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Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting

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Abstract

In this study Inconel 718 cylinders were fabricated by selective laser melting in either argon or nitrogen gas from a pre-alloyed powder. As-fabricated cylinders oriented in the build direction (*z*-axis) and perpendicular to the build direction (*x*-axis) exhibited columnar grains and arrays of γ'' (body-centered tetragonal) Ni_3Nb oblate ellipsoidal precipitates oriented in a strong [200] texture determined by combined optical metallography, transmission electron microscopy, and X-ray diffraction analysis. Fabricated and hot isostatic pressed (HIP) components exhibited a more pronounced [200] columnar γ'' phase precipitate architecture parallel to the laser beam or build direction (spaced at ~0.8 μm), and a partially recrystallized fcc grain structure. Fabricated and annealed (1160 °C for 4 h) components were ~50% recrystallized and the recrystallized regions contained spheroidal γ' precipitates distributed in a dense field of fine γ'' precipitates. The γ'' precipitates were always observed to be coincident with {100} planes of the γ-fcc NiCr matrix. Some δ phase precipitates in the unrecrystallized/recrystallized interfaces and recrystallized grain boundaries were also observed in the annealed samples. The microindentation (Vickers) hardness was 3.9 GPa for the as-fabricated materials, 5.7 GPa for the HIP material, and 4.6 GPa for the annealed material. Corresponding tensile properties were comparable with wrought Inconel 718 alloy.
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Keywords: Nickel alloys; Solidification; Microstructure; Precipitation; Texture

1. Introduction

Nickel-based superalloys with a broad range of alloy compositions have found a wide range of industrial and aerospace applications over the past four decades in cast, wrought and powder metallurgy forms, especially after the development of pre-alloyed powders by rapid solidification technologies [1,2]. Inconel 718, a Ni–Fe–Cr (or Ni–Cr solid solution hardened) austenite (γ) has found particular applications in gas turbine blades, combustors, turbocharger rotors, a variety of corrosion containments and structural applications up to ~700 °C. In its wrought form Inconel 718 normally exhibits three intermetallic precipitation phases: γ', having the composition $Ni_3(Al,Ti,Nb)$ and a cubic (ordered face-centered) Ll_2 crystal structure; γ'', having the composition Ni_3Nb and a body-centered tetragonal (bct) (DO_{22}) crystal structure; an orthorhombic (DO_a) δ phase having the composition Ni_3Nb. The nominal base composition is 51Ni–22Fe–19Cr–5Nb–3Mo–1Co (plus small additions of Ti (~1%) and Al (~0.5%)). Studying alloys with a base composition Ni–25Fe–16Cr, Kirman and Warrington [3] showed that both the γ' and γ'' phases occur when 1.8Ti and 3.5Nb were added, but when the Ti content was increased to 3.5Ti only the γ' phase was obtained, while increasing the Nb content to 6Nb allowed

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only the γ'' phase to form. The γ' precipitates are cuboidal or spherical, while the γ'' precipitates are lenticular, disc-shaped (oblate spheroid) particles with the following orientation relationships [4,5]:

$$(0\,0\,1)\gamma''||\{0\,0\,1\}\gamma;\ [1\,0\,0]\gamma''||\langle 1\,0\,0\rangle\gamma$$

In a recent study of Inconel 718 produced by electron beam melting (EBM) an additive (layer) manufacturing process utilizing pre-alloyed, atomized powder Strondl et al. [6] observed columnar, [200] textured γ grains having low angle boundaries containing coarse (50–100 nm) γ'' precipitates. Coarse (<2 μm) (Ti, Nb)(C, N, B) type precipitates with a B1 structure were also observed to be aligned along the growth (or layer building) direction. The $(001)\gamma||(001)\gamma''$ orientation relationship was also confirmed.

In the present study pre-alloyed, rapidly solidified (atomized) Inconel 718 powder served as a precursor for the production of additive manufactured components using selective laser melting (SLM). In contrast to EBM, a vacuum environment process, the SLM process utilizes an inert atmosphere (argon or nitrogen gas). Consequently, different process parameters produce cooling variations which can affect the residual microstructure and mechanical behavior [7]. This study represents a comprehensive microstructural and mechanical behavior characterization using optical metallography (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) employing energy-dispersive X-ray spectrometry (EDS), and X-ray diffraction (XRD) analysis. The mechanical properties (hardness and tensile strength, including fracture surface analysis by SEM) were also measured for as-fabricated and heat-treated components.

2. Experimental methods

The precursor, pre-alloyed atomized Inconel 718 powder, had the composition 53.5Ni–19Cr–18.3Fe–5Nb–3Mo–1Ti–0.43Al. Fig. 1a shows an SEM view illustrating the powder size and morphology, with an average particle size of 17 μm. An OM view of a mounted, polished and etched particle section of the microdendritic structure is shown in Fig. 1b.

Fig. 2 shows a schematic view representing the EOS M270 SLM system which utilized a 200 W Yb:YAG fiber laser (Fig. 2-1). Cylindrical components measuring 1.6 cm diameter × 8.75 cm length were fabricated in both a vertical and horizontal build orientation, with the cylinder axis parallel to or perpendicular to the beam direction, respectively. The 100 μm diameter laser beam was scanned at 800 or 1200 mm s^{-1} in either argon or nitrogen gas environments surrounding the building components. The build platform (Fig. 2-5) was preheated to 80 °C and maintained at that temperature. Re-coater formed and melted layers (Fig. 2-6) were alternately scanned along the x- or y-axis (at 90°). The as-fabricated cylindrical specimens were annealed at 982 °C for 0.5 h under vacuum and then hot isostatic pressed (HIP) at 1163 °C at 0.1 GPa pressure for

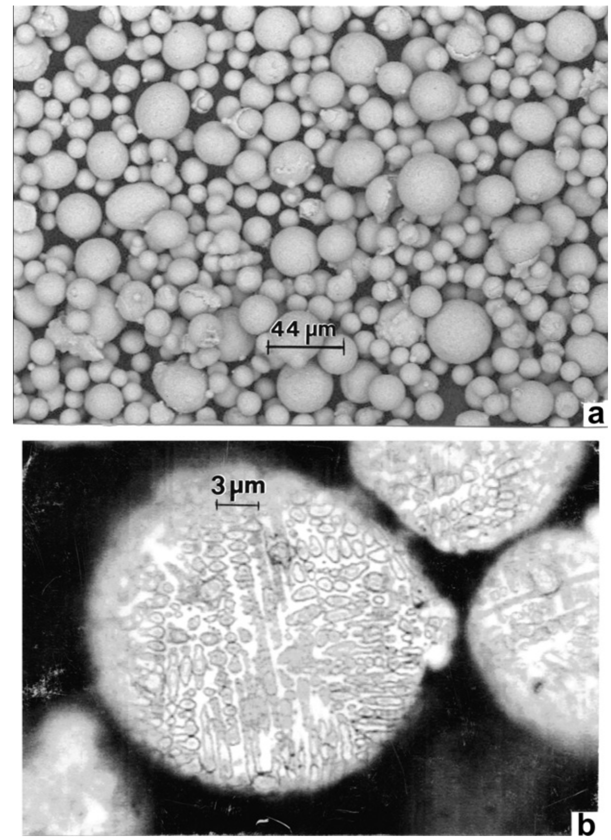

Fig. 1. The pre-alloyed (Inconel 718) precursor powder. (a) Low magnification SEM image showing the range of powder sizes and spherical morphology. (b) Optical metallographic image of a powder particle etched cross-section showing the internal microdendritic microstructure.

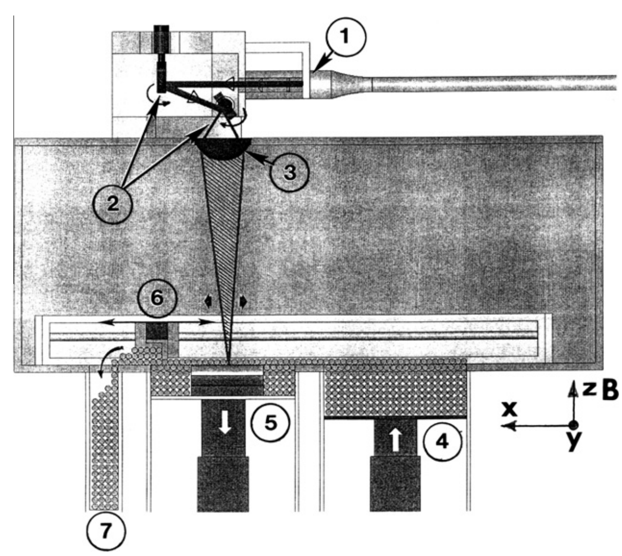

Fig. 2. Components indicated are: (1) laser input; (2) mirror system; (3) beam focus lens; (4) powder feed system; (5) build platform; (6) re-coater system for powder layer formation; (7) powder recovery/recycle bin.