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Neutron tomography methods applied to a nickel-based superalloy additive manufacture build

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ABSTRACT

Selective-laser melting (SLM) is one of the most rapidly developing and promising of all the so-called “Additive Manufacture” routes due to its capability to produce component geometries that would prove impossible using traditional manufacture. A selective-laser melting fabricated cuboid component was built using powder CM247LC, using standard methods, and this was subsequently analysed using neutron tomography methodology to allow for three-dimensional visualisation of the exterior and the interior of the component. The resulting neutron radiographs were processed and analysed for evidence of both porosity and grain boundary segregation within the component.

1. Introduction

Selective layer melting (SLM) is one of the rapidly increasing manufacturing routes [1] that make up the so-called ‘Additive Manufacture’ family of manufacturing processes. The manufacture of structural components from Nickel-based superalloys using these developing additive techniques is increasing in popularity as industries such as aerospace and aero-engine sectors are investing in additive manufacture research. As with many powder processing routes, selective laser melting (SLM) can produce highly complex components with an internal structural build that would be impossible to produce using any traditional manufacturing route [2]. SLM offers one of the most precise additive manufacture processes, largely due to its small laser source diameter (approximately 250 μm) and its very small deposition layer thickness (typically 30–50 μm), which therefore offers a much improved surface finish compared to other additive processes [3]. However this does of course come at the expense of slower deposition rates and thus slower build times.

The ease with which a nickel-based superalloy can be successfully fabricated using SLM largely depends upon the composition of the alloy. Whilst some superalloys are relatively easy to form using SLM, these tend to be alloys with a low volume fraction of γ' precipitates [4]. However, the improved creep-life that can be achieved by nickel-based superalloys with a higher volume fraction of γ' precipitate has led to these alloys being preferred for safety-critical components. This work considers SLM fabrication of high content γ' alloys, and demonstrates the use of neutron tomography methods to investigate porosity during the solidification stage and the resultant localised chemical composition within the builds.

2. Material and methods

2.1. SLM fabrication

CM247LC is an example of a larger volume fraction γ' precipitate-forming superalloys which can give improved creep resistance, strength and thus improved in-service life. CM247LC is a Cannon-Muskegon developed variant of the nickel-based superalloy Mar M 247 developed by Martin Marietta Corporation [5]. An SLM-built CM247LC 15 mm × 15 mm × 30 mm tower was fabricated. The build was then sectioned using EDM wire erosion to cut narrower 7.5 mm × 7.5 mm × 30 mm sub-towers (as shown in Fig. 1), to allow sufficient transmission of neutrons through the sample and hence produce a reasonable image. Two opposing corner sub-builds were examined using neutron tomography.

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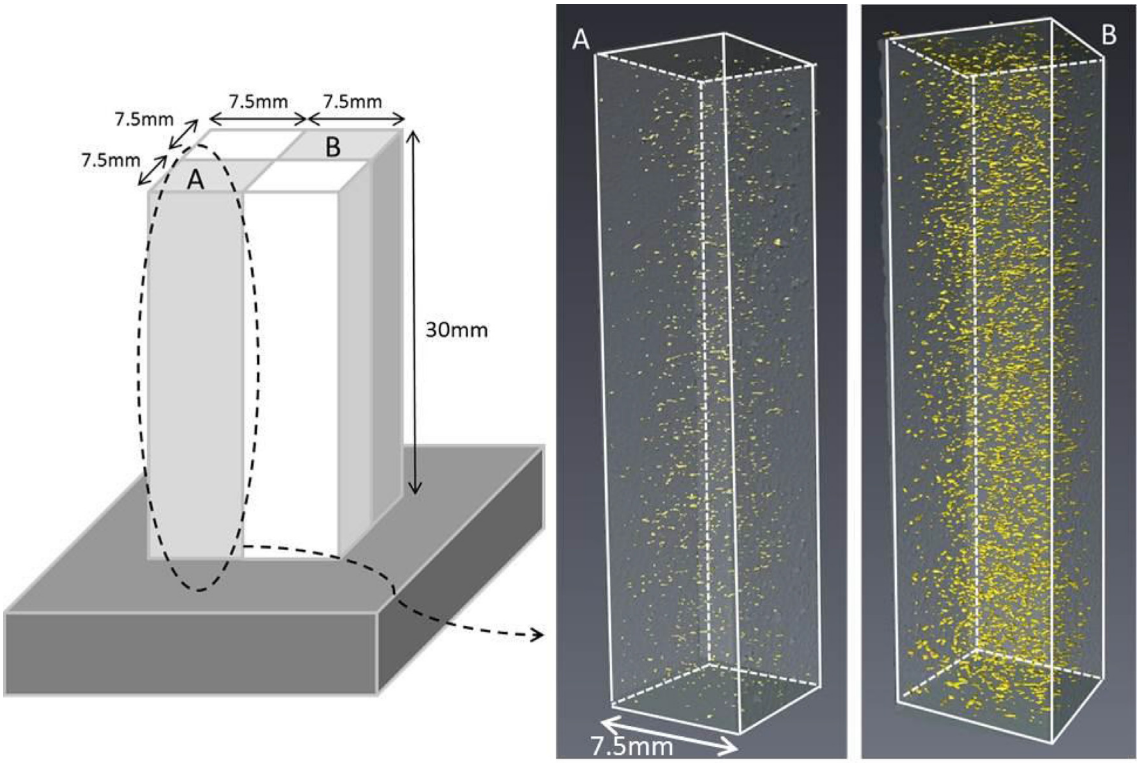

Fig. 1. Neutron tomography highlights significant variation in porosity measured in columns A and B cut from the same SLM-fabricated sample.

2.2. Neutron tomography

Neutron tomography is a non-destructive, non-invasive method allowing through-thickness resolution of a sample [6]. The difference in attenuation coefficient of different elements for a cold neutron beam produces variation/contrast in the measured/recorded radiographs on the CCD detector placed in transmission geometry. Neutron tomography methods can reveal the sub-surface structure of a component. Thus, the approach is highly applicable to determine the presence and distribution of sub-surface porosity within the SLM-built structure [7]. The attenuation of a neutron beam for a uniform sample thickness and homogeneous material of a single isotope is given by:

$$I(\lambda) = I_0(\lambda)e^{-\mu(\lambda)\Delta x} \tag{1}$$

For I and I_0 the transmitted and incident beam intensity, μ the attenuation coefficient, λ the neutron wavelength and Δx the sample thickness [6]. The attenuation coefficient can be calculated using:

$$\mu(\lambda) = \sigma_t(\lambda)\frac{\rho N_A}{M_{molar}} \tag{2}$$

where σ_t is sample cross-sectional area, ρ the density, N_A is Avogadro's constant and M_{molar} is molar mass. Note that neutron attenuation is dependent upon the wavelength of the neutron source [6].

For the experimental set-up, the CG-1D imaging beamline at Oak Ridge National Laboratory, within the High Flux Isotope Reactor (HFIR) facility was used. This tomography system has a line of flight from neutron beam aperture to detector of L = 6.59 m. The aperture was set to D = 4.1 mm, thus producing an L/D ratio of ~1600:1. A rotation stage is positioned in between aperture and detector to mount and rotate the sample through 360° and a CCD detector unit [6,8] positioned behind the sample. The cold neutron wavelength ranged from 0.8 to 6 Å, with a peak neutron intensity at 2.6 Å (2.6×10^{-10} m), and based upon the chemical composition of the CM247LC superalloy (see Table 1), the material density and the sample thickness, the transmitted beam was predicted to have an intensity of $\sim 0.135I_0$–$0.225I_0$, depending upon the rotational position of the cuboid sample (the lower transmission corresponding to the beam travelling across a leading diagonal of the cuboid). The sample was rotated at increments of 0.91° to produce 395 images taken through the full 360° rotation of the sample.

An open-beam image (with no sample in the path of the aperture to detector) must be performed prior to the experimental set-up, in order to account for any beam inhomogeneities. Finally, all neutron tomography radiographs taken by the CCD detector are corrected for dark-field which allows the produced image to correct for electronic noise generated by the CCD detector. The tomography data was reconstructed using a software package called OCTOPUS [9].

3. Results & discussion

3.1. Porosity visualisation

The resulting 3D reconstructed date was visualised and analysed using the Avizo software [10] to study sub-surface porosity. The resulting porosity within two opposing corners A and B of the same SLM build revealed significant variations in porosity measurements – see Fig. 2.

As is typical of powder processing manufacture, the consolidation of powder particles to form the structural component is of critical importance. Microscale void defects (micro-voids) can form within an SLM formed component at various locations due to one of three principal mechanisms: (a) where the metallic powder has not been heated enough to produce melting of the particle to allow a bonding to the adjacent layer, or alternatively (b) the particle has been heated to above the alloy liquidus temperature but due to the speed of the laser heat source, the time in the molten