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Full Length Article

Microstructure evolution induced by inoculants during the selective laser melting of IN718

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ABSTRACT

This study focuses on the microstructure evolution induced by eutectic WC-W_2C inoculants during the selective laser melting (SLM) of IN718. The as-built microstructure observed using an electron microscope indicates that grain nucleation occurred on the surface of inoculants and that the diffusion layer between inoculants and IN718 composed of a mixture of IN718 and inoculants. After the post heat treatment of the as-built SLM specimens, more grains nucleated around the inoculants, and Nb-rich precipitates were formed along the grain boundaries. With an increase in the post heat-treatment temperature, the microstructure evolution became more pronounced. To elucidate the underlying mechanism, both theoretical and experimental analyses were performed. In summary, eutectic WC-W_2C inoculants could provide heterogeneous nucleation sites for grain formation owing to the low wetting angle and the semi-coherent interface with the matrix. Theoretical analysis suggests that the difference in the thermal expansion coefficient between inoculants and IN718 did not provide a significant amount of residual stress. Thus, it can be concluded that heterogeneous nucleation is the primary mechanism by which inoculants can influence the microstructure in the present study.

1. Introduction

Superalloys, one of the most important structural materials with excellent mechanical properties and surface stability at elevated temperatures, have been the key technology to the advancement of aerospace and military industry, because the temperature capability of superalloys can directly influence the engine efficiency. However, the compositions of conventional superalloys are required to be compliant with the traditional processing routes such as forging [1] and welding [2–4], and the fabrication of superalloy components such as turbine disc involves numerous steps including the open-die forging, close-die forging, and machining, thereby increasing the cost and loss of materials. Thereby, it is important to develop a new processing technology to fabricate superalloy components with intricate dimensions. With the advent of additive manufacturing (AM) techniques, components with complex geometry can be fabricated with a high efficiency, and among the AM techniques, selective laser melting (SLM) has received considerable attention owing to its flexibility to control the specimens layer by layer by a specific scanning strategy. Thus, the SLM process for superalloys has become an extremely popular subject in both scientific and engineering community. IN718 is one of the most widely used superalloys because of its prominent mechanical properties and good cost performance; hence, IN718 is also a popular subject of interest in the SLM process. Several reports have indicated that the as-built specimens present strong anisotropy along the [001] direction. Even after heat treatment, this anisotropy could remain, and columnar grains dominate the entire microstructure, resulting in anisotropic properties [5–8]. Scientists continue to study not only the AM scanning strategies and laser parameters but also the microstructures controlled by introducing additional inoculants. J.H. Martin et al. [9] reported that after introducing nanoparticles such as TiB_2 and ZrH_2 into Al7075, these nanoparticles can facilitate fine grain formation and further improve the tensile properties of SLM Al7075. Although a similar method was utilized to promote fine grain formation for nickel-based superalloys during conventional casting route [10–12], the underlying mechanisms associated with the effects of inoculants on the SLM process are still not clear. Therefore, this research aims to clarify the microstructure evolution induced by inoculants during the SLM of IN718. According to the study conducted by W. Fang et al. [13], WC-CrC-Ni can be deposited on IN718 to improve both hardness and wear resistance because they not only possess good surface adherence to IN718 but also render W and C atoms to IN718 as solute atoms to enhance the mechanical properties. Therefore, IN718 powder and eutectic WC-W_2C inoculants were chosen in this research to study the effect of inoculants.

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Table 1
Nominal composition (wt%) of IN718 powders used for SLM.

Ni	Co	Cr	Fe	Al	Cu	Ti	Si	Mn	Mo	Nb	B	C
Bal.	0.07	18.33	16.83	0.56	0.04	0.95	0.14	0.07	2.96	5.19	0.001	0.06

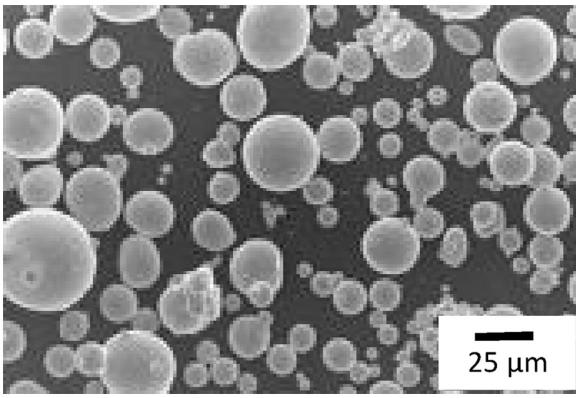

Fig. 1. SEM image of IN718 powders used for SLM.

2. Material and methods

Gas-atomized IN718 powders, with D_{10} = 18.8 μm, D_{50} = 32.4 μm, and D_{90} = 54.6 μm, were supplied by Chia Yi Steel Inc.; the composition is given in Table 1. As shown in Fig. 1, most of the powders were spherical. The inoculants used in this work were spherical particles of eutectic WC-W_2C phase; inoculant powders with an average size of approximately 45 μm were supplied by Tekna Inc. Inoculant powders (0.5 wt%) were mixed with IN718 powders uniformly using a rolling ball mill without the use of ball. SLM was conducted under Ar atmosphere with an oxygen level below 2000 ppm; YLR-AC-500W Ytterbium fiber laser with a beam size of 58 μm was utilized. Carbon steel base plate was used for the SLM process. Powder beds were paved by a rubber recoater to achieve a layer thickness of 50 μm each time. To obtain a dense structure without crack formation, optimized scanning parameters were applied to the whole process: the laser power was between 200 and 220 W, scanning speed was between 600 and 1000 mm/s, and hatch distance was 70–110 μm. The scanning pattern used to produce a 10 × 10 × 5 mm^3 structure is presented in Fig. 2; a 90° rotation was applied between successive layers along the building direction, Z axis. After completion of SLM, all the specimens were detached from the base plate by electro discharge machining (EDM). The specimens were ground by sandpapers and polished by Al_2O_3 suspension to remove the oxide layer and scratches. In addition, specimens were etched in Kalling's No. 2 solution (5 g $CuCl_2$ + 100 ml HCl + 100 ml ethanol) to reveal the grain boundaries.

To examine the microstructure evolution after post heat treatment, some specimens were subjected to two distinct solution heat treatment (SHT) conditions, 1040 °C for 1 h and 1100 °C for 3 h, followed by air-cooling to room temperature. The temperature of the SHT was slightly above the δ solvus to minimize the formation of δ phase [14]. Then, the specimens were further aged at 760 °C for 8 h and then at 650 °C for 8 h before air-cooling. The aging conditions were based on the standard heat treatment for IN718 [15].

The microstructures of the as-SLM and SLM + heat treatment specimens were observed under JSM-7610F high-resolution thermal field emission scanning electron microscope (HRFEG-SEM) equipped with an Oxford Instruments INCA energy dispersive X-ray spectrometer (EDS) and Channel 5-HKL electron backscattered diffraction (EBSD) system. EBSD was conducted under 15 kV, and a subsequent grain size distribution analysis was performed using EBSD Channel 5-HKL software, in which over 250 grains were included. SEM images were captured in either the secondary electron (SE) mode to reveal the morphology such as grain boundaries or the backscattered electron (BSE) mode to reveal the dendritic structure and segregation for the subsequent analysis of chemical composition by EDS detector.

3. Results

3.1. As-built microstructure

Fig. 3(a) and (b) show the EBSD IPF Z maps of the as-built IN718 + inoculants along the transverse direction. Because scanning parameters such as the hatch distance and the scanning pattern can strongly affect the thermal gradient during SLM, the as-built microstructure, Fig. 3(a), was found to possess a regular grain structure induced by the scanning patterns as described in the previous section. Under a higher magnification, Fig. 3(b), a few tiny grains (indicated by various colors in the figure) were found to nucleate along the surface of inoculants, suggesting that eutectic WC-W_2C inoculants could provide heterogeneous nucleation sites for small grains. The longitudinal section, Fig. 3(c), possessed the same microstructure as that of the transverse section. Furthermore, based on SEM images taken along the transverse direction, Fig. 3(d) and (e), dendritic structures were observed around the inoculants. Because of the high-energy laser beam, partially melted inoculants rendered both carbon (C) and tungsten (W) elements to solution into the IN718 matrix, thereby altering the local chemistry near the inoculants. Based on the composition measurements conducted by EDS analysis, Table 2, the region around the inoculants could be divided into three layers. First (in region 2 of Fig. 3(e)), an area of partially melted inoculants mixed with IN718. Second (in region 3 of Fig. 3(e)), a diffusion layer composed of W-rich IN718 with a fine dendritic structure. Finally (in region 4 of Fig. 3(e)), resolidified IN718 matrix with a moderate amount of W, which implies that grains of IN718 could nucleate on eutectic WC-W_2C inoculants.

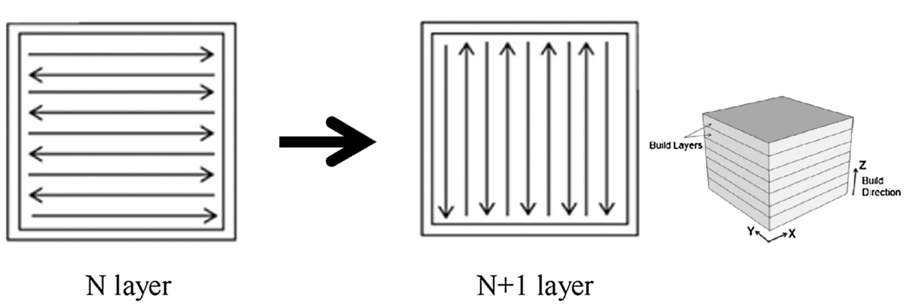

Fig. 2. Schematic representation of the laser deposition. Note that the scanning pattern is rotated by an angle of 90° between successive layers along the Z axis.

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