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Laser metal deposition as repair technology for 316L stainless steel: Influence of feeding powder compositions on microstructure and mechanical properties

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ABSTRACT

Laser metal deposition was used to repair grooves on 20 mm thickness 316L stainless steel plates using two different 316L stainless steel commercial powders – Fe-0.15C-11.8Cr-0.15Mn-0.2Ni-0.031P-0.56Si-0.05S (wt.%) powder and Fe-0.09C-17.05Cr-1.2Mn-11.28Ni-0.019P-0.46Si-0.09S (wt.%) powder. Good comprehensive performance of fine metallurgical bonding with were successfully achieved under optimized processing parameters. The microstructure and mechanical properties (micro-hardness, ultimate tensile strength, bending strength, low-temperature impact toughness) of the repaired specimens were investigated. Results indicated that chemical composition (different element contents) of the powders played an important role in determining the microstructure, phases and properties of the specimens. It was found that the microstructure of the specimens repaired with Fe-0.15C-11.8Cr-0.15Mn-0.2Ni-0.031P-0.56Si-0.05S (wt.%) powder was homogeneous and consisted of Cr-rich martensite while a number of cellular dendrite were presented in microstructure of specimens repaired with Fe-0.09C-17.05Cr-1.2Mn-11.28Ni-0.019P-0.46Si-0.09S (wt.%) powder and the repaired specimens consisted of ferrite and austenite. Due to solid solution strengthening, the average hardness of the specimens repaired with former powder was higher than that of the specimens with later powder. However, in the aspect of mechanical properties, LMD with Fe-0.09C-17.05Cr-1.2Mn-11.28Ni-0.019P-0.46Si-0.09S (wt.%) powder had better performance than the specimens repaired with another kind of powder. The relationship between the microstructure characteristics and mechanical performances of the repaired specimens was also discussed.

1. Introduction

Laser metal deposition (LMD) or laser cladding (LC) is one of the laser additive manufacturing (LAM) process that the laser melted the metallic powder delivered through a nozzle onto a substrate to form a single track, then moved side by side on the surface of substrate to form a layer of dense material [1,2]. Then, 3D part is fabricated through overlapping layers. Due to the advantage of repaired high-value components with low-cost and improved surface properties with coatings, it also appears as a very useful solution as a method to repair components [3]. Traditional repair technologies, including traditional arc welding, cold spray, and plasma spray [4], show limited applications due to various reasons. For example, argon-arc welding usually produces widen heat-effect zones (HAZ), apparent deformations, and is highly impressible to hydrogen cracking [5]. However, LMD can reduce distortion and micro-cracking with optimized parameters. Furthermore, it is used to fabricate metallurgical-bonded and high quality coatings with the advantages of reduced production time, enhanced thermal control, narrowed heat-affected-zone (HAZ), high satisfactory repair of parts, and production of a functionally graded part [6–8]. As LMD is a layer-by-layer build technology, it permits ample chances to influence the microstructure and subsequent mechanical properties [9,10]. Compared with the traditional technology, LMD can optimize the mechanical properties of the repaired specimens through changing the alloying composition of the powder and adjusting processing parameters [11]. Furthermore, the loss of expensive elements such as Ni, Cr and Mo can be reduced or prohibited in the LMD repair process [12].

A wide variety of materials has been used for this process, including austenitic stainless steel such as AISI 316L and AISI 304 stainless steel [13,14]. 316L SS is one of the useful material for marine engineering, potable water systems, food preparation

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equipment, pharmaceutical manufacturing and medical implants, owing to its outstanding corrosion and oxidation resistance [15], high work hardening, and good formability.

The requirement of factors to form high quality repaired specimens includes groove shapes and sizes [16], thicknesses of the material, shielding gas, and other experiments parameters. Paydas et al. [16] observed that the LMD technique performed well in repairing of Ti-6Al-4V with various groove thicknesses. Graf et al. [17] pointed out that LMD is feasible and effective to repair milled grooves (with different shapes such as V-shape and U-shape with different angles) in repair application. Their research indicated that as long as the groove is wide enough for powder jet, they can develop defect-free layer without manual adjustment. However, they had not analyzed the effect of the building strategy on microstructure. Ravi et al. [18] ascertained that the building strategy influence both the microstructure and the ductility of as-built specimens owing to it had a close connection with the thermal history. Additionally, Zhang et al. [19] investigated the influence of powder dimension on densification of laser addictive manufactured 316L SS. According to their discussion, a better particle packing, spherical and well distributed grain increased densification of the clad, even achieving 90% densification. Dadbakhsh et al. [20] investigated the influence of gas flow on the solidification of 316L steel clads. The authors' results indicated that the manufacture strategy and gas flow condition had an insignificant effect on formation of porosity, however they played an important role in the thermal stress and bonding strength which consequently influenced the mechanical properties of final parts. However, among most of the studies carried out on LMD processes, the effect of the chemical composition differences of powders on the LMD repaired parts is rarely published.

The aim of this work was to investigate the effect of feeding powder with small differences in element contents. LMD was used to repair milled grooves on 20 mm thick 316L SS. The repaired geometry, microstructure, micro-hardness distribution with various parameters (laser power, powder feeding rate, scanning speed) were studied. Furthermore, the evaluation of tensile strength, bending strength and low-temperature impact toughness of repaired specimens were conducted. The relationship between microstructure features and mechanical properties of the repaired specimens was also reported.

2. Experimental method

2.1. Material preparation

In order to investigate the influence of mechanical properties caused by different element-content powders provided by different companies on practical applications in industry production, two 316L common commercial powder were chosen as the research objects. Table 1 shows the analyzed elements contents of two kinds of 316L powder (#1, #2) and substrate obtained from Inductively Coupled Plasma-Atomic Emission Spectroscopy. Substrate was provided by Zhenshi Group Eastern Special Steel Co. LTD, China. Powder #1 was provided by Boao Alloy Material Co. LTD, China; while powder #2 was produced by Praxair, U.S.A. The chemical composition of the substrate and feeding powders are listed in Table 1. Also, the mechanical properties of the substrate are presented in Table 2. The mechanical properties of the substrate were tested by electronic universal testing machine (CMT5305). As can be detected, compared to powder #1, powder #2 had a relatively close chemical composition to the substrate. The substrate was 316L SS plate, the thickness of which was 20 mm. The dimensions of 316L SS used as substrate was 200 mm × 65 mm × 20 mm. The shape and size of the groove are presented in Fig. 1(a). As is shown in Fig. 1(a), the groove used for laser remanufacturing had the shape of trapezoidal shape (T-shape). All specimens were polished by abrasive paper of 240 meshes and cleaned with acetone before LMD.

2.2. LMD process

A Semiconductor TruDiode3006 laser system with continuous wave and a coaxial powder feeding nozzle were used for the LMD process. The schematic of the LMD process and scanning strategy is shown in Fig. 1(b). The maximum power output and wavelength range of TruDiode 3006 are 3 kW and 900–1070 nm, respectively. The laser beam was transported to the LMD nozzle through a 600 μm core diameter optical fiber. For the sake of enhancing the flexibility of the LMD process, the YC52 nozzle made by Precitec was used. The focal distance of lens was 100 mm, producing a laser spot size of about 2 mm. Besides, in order to prevent the molten pool from being oxidized a flow rate of Argon was set as 8 L/min during the experiment. The carrier gas was also Argon at the pressure of 0.56 MPa to carry the feeding powder. Before LMD, the abrasive paper and acetone was used to eliminate the oxidation, rust and grease near the gap. Subsequently, in order to ensure adequate constraint, the specimens were fixed on the workbench by the fixture. The length of track approximate was 60 mm and a total of 8 overlapping layers were required to repair the whole T-groove. According to several trials, the width of each track was chosen to be 0.75 mm.

2.3. Characterization

After LMD, in order to observe the metallographic and evaluate the micro-hardness, the specimens were cut from the completed plate using a wire electrical discharge machining (WEDM) and hot mounted. A 240, 600, 1000, 2000, 3000 grit size sand paper

Table 2
Mechanical properties of 316L stainless steel.

Material	Yield strength/MPa	Ultimate tensile strength/MPa	Elongation/%
Substrate	248	566	57

Table 1
Chemical composition of 316L stainless steel and feeding powder (weight in %).

Element	Co	Cr	Cu	Mn	Mo	Ni	P
Substrate	0.23	16.77	0.0459	1.11	2.03	10.39	0.0287
Powder #1	–	11.8	–	0.15	–	0.2	0.031
Powder #2	–	17.05	–	1.2	2.8	11.28	0.019
Element	Si	Ti	V	W	C	S	Fe
Substrate	0.513	0.007	0.0773	<0.015	0.0076	0.0032	Bal
Powder #1	0.56	–	–	–	0.15	0.05	Bal
Powder #2	0.46	–	–	–	0.017	0.09	Bal