DEFECT STATISTICS AND FRACTURE INITIATION MECHANISMS IN AS-BUILT AND HEAT-TREATED ADDITIVE MANUFACTURED 17-4 STEEL

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Abstract

Defects in additively manufactured metals are detrimental to the manufactured components. Due to the rapid melting and solidification during printing, a non-homogeneous microstructure is typical in the metal specimens additively manufactured using laser powder bed fusion. The present study aims to understand the fracture initiation mechanism in as-built and heat-treated additively manufactured 17-4 stainless steel. To this end, 17-4 stainless steel unnotched and notched specimens additively manufactured using direct metal laser sintering were used. Solution annealing and subsequent aging were performed as the post-heat treatment of the stainless steel test specimens. Postmortem fractography using scanning electron microscopy (SEM) of the fracture surface and micro-computed tomography (micro-CT) of the test specimens before and after fracture revealed that the large coalesced microvoids with sizes greater than 120 µm significantly influence the ductile fracture initiation in the additively manufactured steel specimens.

1. Introduction

The objectives of this study are: (a) to perform a statistical analysis of the inherent defects in as-built specimens, (b) to quantify the change in the defect statistics after heat treatment, and (c) to elucidate the fracture initiating mechanism in as-built and heat-treated specimens. The additively manufactured 17-4 stainless steel exhibits different microstructural and mechanical characteristics than its conventional rolled or wrought counterparts [1,2]. The additively manufactured components have inherent defects due to a lack of fusion and gas porosity. Thus, a proper understanding of the defect statistics is required to optimize the process parameters in additive manufacturing and quantify the fracture initiation mechanism. A two-step heat treatment consisting of solutionizing at 1040 °C and hardening at 480 °C was performed to investigate the performance of defect healing. The test specimens were loaded until the fracture using a servo-hydraulic MTS 809 load frame, maintaining a uniform displacement rate of 0.02mm/s monitored by a contact extensometer. A conventional fractography study using SEM on the fracture surface was conducted on the additive manufactured specimens which failed to provide insights into the fracture initiating mechanism of additively manufactured 17-4 stainless steel. Therefore, micro-CT analyses were conducted on the different segments of the test specimens before and after the fracture test for both the as-built and heat-treated specimens. The results obtained from the micro-CT analysis were used to perform the statistical characterization of the manufacturing defects and to identify the size range of the defects responsible for initiating ductile fracture in additively manufactured 17-4 stainless steel.

2. Results

The electron backscatter diffraction (EBSD) orientation map reveals the microstructure in the as-built additively manufactured 17-4 stainless steel presented in Figure 1a. The fracture surface analysis using SEM confirms the existence of significantly smaller microvoids, however, it is difficult to capture the coalesced microvoids from the SEM micrographs (Figure 1c). The micro-CT analysis quantified the defects in the additive manufactured 17-4 stainless steel for both as-built and heat-treated conditions. The defects in the as-built steel specimen had a lognormal distribution revealed by micro-CT analysis, and the distribution of the smaller voids remained the same before and after the fracture (see Figures 2b and 2d). The porosity and number of voids per unit volume increase with the deformation, indicating dilation of existing voids and nucleation of new voids. The large coalesced void colonies are found to significantly influence the ductile fracture initiation in the steel specimens, and voids with sizes larger than 120 µm are mainly responsible for initiating fracture (see Figure 2c). The presence of void nucleation, growth, and coalescence confirms ductile fracture as the fracture initiating mechanism in as-built additive manufactured 17-4 stainless steel.

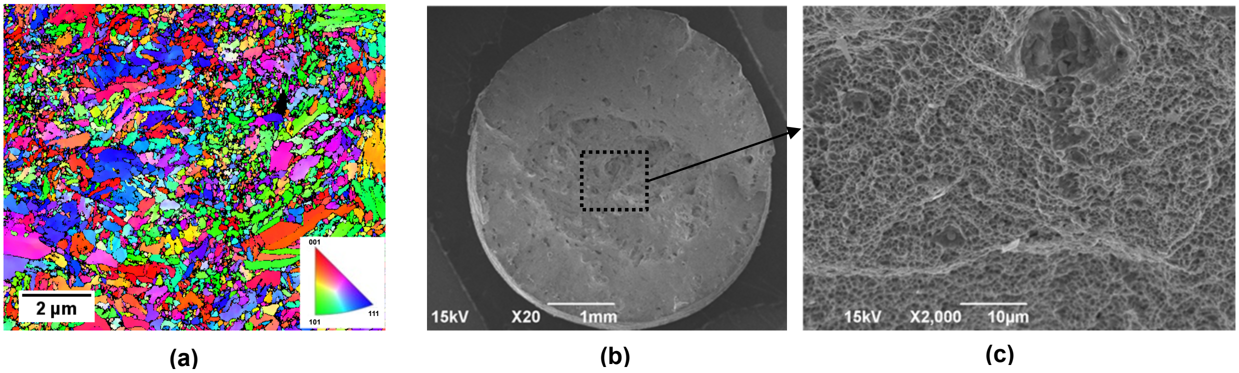

Fig.1: (a) EBSD orientation map of the cross-section; (b) SEM fractograph; and (c) magnified fracture surface of the as-built 17-4 stainless steel specimen. (secondary microvoid sizes in the SEM image are less than 1 μm size)

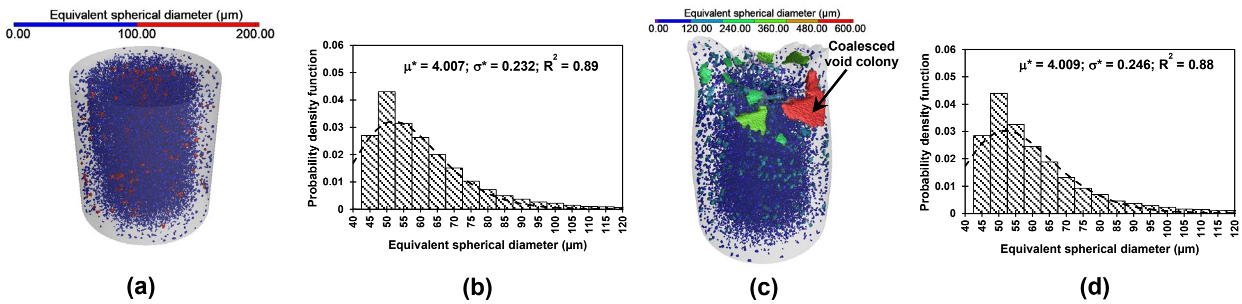

Fig.2: (a) Visualization of defects before fracture; (b) distribution of equivalent spherical diameter of defects before fracture; (c) visualization of defects after fracture; and (d) distribution of equivalent spherical diameter of defects after fracture of the as-built 17-4 stainless steel specimen. (equivalent spherical diameter followed lognormal distribution and larger coalesced voids are responsible for fracture initiation)

3. Conclusions

The size of the microvoids on the fracture surface observed using SEM were mostly found to be less than 1 μm, which is very small compared to the inherent defects that resulted from the additive manufacturing process. Voids larger than 120 μm contribute to the fracture initiation in 17-4 stainless steel specimens. The porosity and number of voids per unit volume increased by 62% and 70%, respectively in the as-built additively manufactured 17-4 stainless steel specimens before and after deformation.

Acknowledgement

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Reference

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