5-2020

Extremely Low Cycle Fatigue Behavior of Additively Manufactured 17-4PH Stainless Steel

Kaley Collins

Extremely Low Cycle Fatigue Behavior of Additively Manufactured 17-4PH Stainless Steel

An Undergraduate Honors College Thesis

in the

Department of Civil Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

By

Kaley Collins

May 2020

Abstract

Steel structures survive seismic loading thanks to components capable of dissipating large amounts of energy through large deformations. Future optimizations of these components include complex free-form geometries that are difficult to fabricate with traditional casting processes. Additive manufacturing (AM) is an alternative for producing optimized free-form geometries. AM material contains significant differences in microstructural characteristics and mechanical behavior compared to its wrought counterparts. Research has been conducted to understand the effect of microscopic features in the high cycle fatigue (HCF) and low cycle fatigue (LCF) regimes. This study focuses on the behavior of 17-4 Precipitation Hardening (PH) stainless steel in the extremely low cycle fatigue (ELCF) regime where large plastic strains lead to ductile failure in few cycles (less than 100 cycles). The goal of this project is to develop strain-life curves for AM 17-4PH steels and provide a better understanding of behavior in the ELCF regime. This is accomplished through material fatigue testing and fractographic analysis.

Introduction

The future of energy-dissipating devices depends on the ability to produce components with complex geometries, not possible with current casting processes. Additively manufactured metals (such as metals produced through 3-D printing) provide a fabrication approach for achieving the complex geometries needed; however, the material behavior of AM metals can differ from traditional metals. To better understand the behavior of AM steels for use in seismic dissipation devices, this study investigates the behavior of both traditionally produced and 3-D printed 17-4 precipitation hardened stainless steels.

One potential difference in mechanical behavior between traditionally produced and AM stainless steels, is that AM processes produce internal defects, most notably voids and layered boundaries [1]. Voids result from entrapped gas or unmelted particles. These voids may act as stress concentrations and contribute to premature failure in the part. AM processes also create layered heat-affected zones that may act as slip-boundaries and serve as weak points in the material [2].

Previous research on AM 17-4 PH stainless steels studied the material's performance in low cycle fatigue (LCF), with heat treatment, and in various build orientations [3]; however, material performance in the extremely LCF regime (ELCF) (such as that induced by earthquakes) is not well understood. Prediction methods for LCF conditions may differ from ELCF due to differences in crack initiation mechanisms.

ELCF can be found during earthquakes, for example, where buildings are subject to an intense repeated loading similar causing large plastic strain cycles. A better understanding of how AM materials perform in the ELCF regime will provide an understand of material performance during earthquake-type loadings and allow construction of optimized free-form geometries for earthquake dissipating devices.

The following sections outline the research approach taken in this study, including the testing methods (loading, specimen geometry, materials, etc.) for ELCF behavior characterization, and results from the fatigue testing and fractographic analyses.

Test Methods

Extremely low-cycle fatigue (ELCF) occurs during large plastic strain cycles; therefor all fatigue loading in this study was strain-controlled, with all specimens tested being cycled until failure. Five of the AM specimens tested herein were produced by industry partners (designated XS), and eight specimens were made at the National Institute of Standards and Technology (designated NS). The NS samples were heat treated prior to removal from the build plate, while the XS samples received no heat treatment. All specimens were fabricated to a rough geometry and then machined to final shape to remove any surface defects that may affect the fatigue results. Figure 1 shows the specimen geometry, conforming to current ASTM E606 standards for strain-controlled fatigue testing of metals.

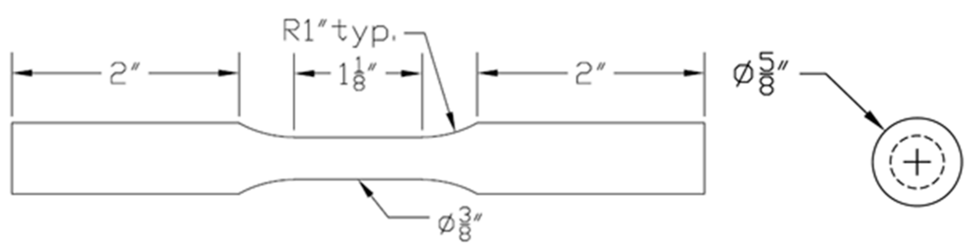

Figure 1. Specimen geomtry from ASTM E606

Each ELCF test was performed using a servo-hydraulic fatigue testing machine capable of applying controlled strains to the material samples. Constant amplitude strain cycles were considered for each test, allowing the creation of strain-versus-cycles fatigue-life graphs. Table 1 shows the applied strain ranges for each sample. Note in Table 1 that all strain ranges considered are beyond the material yield strain (indicating that induced strains are no-longer proportional to the resulting material stresses). Following the testing procedure outlined in ASTM E606, a knife-blade extensometer is used to ensure the appropriate strain ranges are applied during testing.

Table 1. Applied strain ranges for each specimen

Build Location	Speciman Number				
	1	2	3	4	5
XS	0.4	0.4	0.3	0.2	
NS	0.4	0.4	0.3	0.3	0.2

Following the ELCF testing micro-hardness measurements of the steel cross-section are taken to document microstructure changes during loading. The micro-hardness measurements use a diamond shaped indenter and controlled load to measure hardness of steel surface, which can be related to material properties. Figure 2 shows an example of the micro-hardness indenting process, which is performed at the microscale allowing localized measurements within material microfeatures to be determined.

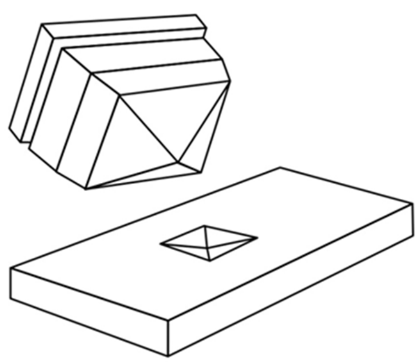

Figure 2. Micro-hardness test with diamond shaped indenter [4].

In addition to the micro-hardness testing, fractographic analyses (analysis of the specimen fracture surfaces) are conducted using scanning-electron microscopy. This analysis will allow determination of fracture initiation mechanisms within the AM produced steels and help understand the underlying behavior driving the ELCF behavior.

Results and Discussion

Figure 3 shows the cyclic degradation of a wrought steel specimen during the constant strain amplitude cycles. In Figure 3, the repeated constant strains resulted in necking and ultimately fracture of specimen after only a few inelastic cycles (falling within the ELCF regime). The behavior shown in Figure 3 was similar to all specimens tested, for all applied strain ranges; however, the number of cycles to failure varied.

The following sections compare the behavior of the AM heat treated (NS) specimens and AM non-heat treated (XS) specimens, as well as the ELCF behavior of the AM steel with traditionally rolled wrought 17-4PH stainless steel materials.

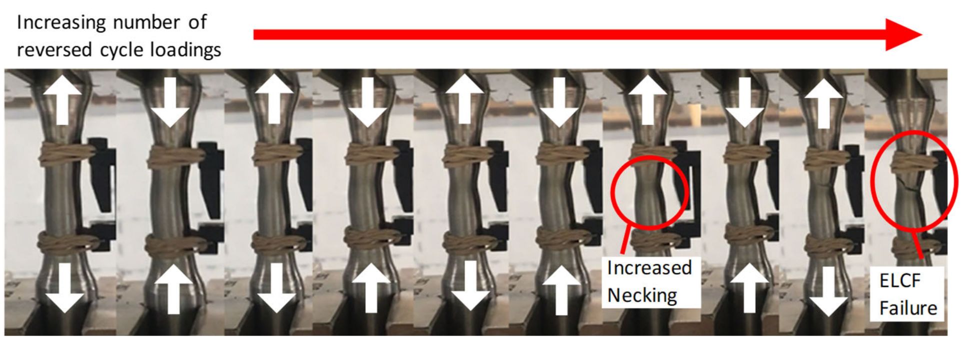

Figure 3. ELCF fracture of wrought steel specimen reversed strain cycles.

Effect of Heat Treatment and AM Processes on ELCF in AM 17-4PH Stainless Steels

Heat treatment to anneal the residual stresses within the selectively laser melted powders of the AM 17-4PH stainless steel had no observable effect on the ELCF behavior. Figure 4 shows the applied strain versus number of cycles to fatigue failure for both the XS and NS specimens. In Figure 4, the XS and NS fatigue life curves overlap, indicating that the heat treatment has no effect on the ELCF behavior. This is not too surprising, as the large inelastic strains applied could be expected to remove any residual stress effects from the powder melting processes. It is likely that the heat treatment procedure would have more of an effect within the high-cycle fatigue regime where local elastic stresses dominate the crack growth.

Comparing the behavior of the AM steel with that of the rolled (wrought steel) indicates a lower ELCF fatigue performance for the AM steel. In Figure 4, which is plotted on a log-log scale, the AM 17-4PH steel consistently fails at a much lower cycle count than the rolled steel counterpart. At higher strain amplitude cycles (0.04 strain cycles), a near 70% reduction in fatigue life is noticed. This indicates that existing material data gathered from traditionally manufactured 17-4PH stainless steel is inadequate in characterizing the behavior of AM 17-4PH stainless steels.

Examination of the AM steel under a scanning electron microscope (SEM) revealed many voids in the material caused by unmelted powders during the manufacturing process. These defects found throughout the AM steel specimens help explain the observed reduction in fatigue life as similar voids were not observed in the rolled (wrought steel) material. Figure 5 shows the fractographic image of the AM steel surface with several unmelted powder particles resulting in a large (on the order of 100 microns) void in the material. The void shown in Figure 5 was common within the AM steel specimens following investigations of the fracture surfaces.

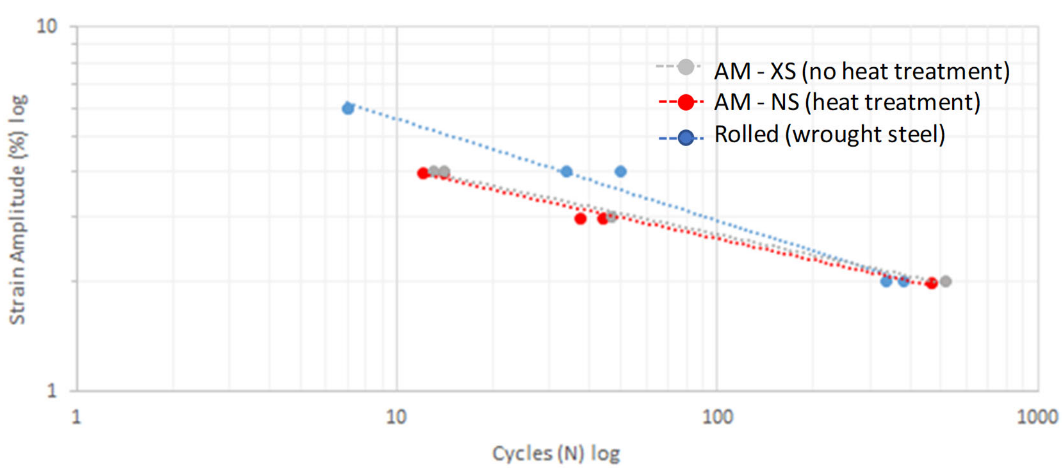

Figure 4. Strain-life curves for AM and rolled 17-4PH stainless steel.

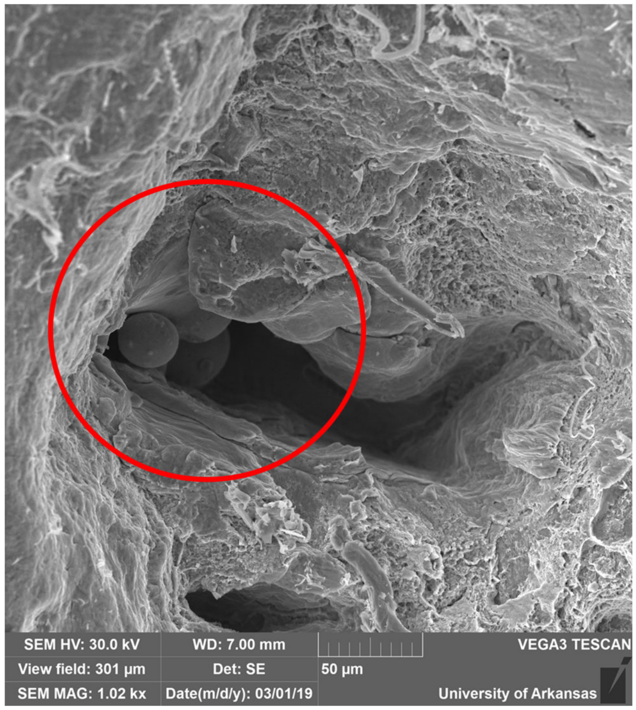

Figure 5. Fractographic image taken from AM steel failure surface.

Effect of Heat Treatment on Material Hardness Following Large Strain Cycles

During testing, the steel yields and hardens through a process known as strain hardening. To evaluate the differences in strain-hardening behavior between the AM and rolled steels, hardness testing was performed on the fractured samples at two locations: 1) the grip area which remained elastic, and 2) the gauge area which underwent yielding. Note that the heat-treated steel specimen would be expected to have an increased hardness, toughness, etc, as the heat treatment process often results in smaller grain structures [5]. It is used, generally, to increase desired properties of the metal. Due to time constrains, only one wrought steel sample could be directly compared to as-built AM steel, and an as-built AM sample could then be directly compared to a heat-treated AM sample. Because the grip section of the specimens was not subject to much strain, it may be comparable to the original hardness of the specimens. Looking at the grip averages, the wrought and as-built AM steel were relatively similar. However, the gage section was the target of the change in strain, and the as-built AM steel hardness in that section of the specimens was about thirty-three percent (33%) larger than the wrought steel gage hardness; therefore, the hardness test showed that the AM steel post-yield hardening differs from that of traditionally fabricated steels.

Table 2. Micro-hardness measurements for AM and Rolled (wrought steel) specimens

Strain Amplitude	Grip Average			Gage Average		
	Wrought Steel	As-Built AM	Heat-Treated AM	Wrought Steel	As-Built AM	Heat-Treated AM
2%	335.8	314.7	-	356.7	475	-
3%	-	310.9	-	-	459.4	535.6

Conclusions

In this study, the fatigue behavior of AM 17-4PH stainless steel was compared with traditionally produced 17-4PH stainless steel. Large, constant amplitude, strain cycles were applied to determine material fatigue life. Additionally, micro-hardness testing and fractographic analyses of the steel failure surfaces were conducted. The following conclusions are from the experimental fatigue testing:

1. AM 17-4PH stainless steel had a lower fatigue life when compared to wrought 17-4PH stainless steel when subjected to large inelastic cyclic strains. Voids and defects within the AM steel due to unmelted particles contributed to the reduction in fatigue life.
2. AM 17-4PH stainless steel exhibits higher post-yield strain hardening that wrought 17-4PH stainless steel. Micro-hardness measurements within the grip and gauge sections of the specimens showed that the AM steel post-yield hardening differs from that of traditionally fabricated steels.

3. Post fabrication heat treatment was found to make no difference on the ELCF performance of AM 17-4 PH stainless steel.

References

[1] Aboulkhair, N. T., Simonelli, M., Parry, L., Ashcroft, I., Tuck, C., Hague, R., "3D printing of Aluminium alloys: Additive Manufacturing of Aluminium alloys using selective laser melting" Progress in Materials Science, Vo. 106, 2019.

[2] Li, Wei & Liou, Frank & Newkirk, Joseph & Taminger, Karen & Seufzer, William. (2017). Investigation on Ti6Al4V-V-Cr-Fe-SS316 Multi-layers Metallic Structure Fabricated by Laser 3D Printing. Scientific Reports. 7. 10.1038/s41598-017-08580-z.

[3] Yadollahi, A., Shamsaei, N., Thompson, S. M., Elwany, A., Bian, L., "Effects of building orientation and heat treatment on fatigue behavior of selective laser melted 17-4 PH stainless steel," International Journal of Fatigue 94 (2017) 218-235

[4] "Hardness Tests", https://www.conecband.com/entrada/857/ensayos-de-dureza/

[5] "Strengthening/Hardening Mechanisms" https://www.ndeed.org/EducationResources/CommunityCollege/Materials/Structure/strengthening.html