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Microstructural and texture development in direct laser fabricated IN718☆

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Microstructural characterisation was performed for IN718 thin-walled builds, produced using direct laser fabrication (DLF), to understand the influence of the variations in the deposition path and the laser power on the microtexture, grain structures and intermetallic particle morphology development. Considerable differences were observed, with the high laser power input generating a columnar grain structure, with a strong <001> fibre texture along the build height, compared to a mixture of fine uniform and large columnar grains in the low power builds, with a near random texture. The influence of different DLF conditions on the formation of Laves and of δ phase was also found to be significant, with the Laves phase precipitates being larger in the high laser power sample. Carbides and δ were also present in the high power build, but were not observed in the low power samples regardless of the deposition path.

1. Introduction

Direct laser fabrication (DLF) is a near net shaping technique where three-dimensional components are produced layer-by-layer by consolidating powder using a focused laser heat source. Over the past decade, DLF has shown to be capable of producing components with complex geometries to near net-shape, with considerable cost and material savings for low batch runs in Ni-base superalloys [1–3]. One of the major drawbacks in the process is the bonding defects and porosity in the builds, as well as the creation of heterogeneous microstructure, which resulted in extensive work being undertaken in the past decades to produce structurally-sound builds with acceptable mechanical properties [4,5]. Although sound builds could be produced using DLF, their mechanical properties were poor compared to wrought products [4–6], which highlights the influence of the microstructure. Generally, the builds were reported to have a columnar grain structure, growing epitaxially from the substrate, with the orientation of the grains being strongly influenced by the deposition strategy [7]. Some builds were found to have a banded grain structure with alternate coarse and fine grain bands due to different cooling rates, where the fine grains are typically found in the locations associated with rapid cooling rates [4,8]. Furthermore, the build direction appears to influence the mechanical properties, whereby the tensile strength along the deposition direction was found to be ~55–60% higher than across the build direction in IN718 builds [5]. Although limited work is available in the literature on the effect of this deposition strategy on the build microstructure, it is important to understand the grain size distribution and texture between the layers in detail [7]. With respect to the texture development, it was previously reported that IN718

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builds have a banded microstructure with random texture in IN718 builds [4]. Nonetheless, limited work is done previously on the influence of the laser power (a key process parameter) on the build microstructure and texture development [9].

IN718 is a $\gamma' + \gamma''$-strengthened Ni-superalloy [10]. It is generally less prone to solid-state cracking (e.g. strain age/reheat cracking) than γ'-strengthened alloys due to the relatively sluggish γ'' precipitation kinetics, which makes it suitable for DLF [6,11]. Nonetheless, IN718 is prone to the formation of Laves phases at elevated temperatures, whereas long thermal exposures lead to the formation of precipitates of the brittle δ phase which can act as stress raisers [12]. Segregation of Nb leading to the formation of Laves phase was previously observed in IN718 DLF builds [6,13], but the influence of the process parameters on the morphology and the density/volume fraction of these phases was not studied. It is believed that the as-fabricated builds typically have poor mechanical properties compared to the wrought products due in part to these detrimental phases. Qi et al. showed that the mechanical properties can be improved by performing a homogenisation heat treatment at ~1100 °C for 1–2 h, followed by a solution and aging treatment for precipitation of strengthening γ' and γ'' phases [13]. It is conceivable that the parameters that influence the thermal cycle during DLF (e.g. the deposition path and laser power) might also influence the formation and morphology of these detrimental phases, making it possible to tailor a microstructure with good properties by controlling the parameters.

In the present investigation, the development of texture, the grain structure and particle morphology will be investigated in IN718 builds, focusing on the influence of the deposition path (unidirectional or bidirectional), as well as the use of high laser power on the dendrite orientation and texture. The aim of the study is to assess the different microstructures that can be formed due to DLF of IN718, in order to identify the sensitivity of the grain and precipitate morphology to the variations in the process parameters (mainly the scanning strategy and the laser power).

2. Materials and Methods

Commercially available gas-atomised IN718 powder was used in this investigation, with the chemical composition given in Table 1. The average particle size of the powder is ~60 μm, with 90% of the particles falling within the size range of 40–100 μm, which is the typical range used for DLF [13]. The powder particles are mostly spherical in shape, with internal porosity infrequently observed in the particles and very fine satellite particles attached to the particles (Fig. 1a). The microstructure of the particles shows a fine dendritic network, which is caused by the rapid solidification during gas atomisation (Fig. 1b). The powder was used to build straight, single bead-width, thin-walled samples of dimensions 20 mm × 0.7 mm × 10 mm (*x*, *y*, *z*) to simulate the repair application of DLF. A Quantum DLF machine, fitted with a Wegmann–Baasel CO_2 laser (maximum power of 1750 W), was used to deposit the builds in an argon atmosphere within a glove box, with the O_2 level being kept under 50 ppm. The *Z*-increment (the vertical spacing between the successive build layers) was kept at 0.3 mm throughout the build. The laser beam was focused to a spot size of 0.7 mm using a ZnSe lens, with a focal length of 127 mm. A four-beam nozzle assembly was used for powder feeding, where the powder focus was set to coincide with the laser beam focus which is ~3–4 mm from the substrate, using argon both as a carrier gas with a flow rate of 5.5 l/min and a nozzle gas to protect the lens from the rebounding particles from the build.

Identification of the process parameter window was performed by depositing a series of specimens, varying the laser power between 300 and 500 W, scan speed between 200 and 400 mm/min and powder flow rate between 18 and 55 g/min. Following the identification of the process window, four thin-walled builds were deposited for each condition. The dimensions of the builds were found to be within ±200 μm from the target dimensions for all the conditions. Although this is beyond the scope of this paper, the authors have investigated deposition scaling up to 2 mm thick walls and 10 mm wide solid blocks (deposited with several beads). Generally speaking, the structural and geometrical integrity becomes more difficult to control with the increase in the wall width.

Builds which did not show any cracking or bonding defects, either between the individual layers or between the build and the substrate, were chosen for further microstructural studies. In this particular study, three conditions from the above, which produced sound builds were investigated in order to understand the influence of the deposition path and the laser power on the microstructural development. With the first two conditions the effect of deposition path on the microstructure was studied keeping the other process parameters constant (laser power of 390 W, laser scan speed 200 mm/min, and powder flow rate 18 g/min). The two builds were performed using a unidirectional (B1) and a bidirectional (B2) deposition path (Fig. 2). In B1 the laser was switched off between the layers for a time equal to deposition of one layer (~6 s). Also, during this laser off time, the laser head moved back to the initial position with powder flow continuing stably and the carrier gas continuing to flow cool gas across the deposit. In B2 the laser beam continuously moved back and forth for deposition, which reduces the time available for cooling (in the wake of the laser beam), with no forced cooling between the layers as in B1. A third build (B3) was deposited using a bidirectional deposition path to understand the influence of laser power on the build microstructure. In order to see a significant effect a considerably higher laser power (910 W) was used. To ensure that the build did not contact the nozzle in B3 condition, the powder feed rate was reduced to 7 g/min. The aim of this reduction in feed rate is to prevent the uppermost built layers (melt pool) from approaching the nozzle due to the enhanced powder catchment efficiency caused by the increase in melt pool dimensions with the increase in laser power.

Table 1 – Chemical composition of the base IN718 powder.

Element	Ni	Cr	Fe	Nb	Mo	Ti	Al	C	B	O	Si
wt.%	53.34	18.2	18.9	5.1	3.1	0.9	0.29	0.021	0.005	0.004	0.14