Environmental Cracking of Additively Manufactured 316L Stainless Steel

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Abstract

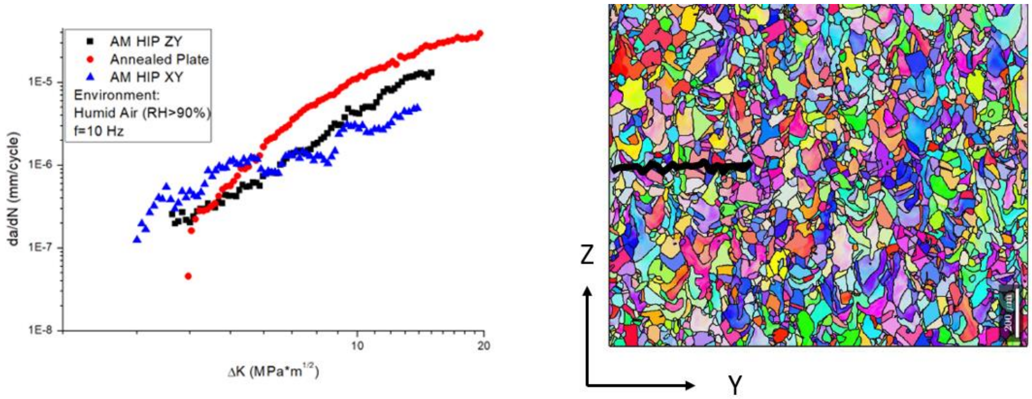
The widespread use of 316L stainless steel for applications requiring increased corrosion resistance has motivated interest in leveraging additive manufacturing (AM) for in-service production of replacement components. However, while a large number of studies have examined the effect of AM processing parameters on yield strength and fracture toughness, detailed assessments of the environment-assisted cracking (EAC) susceptibility of AM alloys are limited. The objective of this study is to compare the corrosion fatigue and stress corrosion cracking behavior of AM and wrought 316L with similar yield strengths in aqueous chloride environments at temperatures ranging from 293 to 358 K. As built material will be compared with cold drawn bar, and hot isostatic pressed (HIP) material will be compared with plate in the annealed state to minimize the effect of different yield strength between material form. Differences in microstructure and build-introduced stresses are correlated with EAC performance, thereby providing mechanistic insights into the factors governing EAC behavior of AM 316L. In particular, the influence of build direction, residual stresses, texture, and compositional heterogeneities are all assessed.

1. Introduction

Engineering materials rarely fail due to mechanical overload. Much more common, and insidious is that a subcritical crack will propagate slowly due to EAC until a critical crack length is reached and the structure fails. EAC properties have been shown to be heavily dependent on microstructure. Due to the rapid heating and cooling during the additive manufacturing build process, parts produced by AM have inherently heterogeneous microstructures that are distinct from that of their wrought counterparts. The link between these AM microstructures and EAC is not well understood and needs to be characterized before AM parts can be used as critical components in aggressive environments. This work advances understanding of EAC in AM austenitic stainless steels so that they can be implemented into mission critical components.

2. Results

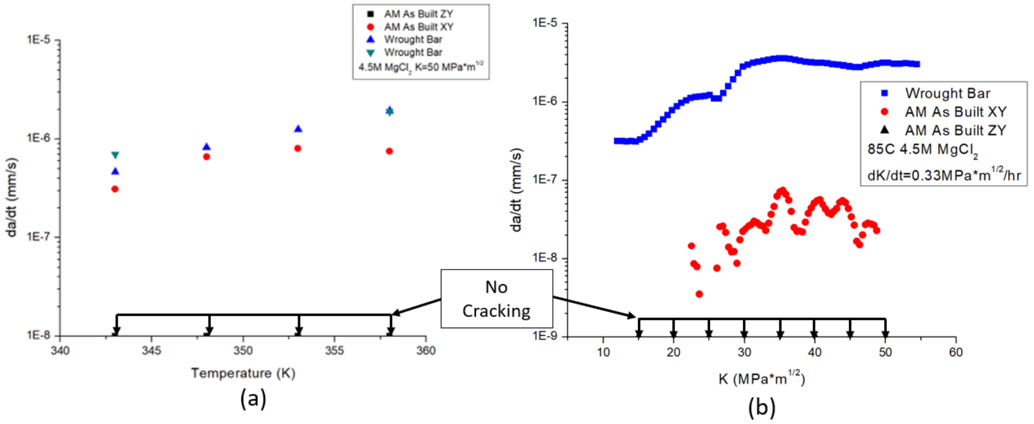
Linear elastic fracture mechanics (LEFM) based experiments were performed to establish fatigue and stress corrosion crack (SCC) growth kinetics using direct current potential drop (DCPD) for active crack length monitoring. Active crack length monitoring enables experiments to be run under stress intensity, K, control. AM samples were loaded both parallel (ZY) and perpendicular (XY) to the build direction.



(a) (b)

Fig.1 – (a) Fatigue crack growth rate (da/dN) vs ΔK in 293K humid air at 10Hz. (b) Fatigue crack path schematic for AM HIP ZY samples.

Fatigue crack growth rate (FCGR) experiments were performed with single edge notch tension (SENT) samples at a fixed stress ratio, R=0.5. FCGR experiments were performed in both 0.6M NaCl and humid (RH>90%) air. Figure 1a shows the results of the humid air FCGR experiments and Figure 1b is a schematic of the crack progressing through the microstructure of an AM HIP ZY specimen. The AM material when loaded in both directions relative to build shows a slightly lower but still comparable ΔK_{th} and lower crack growth rates at higher driving forces when compared to an annealed plate.



(a)

(b)

Fig.2 – (a) Stress Corrosion Crack growth rate (da/dt) vs Temperature in 4.5M $MgCl_2$ at a constant stress intensity. (b) da/dt vs K in 4.5M $MgCl_2$ at 85C° with a fixed dK/dt=0.33MPa*$m^{1/2}$/hr.

Stress corrosion cracking experiments were also performed using SENT samples. Experiments were performed at constant K in 4.5M $MgCl_2$ solution with varying temperatures, as well as rising K experiments at fixed dK/dt=0.33 MPa*$m^{1/2}$/hr in 4.5M $MgCl_2$ at constant temperature. Figure 2a shows the results of the constant K experiments. The traditionally manufactured wrought bar shows a monotonic increase in crack growth rate with temperature. The AM as built XY samples shows slower growth rates than wrought and those growth rates level off at the higher temperatures tested. The AM as built ZY showed no cracking across all temperatures. Figure 2b shows the results of the rising K experiments in 4.5M $MgCl_2$ at 85C°. The wrought bar cracked significantly faster than the AM XY under rising K conditions. This is believed to be due to the presence of delta ferrite stringers in the wrought based on the results of a companion study. AM ZY remains immune to SCC even under active loading for the environment tested.

3. Conclusions

After undergoing a HIP heat treatment, the AM samples when loaded in both ZY and XY orientations showed comparable ΔK_{th} to an annealed plate. The growth rates at higher ΔK were lower than the annealed plate. This indicates that the AM HIP material is more fatigue crack damage tolerant.

The AM as built samples showed a higher resistance to SCC compared to the cold drawn bar. Particularly the AM as built ZY samples which has been shown to be completely immune to SCC in all environments tested.

This research will be further expanded upon using microstructural characterization of the crack wake and samples with intact crack tips at various ΔK and K-values to illuminate the microstructures influence on the improved EAC performance of AM 316L compared to its traditionally manufactured counterparts.

Acknowledgements

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