cr	Fe
AISI 316L	–	0.08	1	2.1	12.5	17.8	Bal.
316 SS Zhang et al. (2014)	0.035	0.08	1	2.5	12	17	Bal.

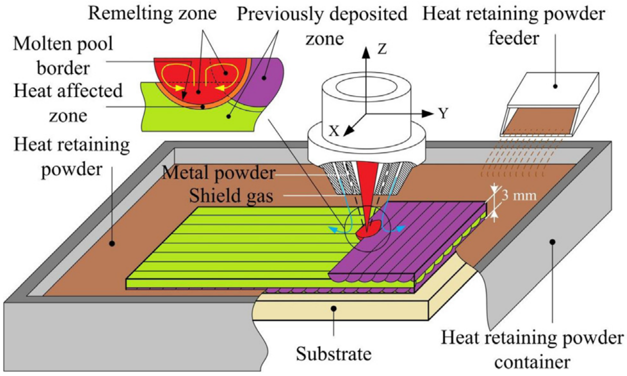

Fig. 2. A sketch of the HP DLD process.

Tensile test specimens were designed according to the ISO 6892-1:2009 standard. The specimens were sectioned from the additive manufactured stainless steel samples by wire electrical discharge machining (WEDM), for both of the building directions of 0° and 90°. The dimensions of the specimens are presented in Fig. 4. The tensile properties, including ultimate tensile strength (UTS), yield strength ($\sigma_{0.2}$) and elongation (EL), were measured utilizing a tensile testing machine (INSTRON 8801, UK), at room temperature. The final values were obtained by averaging the measured results of three tensile specimens, for each building direction. Following tensile testing, fractographic analysis was carried out. The polished samples were etched in aqua regia prior to microstructure observation and hardness testing. A KEYENCE VK-X200K microscope was used to assess the microstructure and a 320HBS-3000 hardness tester (HUA YIN, China) was utilized to measure the macro-hardness. Moreover, nano-indentation testing