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Microstructure and electrochemical anodic behavior of Inconel 718 fabricated by high-power laser solid forming

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ABSTRACT

Improvements to the surface of high-power laser solid formed Inconel 718 by use of electrochemical methods were systematically investigated. Formation features (surface microstructure characteristics and surface morphology) and the corresponding electrochemical anodic behavior (electrochemical dissolution behavior and surface levelling mechanism) were analysed. The electrochemical results show that the surface energy difference between the horizontal section and vertical section causes no difference to their transpassive current densities in 10 wt.% $NaNO_3$ solution up to 2.5 V, owing to the existence of a passive film. Analysis of micro-morphologies indicates that the high current density leads to a smooth micro-morphology due to the higher detachment rates of the interdendritic phases and surface products. Numerical simulations suggest that surface peaks dissolve faster than depressions during the electrochemical levelling process owing to the higher local current density on the surface peaks. Importantly, a detailed microstructure selection map for as-deposited Inconel 718 and an anodic current-density-potential map were developed, and the electrochemical levelling mechanism of its wavy surfaces was proposed. This work has the potential to integrate understanding of laser solid forming-process conditions, formation features, and electrochemical anodic behavior.

1. Introduction

Laser solid forming (LSF) is a solid free-form additive manufacturing (AM) method that fabricates 3D components directly with almost any desired geometry by the successive addition of material in a layer-by-layer fashion [1,2]. Inconel 718, a nickel-based superalloy, is widely used in aircraft engines, gas turbines, and other high-temperature applications due to its resistance to oxidation at high temperatures, excellent mechanical properties, and structural stability up to 650 °C [3]. However, Inconel 718 is difficult to machine by traditional processing methods owing to its self-hardening tendency and retention of excellent mechanical properties at elevated temperature, leading to low material removal rate, significant tool wear, and poor surface quality [4–6]. Therefore, the fabrication of large, complex, and high-performance Inconel 718 components by LSF has received increasing attention in recent years [7–9].

High manufacturing efficiency and excellent mechanical properties are desirable in the fabrication of Inconel 718 components; thus, a laser with high power and large spot diameter, high powder feeding rate, and large scanning speed are used to optimize the manufacturing efficiency of the LSF process [1]. However, due to the overlap between cladding tracks and the stacking effect between deposited layers, the top and side surfaces of the as-deposited components are waved with a large waviness. Consequently, there is a trade-off between operational efficiency and problems related to poor manufacturing precision and surface integrity, which has become an obstacle for industrial applications. This suggests that although high-power LSF-fabricated Inconel 718 is a high efficient net-shape manufacturing technology, the as-deposited components still need subsequent machining before being put into application due to the need for high precision and good surface quality.

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Electrochemical machining (ECM) removes anodic materials via controlled electrochemical anodic dissolution reactions whereby metals dissolve into metal ions diffusing from the metal/electrolyte interface to the electrolyte [10,11]. Compared to conventional machining techniques, ECM possesses many advantages, such as no tool wear damage, no surface residual stresses due to the non-contact manner of working, high material removal rate induced by the fast kinetic rate of the metal electrode process, and high processing accuracy using ultra-short pulses [12–14]. In addition, good surface integrity can be achieved regardless of material strength and hardness during the ECM process [14–17]. It is important to note that ECM is one of the most cost-effective technologies in the case of large batch sizes [18]. Therefore, the combination of LSF and ECM can promote the development of both technologies in manufacturing difficult-to-cut materials efficiently, precisely, and economically, which is of significant interest from both scientific and industrial perspectives.

One of the main concerns is the formation of surface features including surface microstructure characteristics and surface morphology. Several authors [7,19–21] have investigated the microstructure of laser additive manufacturing (LAM)-fabricated Inconel 718 and found that columnar grains with a substructure of directional columnar internal dendrites always grow epitaxially over several successive layers along the build direction. In addition, some investigators [22,23] studied the columnar-to-equiaxed transition (CET) using numerical simulation methods. These authors provided an important guideline for understanding the microstructural evolution of AM-produced Inconel 718. However, the relationship between microstructural features (e.g., microstructure morphology and its size) and solidification conditions (such as the thermal gradient and interface velocities) is still not fully understood. Research into surface morphology [24–31] has considered the influence of processing parameters on the quality of the surface formed by direct metal laser sintering (DMLS), selective laser melting (SLM) and laser cladding processes. These authors provided much important information for understanding the relationship between processing conditions and the as-deposited surface morphology i.e., the maximum relief of undulations for laser cladding, and surface roughness for DMLS and SLM. In addition, shot peening, laser re-melting, and selective laser erosion can effectively reduce the surface roughness and improve surface quality [28,32]. However, little attention has been focused on the surface morphology of LSF-fabricated components due to the complexity of factors that influence it and the lack of related evaluation standards. Note that the initial surface morphology can significantly influence the electrochemical levelling process. Thus, it is necessary to study the surface morphology of LSF-fabricated Inconel 718.

The other topic of significant interest is the electrochemical anodic behavior of LSF-fabricated materials, including anodic dissolution behavior and surface levelling mechanisms. To date, many reports have shown that microstructural features significantly influence the anodic dissolution behaviors of many metal materials. For instance, the rolling surface in AZ31 Mg alloy and the depleted β-Ti phase with large amounts of acicular α' martensite in Ti-6Al-4V both exhibit poor corrosion resistance (anodic dissolution occurs easily at low current densities) in corrosive environments [33–35]. Furthermore, high number of grain boundaries and crystal planes with high surface energy will both lead to high metal dissolution rates [36,37]. Our previous work [38–40] investigated different aspects of the anodic dissolution behavior of LSF-fabricated Inconel 718, including the corrosion behavior and anodic dissolution behavior of the constituent phases in $NaNO_3$ solution. However, the relationship between the microstructure and anodic behavior for as-deposited Inconel 718 in flowing electrolyte has yet to be systematically investigated. It is well known that ECM is applied to obtain a desired dimension and surface quality, and thus, the levelling effect is of great importance for an uneven surface. Zhang et al. [41] investigated the potential of electrochemical polishing to improve the surface of Inconel 718 that had been prepared by SLM and found that the surface roughness decreased measurably. Gurumurthy et al. [42] studied the smoothing process of an anode surface with various profiles and found that a sinusoidal profile was obtained before attaining the final shape. Furthermore, Chetty et al. [43] found that the orientation of the profile with respect to the electrolyte flow direction influences the levelling effect. However, the levelling mechanism of different surface profiles during ECM is not completely understood, especially for the unique top and side surface morphologies of high-power LSF-fabricated Inconel 718 components.

The study was organized as follows: 1) We observed the microstructural features (microstructure morphology and size, etc.) of high-power LSF-fabricated bulk Inconel 718. A detailed solidification microstructure selection map was established to predict the microstructure morphologies and sizes of Inconel 718 fabricated by various LSF processes. 2) A current-density-potential map was developed to study the electrochemical anodic behavior of the as-deposited Inconel 718 in $NaNO_3$ solution during the ECM process. 3) We investigated the surface morphologies of the LSF-fabricated bulk Inconel 718 and the electrochemical levelling mechanism.

2. Experimental

The LSF experiments were conducted using a LSF-VII system, consisting of a 6 kW semiconductor laser, a three-dimensional numerical controlled working table with a glove box, and a powder feeding system. The processing parameters are as follows: laser power 4 kW, laser spot diameter 5.3 mm, scanning speed 15 mm s^{-1}, powder feeding rate 30 g min^{-1}, hatch spacing 2.65 mm and layer thickness 0.9 mm. To obtain an as-deposited component of good quality and low residual stress, a staggered laser scanning strategy (shown in Fig. 1a) was used; the starting point of each layer was 1, 2, 3, and 4 in turn. Gaseous atomized Inconel 718 powder with particle diameter ranging from 45 to 125 μm was used as the original material and, in terms of wt.%, its chemical composition was measured as Fe-17.83, Cr-18.80, Nb-5.04, Mo-3.00, Ti-0.92, Al-0.44, Mn-0.05, Si-0.04, and Ni-balance. Prior to the LSF experiments, the powder was dried in a vacuum oven at 120 °C for 4 h to remove the absorbed water. In addition, to achieve metallurgical bonding between the substrate and the deposit and reduce costs, a Q235 substrate ($160 \times 70 \times 20$ mm^3) with a nominal composition (wt.%) of 1.40Mn, 0.35Si, 0.22C, $\leq$ 0.045P, $\leq$ 0.055S, and Fe balance was used. Its surface oxide layers were removed using 600# aluminum oxide waterproof abrasive paper and then the substrate was degreased with acetone. The deposit ($130 \times 60 \times 90$ mm^3) of Inconel 718 displayed in Fig. 1b was fabricated in an argon atmosphere (oxygen gas content less than 50 ppm). Prior to electrochemical tests, stress-relief annealing (SR) was conducted on the deposit at 550 °C for 3 h followed by air cooling (AC) to avoid the effect of residual stress on the electrochemical behavior of the as-deposited Inconel 718.

Cubic samples ($10 \times 10 \times 10$ mm^3) containing the top and side surfaces of the deposit and cylindrical specimens (15 mm in diameter and 5 mm in height) from inside the deposit (Fig. 2a) were machined using a wire-cut electric discharge machine. The cylindrical specimens were used for anodic polarization tests, and the cubic samples were used for metallography, observation of surface morphology, electrochemical anodic dissolution and electrochemical levelling experiments. The sampling locations are shown in Fig. 2a. The electrochemical polarization tests were conducted