Optics and Laser Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Control of microstructure and mechanical properties of laser solid formed Inconel 718 superalloy by electromagnetic stirring

Fencheng Liu [a,*], Hongmao Cheng [a], Xiaobin Yu [a], Guang Yang [b], Chunping Huang [a,c], Xin Lin [c], Jing Chen [c]

[a] School of Aeronautical Manufacturing and Engineering, Nanchang Hangkong University, Nanchang, Jiangxi 330063, PR China
[b] Key Laboratory of Fundamental Science for National Defence of Aeronautical Digital Manufacturing Process, Shenyang Aerospace University, Shenyang, Liaoning 110136, PR China
[c] Stake Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, Shannxi 710072, PR China

ARTICLE INFO

Article history:
Received 14 April 2017
Received in revised form 18 July 2017
Accepted 12 September 2017
Available online xxxx

Keywords:
Laser solid forming
Electromagnetic stirring
Superalloy
Microstructure control

ABSTRACT

The coarse columnar grains and special interface in laser solid formed (LSFed) Inconel 718 superalloy workpieces seriously affect their mechanical properties. To improve the microstructure and mechanical properties of LSFed Inconel 718 superalloy, electromagnetic stirring (EMS) was introduced to alter the solidification process of the molten pool during LSF. The results show that EMS could not completely eliminate the epitaxially growing columnar grains, however, the strong convection of liquid metals can effectively influence the solid–liquid interface growing mode. The segregation of alloying elements on the front of solid–liquid interface is inhibited and the degree of constitutional supercooling decreases correspondingly. Comparing the microstructures of samples formed under different process parameters, the size and amount of the γ+Laves eutectic phases formed in interdendritic area decrease along with the increasing magnetic field intensity, resulting in more uniformly distributed alloying elements. The residual stress distribution is proved to be more uniform, which is beneficial to the grain refinement after recrystallilzaiton. Mechanical properties testing results show an improvement of 100 MPa in tensile strength and 22% in elongation was obtained after EMS was used. The high cycle fatigue properties at room temperature was also improved from 4.09×10^4 cycles to 8.21×10^4 cycles for the as-deposited samples, and from 5.45×10^4 cycles to 12.73×10^4 cycles for the heat treated samples respectively.

1. Introduction

Laser solid forming (LSF) is an additive manufacturing technology using laser beam as the heat source to melt powders and forms metal structures layer by layer under a control of re-established program [1]. Unlike traditional materials manufacturing processes, *e.g.*, casting, forging and welding, LSF can fabricate complex structures freely and rapidly, and the fabricated materials have a dense structure which leads to outstanding mechanical properties. For example, the tensile property of LSFed Inconel 718 superalloy sample has been proved to be higher than the forging criterion for engineering applications [2]. However, the fatigue property of the LSFed Inconel 718 superalloy samples is too low to satisfy the actual application in aeronautics and astronautics industries due to the large columnar grains and their uneven distribution even after heat treatment [3]. Therefore, the application of LSF technique in manufacturing of superalloy structures is restricted in recent years.

Electromagnetic stirring (EMS) has been successfully applied in the welding process to reduce metallurgical defects and distortions through changing the solidification behavior of liquid metals in the molten pool. Kern et al. [4] have investigated the influence of magnetic stirring in laser beam welding, and they found that the utilization of magneto-fluid dynamic mechanisms makes it possible to "laminarize" the melt flow and to modify the velocity distribution in the weld pool. The solidification behavior of liquid metals in molten pool during LSF has the similar characteristics compared with that of the welding process, so the combination of electromagnetic stirring and laser solid forming can give a new solution to improve the microstructure and mechanical properties of LSFed samples. Qin et al. [5] have studied the effects of magnetic field stirring on the laser metal deposition of titanium alloy and they found the rotating magnetic field intensifies the convection in the molten pool and increases its cooling speed, which leads to finer microstructures and better mechanical properties. Yu et al. [6] reported the usage of electromagnetic stirring on laser cladding of WC/Co based layers on steel substrates. The results showed that the cladding was free of porosity and cracks for the stirring effects of electromagnetic field. To improve the microstructure of LSFed

---

* Corresponding author.
E-mail address: fencheng999@163.com (F. Liu).

http://dx.doi.org/10.1016/j.optlastec.2017.09.022
0030-3992/

Please cite this article in press as: F. Liu et al., Control of microstructure and mechanical properties of laser solid formed Inconel 718 superalloy by electromagnetic stirring, Opt. Laser Technol. (2017), http://dx.doi.org/10.1016/j.optlastec.2017.09.022

Inconel 718 superalloy, Yu et al. [7] added rotating magnetic field into LSF processing, and found that electromagnetic stirring can effectively influence the formation of γ+Laves eutectic phases in the interdendritic areas and increased the microhardness of the LSFed materials.

In this paper, electromagnetic stirring is introduced to LSF of Inconel 718 superalloy, and the microstructure, tensile property and high cycle fatigue property of as-deposited and heat treated samples were experimentally investigated. The aim is to optimize the microstructure and mechanical properties of the LSFed Inconel 718 superalloy.

2. Experimental procedure

The Inconel 718 superalloy powder using in this experiment is prepared by plasma rotation electrode process (PREP) with a sphere shape and a size of about 175 µm. The chemical composition of the powder is listed in Table 1. The substrate was cut from a 304 stainless steel sheet with dimensions of 150 mm × 60 mm × 6 mm. The surface of the substrate was polished using sand papers and then cleaned with acetone before LSF process.

The LSF of Inconel 718 superalloy samples were carried out on a laser metal deposition system built by Shenyang Aerospace University, consisting of a 5 kW DL-HL-T5000B fast-transverse-flow CO_2 laser, a digital controlled working table, a controlled atmosphere chamber and a powder feeding system with a coaxial nozzle. To achieve the electromagnetic stirring effect on the molten pool, an electromagnetic stirring set-up was used, which was mainly consisted of two pairs of permanent magnets, a turnplate made of aluminium and a stepping motor. Different magnetic field intensities can be realized through the regulation of gaps between the magnets and different frequencies can be obtained by varying the rotating speed of the motor. The substrate was fixed on the working table and did not rotate with the turnplate and the magnets. Before the LSF process, the magnetic field intensity was measured using a HT201 Gauss meter on the centre point of tow magnets (where the LSFed Inconel 718 superalloy samples were deposited) when the direction of magnets was not changed. Because the magnets was much higher than the deposited samples, so the magnetic field intensity was considered to be uniform distributed in the molten pool during the LSF process. The frequency of the magnetic field used in experiments was 50 Hz and was maintained as the same to all samples. The electromagnetic field intensities used in this experiment were 0, 30, 50 and 80 mT for different samples, respectively. The detailed schematic diagram of the LSF is shown in Fig. 1. The process parameters are as follows: laser power P = 1800 W, scanning speed v = 9 mm/s, spot diameter D_0 = 3 mm, overlap of adjacent passes η = 40%, increment in the Z direction ΔZ = 0.3 mm, and shielding gas flux (Ar) f_{gas} = 6 L/min. Several blocks were deposited for the microstructure observation and mechanical properties tests (see Fig. 2).

To observe the microstructure of the as-deposited LSFed Inconel 718 superalloy samples, small sections perpendicular to the laser scanning direction were cut from the blocks, ground and polished with sand paper, and etched with a mixture of 10 mL $CH_5(OH)$ + 10 mL HCl + 5g$FeCl_3$. The heat treatment process used is as follows: solution treatment at 1100 °C for 1.5 h with air cooling to room temperature, followed by aging at 980 °C for 1 h and air cooling to room temperature, then aging at 720 °C for 8 h, furnace cooling to 620 °C continuously, holding at 620 °C for 8 h and finally air cooling to room temperature. The microstructures were observed through a MR 5000 optic microscopy (OM). Residual stress was measured with Vickers micro-indentation method, which was first reported by Suresh et al. [8] and applied to metal materials by Carlsson et al. [9]. The actual area of Vickers microhardness indentation was measured and compared with the nominal area, and the residual stress was calculated through a fitting formula. The detailed description of the method and some measured data can be found in Ref. [10]. The tensile test of the samples were carried out on a INSTRON 3382 universal material tester with a tensile speed of 2 mm/min. The high cycle fatigue property of the samples were tested on a INSTRON 8802 hydraulic fatigue machine, with testing conditions as follows: sine wave at a stress ratio of R = −1, smooth fatigue samples, a load frequency of f = 10 Hz, and a maximum stress of F_{max} = 750 MPa. For tensile and fatigue tests, three samples were tested for each condition and the average values of tensile strength, elongation and fatigue life cycles were calculated to ensure the accuracy of the result. After tensile and fatigue tests, the fractography was performed with a TESCAN VEGA II-LMH scanning electron microscopy (SEM).

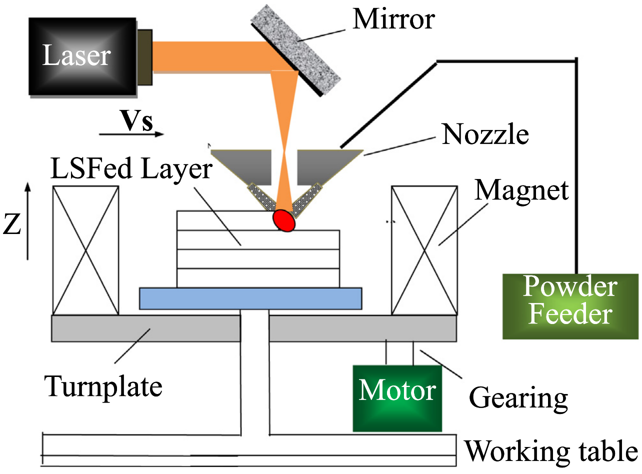

Fig. 1. Schedule of electromagnetic stirring aided laser solid forming set-up.

3. Results and discussion

3.1. Microstructure of LSFed Inconel 718 superalloy samples

Fig. 3 shows the effect of EMS on microstructure of LSFed Inconel 718 superalloy samples. The typical microstructure of the as-deposited LSFed Inconel 718 alloy (samples fabricated without EMS) is the columnar dendrites growing epitaxially along the deposition direction as shown in Fig. 3a. This kind of coarse columnar grain structure is recognized as the typical structure of laser additive manufacturing materials, and can be found in many kind of laser additive manufactured materials, such as superalloys and titanium alloys . The as-directional solidification structure also leads to the anisotropic properties of the materials [11]. For the samples deposited with EMS, the dendrite structure remains the same to the as-deposited samples, indicating EMS does not change

Table 1
Chemical composition of Inconel 718 superalloy powder (wt.%).

C	Nb	Cr	Ni	Al	Ti	Mo	Mn	Si	S	P	Fe
0.034	4.91	19.68	51.75	0.63	0.97	3.18	0.11	0.23	0.001	0.004	Bal.

Please cite this article in press as: F. Liu et al., Control of microstructure and mechanical properties of laser solid formed Inconel 718 superalloy by electromagnetic stirring, Opt. Laser Technol. (2017), http://dx.doi.org/10.1016/j.optlastec.2017.09.022