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Failure Characterization in 17-4PH Stainless Steel Across Multiple Manufacturing Methods

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Abstract

Accurate models of additively manufactured (AM) materials require extensive mechanical testing for proper calibration and verification/validation. The process-structure-property relationships in 17-4PH stainless steel from multiple manufacturing modes were examined via mechanical testing across several strain rates and post-mortem characterizations of the fracture surfaces and microstructure. Under all manufacturing modes and testing conditions, optical and scanning electron microscopy showed ductile failure characteristics. Higher porosity concentration (determined by density measurement) resulted in lower ultimate strength in cast samples; the pores often acted as crack initiation points. Strain-rate dependence and failure modes were also affected by process-dependent anisotropy in the microstructure, which was quantified through electron backscatter diffraction (EBSD) imaging. This data will be used to inform models of failure in the 17-4PH for multiple manufacturing forms.

1. Introduction

Additive manufacturing (AM) and near-net shaping processes are enticing for the ability to quickly prototype components. The relationships between fabrication method, microstructure, and performance (Process-Structure-Property) need further evaluation to develop effective models to predict the behavior of the components under multiple loading conditions. However, efforts to model the mechanical response of additively manufactured (AM) metals are complicated by anisotropic stress/strain responses that arise from processing conditions and the microstructures produced.

The efforts presented in this work are twofold: first, the performance of mechanical tests across a range of strain rates (10^{-4} – 10^{3} s^{-1}) were examined to inform how manufacturing modes affect mechanical performance and to evaluate existing failure models for different impact scenarios; second, an examination of the microstructure and fracture surfaces across manufacturing techniques were performed to determine how the microstructure and defects inherent to manufacturing processes affect the mechanical and failure behavior of the stainless steel. Combined, this work builds a process-microstructure-behavior relationship of the material to inform and calibrate models.

2. Results

Heat Treatment and Mechanical testing

17-4 precipitation hardened (PH) stainless steel was prepared under six manufacturing and heat treatment conditions, outlined in Table 1. Cylindrical tension specimens (0.25” gauge length) were cut from orthotropic directions in the specimens to examine anisotropic behavior.

Table 1: Manufacturing modes for 17-4 stainless steel

	Wrought	*Cast*	*Laser powder-bed*	*Electron beam wire-fed*
As-Prepared			x	x
H1025 (ASTM 564)	x	x	x	x

Specimens were subjected to tensile strain rates ranging from 10^{-4} s^{-1} (quasistatic) to 10^{3} s^{-1} (split-Hopkinson pressure bar). The mechanical properties of the samples showed a weak dependence on strain rate across manufacturing conditions, with higher ultimate strengths at higher strain rates. Notably, the strain at failure reduced as the strain rate increased at quasistatic rates (10^{-4} – 10^{0} s^{-1}). However, at higher (Hopkinson bar) strain rates, strain to failure increased, indicating a change in microstructural behavior between the regimes.

Fracture Surface and Microstructural Characterization

Within the range of tested strain rates, fracture surfaces exhibited ductile failure. Optical and scanning electron microscopy (SEM) examination of the fracture surfaces showed dimples characteristic of ductile fracture. Samples with higher porosity (such as the cast condition) showed a higher number of pores across the fracture surface, corresponding with a lower ultimate tensile strength. Anisotropic failure conditions were observed in other manufacturing conditions; in the wrought condition, tensile bars taken from material parallel to the rolling direction showed more necking than the sliding direction (Figure 1).

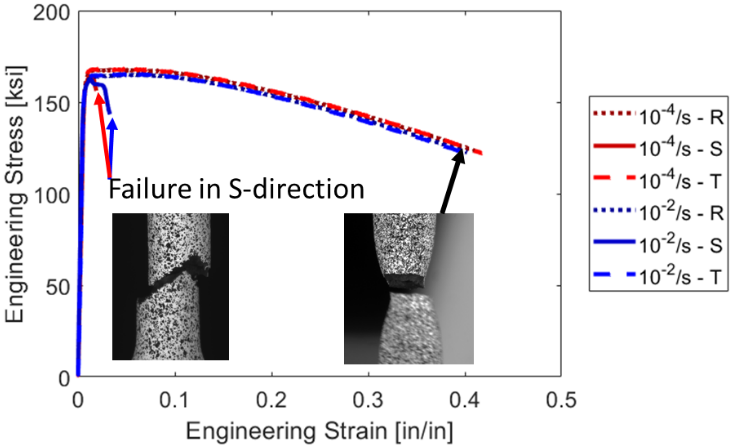

Figure 1: Anisotropic failure behavior in wrought 17-4 stainless steel. R = rolling direction, S =short tranverse (through-thickness), T = long transverse (width)

Electron backscatter diffraction (EBSD) imaging revealed strongly textured grains in the wire-fed AM condition and some texturing in the wrought condition; other specimens showed a more equi-axed microstructure (Figure 2). This likely explains the anisotropic failure behavior seen in those conditions.

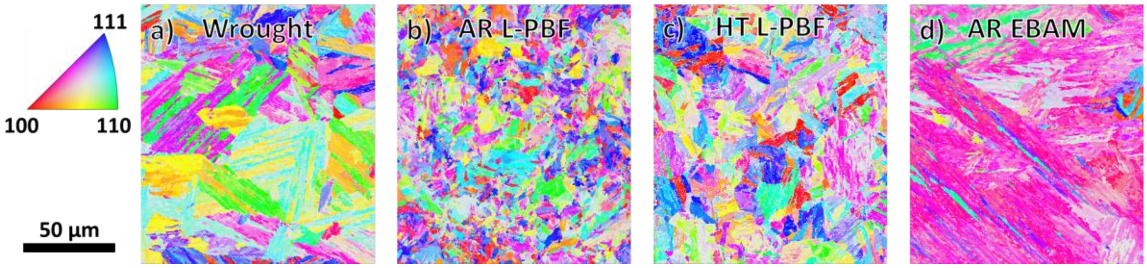

Figure 2: Texturing observed in wrought and wire fed (EBAM) 17-4PH via EBSD. Laser powder bed (L-PBF) showed a more equi-axed structure.

3. Conclusions

Extensive mechanical testing and characterization of 17-4PH stainless steel across multiple manufacturing modes has given insight into the process-structure-property relationship that governs the strength and failure mode of the material. Anisotropic failure behavior was tied to texturing seen under various loading conditions. This data will be used in the generation of models to predict the behavior of the steel under multiple strain conditions.

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