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Effect of electric-magnetic compound field on the pore distribution in laser cladding process

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ABSTRACT

The porosity defect and the inhomogeneous pore distribution are intractable problems in the conventional laser cladding process and the laser melting porous metal separately. Therefore, it is necessary to develop a common approach to achieve the rational distribution of pores for different manufacturing processes. In this paper, electric-magnetic compound field has been applied to change the stress state of pores in the molten pool which obviously influenced the overflow speed of pores. In experiments, the laser cladding powder containing 92% AISI 316L and 8% TiH_2 was adopted to obtain stable pore distribution. Results of experiments indicated that both the porosity and the pore size decreased and the pore distribution converged on the surface of the cladding layer when downward Ampere force was applied. Also an increasing tendency of porosity was observed and the pore distribution was more uniform when upward Ampere force was applied. The porosity decreased by 64.71% when the substrate current was 120 A while it increased by 144% when the substrate current was −90 A. The change of cladding shapes, microstructure and Vickers hardness of cladding layers under different Ampere force was also expounded.

1. Introduction

Laser Engineered Net Shaping (LENS) is an additive manufacturing (AM) technology which builds three-dimensional (3D) parts through the layer-upon-layer method guided by a digital model [1–3]. The process is that the wire or the metal powder is cladded on the specific surface of substrates by high power laser beam [4]. Compared with traditional manufacturing methods, this technology possesses unique advantages, such as, high degree design freedom and high processing efficiency, being able to produce functionally graded materials and manufacturing complex parts without complex dies or casting models [5,6]. Laser cladding is the foundation of producing multi-layered components and it has been used to remanufacture components and improve the comprehensive performance of the surface [7–9]. The research on improving quality of laser cladding has a positive significance for the development of laser additive manufacturing.

Pore is a common defect in the laser cladding process, which has a detrimental influence on the reliability of the cladding layer [8]. Generally speaking, the porosity defect will raise the local stress level and dramatically reduce the fatigue life of mechanical components [10]. The wear and corrosion properties are also affected significantly by porosity defect [11,12]. According to previous studies, pores in cladding layers occur due to many different reasons. The keyhole-induced porosity could be attributable to the bubble formation caused by the instability of the keyhole [13]. Low laser power and high powder feed rate can intensify porosity defect [14,15]. When the cladding powder was doped with WC, the porosity defect formed because the free C and O elements in the molten pool would generate CO or CO_2 [16,17]. Concerning the selective laser melting of aluminum alloy, the hydrogen porosity formed easily for the low hydrogen solubility in solid aluminum alloy [18,19]. In order to improve comprehensive properties of cladding layer, it is necessary to develop a method to reduce the porosity in the laser cladding process.

On the other hand, homogeneously distributed pores in the cladding layer are useful. The porous metal containing abundant pores has many characteristics such as low weight, high sound and impact absorption, electromagnetic shielding performance. It has been used in the vehicle, medical treatment and chemical industry [20]. In recent years, researchers pay more attentions to the laser melting porous metal. In general, the laser melting porous metal contains two forming ways: adopting special scanning

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strategies [21,22] and adding foaming agent to cladding powder [23,24]. While, for the second method, pores show the inhomogeneous distribution in different layers along vertical direction [24]. In order to improve the porous metal properties, it is worthy of in-depth study to achieve the uniform distribution of pores.

The application of magnetic field has been widely studied to improve cladding quality as it can distinctly affect the electrically-conducting fluids [25]. Both oscillating and steady magnetic fields have significantly positive effect on the cladding process quality. Marcel et al. [26] and Bachmann et al. [27] discovered that the electromagnetic field was beneficial to avoid the melting sagging, reduce the spattering and pores, decrease surface roughness in laser welding. Chen et al. [28] detected that the steady magnetic field could reduce the austenite grain size and crack, stabilize the weld. Zhou and Tsai pointed out that applying electromagnetic force could effectively prevent porosity in pulsed laser keyhole welding because the external electromagnetic force could increase the back filling speed of the liquid metal during the keyhole collapse process [29]. André et al. indicated electromagnetic field in laser welding of aluminum die casting conduced to a significant reduction of the porosity and surface smoothing [30]. The electromagnetic stirring technology was also applied to laser beam welding [31] or laser solid forming [32]. It had obvious effect on modifying the microstructure and improving the mechanical property.

From the above two aspects, it is crucial to reduce the porosity in conventional laser cladding process, while, for the laser melting porous metal, attaining the uniform distribution of pores in the layer is significant. Therefore, it is necessary to develop a common approach to achieve the rational distribution of pores for different manufacturing processes. In fact, the final distribution of pores is determined by both floating speed of pores and solidification front velocity of the molten pool. While, the overflow velocity of pores depends on the stress state in the molten pool. In this study, electric-magnetic compound field providing additional body force was applied to change the stress state of the gas pore in the molten pool. In detail, the body force, similar to gravity, was added in the form of Ampere force and the distribution of pores would change obviously under the influence of Ampere force. The relationship between the pore distribution and Ampere force was studied. The shape, microstructure and microhardness of cladding layers under different intensities Ampere force were also analyzed.

2. Experiments

2.1. Materials

In this study, pores in cladding layers with dimensional stability and quantity consistency were beneficial to the comparison and analysis of the experimental results. This meant that the sizes, quantities, and distributions of pores should be roughly the same in repeated experiments with the same parameter. However, it was difficult to achieve this requirement by using conventional methods. In order to obtain more stable pore distribution during the laser cladding process, a new type of laser cladding powder was designed in the experiments. In detail, the powder contained 92% AISI 316L and 8% TiH_2. When the temperature reached 675 K to 823 K, the TiH_2 would decompose according to the following formula [33]:

$$TiH_2(s) \rightarrow Ti(s) + H_2(g) \tag{1}$$

The size of AISI 316L powder ranged from 90.3 μm to 164.9 μm and the chemical compositions were listed in Table 1. The size of TiH_2 powder ranged from 11.5 μm to 55.2 μm, the chemical compositions were listed in Table 2. The ball-milling method was adopted to make the mixed powder more homogeneous. The ball-to-powder weight ratio was 1.5 and the blending time was 40 min in the experiments.

Table 1
Chemical compositions of the AISI 316L powder (wt.%).

C	Mo	Ni	Mn	Cr	Si	Fe
0.006	2.6	12.8	1.5	17.0	0.7	Balance

Table 2
Chemical compositions of the TiH_2 powder (wt.%).

Fe	Si	Mg	Mn	O	C	N	Cl	TiH_2
0.06	0.02	0.01	0.01	0.25	0.02	0.06	0.04	Balance

For the purpose of improving the convenience of the experiments, slender laser cladding substrate was adopted and the detail size was 6 × 10 × 170 mm^3. The material of the substrate was AISI 316L stainless steel and the material properties were shown in Table 3. The relative magnetic permeability of AISI 316L was similar with air and the magnetic field intensity did not change obviously at the sample position.

2.2. Processing techniques

The Ampere force was applied during the laser cladding process through a set of self-made electric-magnetic compound field system. The figure of the experiment equipment and the schematic diagram were shown in Fig. 1. As illustrated in Fig. 1(b), the laser device provided the necessary energy input for the laser cladding process. The motion of the laser beam was supported by a KUKA six-axis industrial robot (KUKA KR30HA). Besides, the coaxial powder-feed equipment provided the cladding powder timely during the laser cladding process. The electromagnet was used to output amplitude adjustable magnetic field and the direct-current power could supply amplitude adjustable direct current for the laser cladding substrate. During the laser cladding process, the substrate was placed in the steady-state magnetic field. Under the interaction of the magnetic field and the direct current, the Ampere force was applied to the molten pool. According to the basic formula of ampere force, the Ampere force on the laser cladding substrate could be calculated as follows:

$$F = IBL \sin\alpha \tag{2}$$

In the formula, I was the direct current in the substrate; B expressed the magnetic intensity; L was the length of the substrate; α was angle between the direct current and the magnetic field. In the experiments, the value of α was 90° which was a constant. The direction of Ampere force was determined by the direction of the direct current and the magnetic field.

The semiconductor laser unit (Laserline LDF 4000-100) was adopted in the experiments. The laser cladding parameters were respectively as follows: laser power 1000 W, cladding speed 3 mm/s and spot diameter 3 mm. In the contrast experiments, the magnetic field remained the same and the Ampere force changed with the adjustment of the current value. Several different parameters were set up to demonstrate the trend. The specimen

Table 3
Material properties of AISI 316L.

Density	Melting point	Resistivity	Tensile strength	Hardness
7980 Kg/m^3	1643–1671 K	0.73 $\Omega\ mm^2\ m^{-1}$	≥520 MPa	≤200 HV