EFFECTS OF PROCESS CONDITIONS AND MICROSTRUCTURE ON THE FATIGUE AND FRACTURE OF AM IN718

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Abstract
Additive manufacturing (AM) dramatically increases the design freedom for difficult to machine alloys like IN718. For turbine applications for aerospace and energy, additional freedom in component design allows for lightweighting and better cooling efficiency. This study seeks to elucidate and model the effects of porous and crystallographic microstructural elements on the fatigue life and fracture behavior of AM IN718 through X-ray computed tomography (XCT), scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD) of specimens tested under high temperature high cycle fatigue.

1. Introduction

While IN718 exhibits the necessary corrosion resistance and fatigue properties to make it a suitable candidate for many turbine-based applications for aerospace and energy, the poor machineability of it serves as a major hurdle in production. AM avoids this entirely by forming a component in the desired shape with minimal to no machining required. In addition, AM enables the use of internal cooling pathways and lightweighting design processes difficult or impossible to implement through conventional manufacturing. With its benefits, AM also introduces new mechanisms for defect creation and anisotropic microstructures that directly impact fatigue properties and fracture. To understand these impacts, ten walls shaped like thick dogbone fatigue specimens were built, each with varying AM process parameters, through laser powder bed fusion. These walls were all heat treated using a direct age heat treatment (720°C 8h/FC + 620°C 8h/AC) then sectioned into fatigue specimens with a gage section nominally 6 mm x 2 mm x 2 mm and polished to mirror finish. All porosity within the gage regions of the AM IN718 dogbone fatigue specimens were segmented and quantified using XCT. The microstructure of the AM IN718 was investigated using EBSD on sections of the AM walls between the fatigue specimens. High cycle fatigue testing at 538°C with a max stress of 690 MPa, a stress ratio of 0.1, and a loading frequency of 20 Hz was conducted on all AM specimens. All fracture surfaces were viewed in SEM to identify to location of fatigue crack formation and correlate it to either a defect, a region of vulnerable microstructure, or some combination of both.

2. Results

XCT analysis of porosity within the gage regions of the fatigue specimens prior to HCF testing has shown that the number and morphology of pores is directly related to the process conditions. In combinations of process parameters that create a relatively low volumetric energy input, also known as being in the conduction regime, porosity manifests in large irregular pores created by subsequent layers inadequately fusing. These lack of fusion pores are often large (100 – 500 µm) and contain sharp edges. On the other side of the spectrum, in the keyhole regime with high volumetric energy inputs, porosity manifests as mainly round or generally spherical keyhole pores. Pore morphology directly influences the effect any given porosity has on the fatigue properties of AM IN718. Fig. 1 depicts the general trend of increasing fatigue life with decreasing volume fraction of porosity within the gage region. Also in Fig. 1, cross sectional slices of the segmented XCT pore reconstructions of specimens 15E and 10J show that within specimens with the same total amount of porosity, having large irregular lack of fusion pores causes the fatigue life to be an order of magnitude lower than a specimen containing spherical keyhole type pores. The general trend of increasing life with decreasing volume fraction of porosity is not observed in specimens with minimal porosity. It is in these specimens where pores are infrequent that fatigue crack formation has been observed to originate simply from crystallographic grains with orientations and sizes that are particularly vulnerable to the applied cyclic load. The highest fatigue life specimens from samples 11 and 13 show this type of initiation that closely resembles fatigue crack formation in wrought IN718 specimens tested under the same conditions. The fracture surfaces of specimens 11K and 13J are shown in Fig. 2. In the fracture surface of 11K, the faceted nature of the surface around the region of initiation is evidence that it was a crystallographic microstructural feature that caused failure. In contrast, in 13J the faceted surface in direct proximity to a near-surface pore shows that both microstructure and the porosity led to fatigue failure.

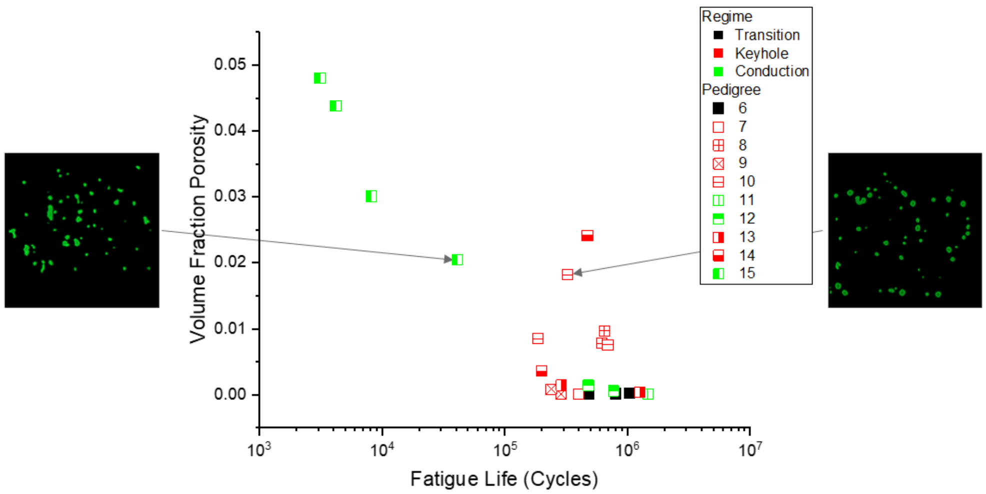

Fig.1 – Relationship between fatigue life and volume fraction with XCT cross sectional slices of specimen 15E containing lack-of-fusion porosity (left) and 10J containing keyhole porosity (right).

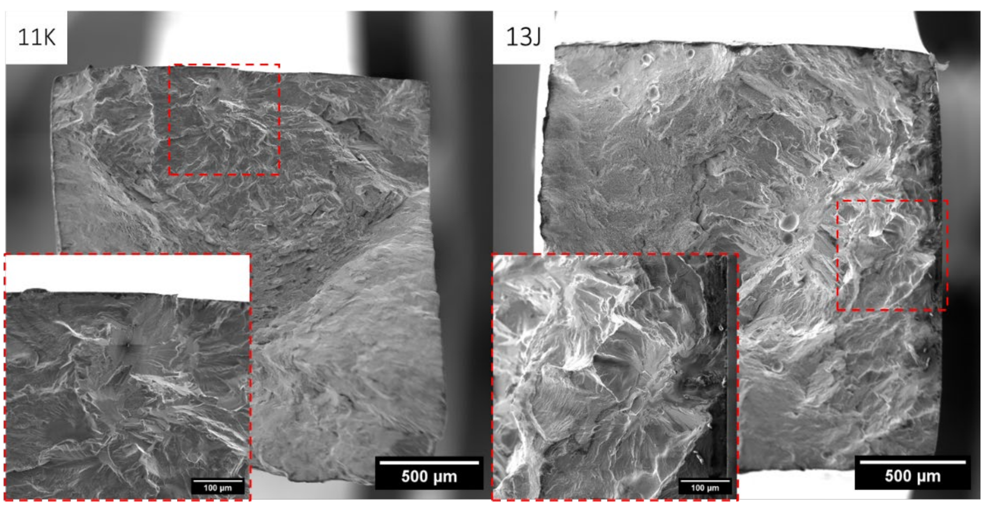

Fig.2 – SE-SEM fractographic images of two specimens having minimal porosity, 11K and 13J, with higher magnification overlays of the site of fatigue crack initiation.

3. Conclusions

The fatigue behavior of AM IN718 is dependent on pores and crystalline grains within the microstructure. In specimens with non-ideal process parameters, large pores with irregular morphologies degrade fatigue life the most, but in specimens with mostly smaller spherical porosity or minimized porosity, it is the grain structure that primarily influences fatigue crack formation with the pores having a secondary effect.