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High-throughput stochastic tensile performance of additively manufactured stainless steel☆

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ABSTRACT

An adage within the Additive Manufacturing (AM) community is that “complexity is free”. Complicated geometric features that normally drive manufacturing cost and limit design options are not typically problematic in AM. While geometric complexity is usually viewed from the perspective of part design, this advantage of AM also opens up new options in rapid, efficient material property evaluation and qualification. In the current work, an array of 100 miniature tensile bars are produced and tested for a comparable cost and in comparable time to a few conventional tensile bars. With this technique, it is possible to evaluate the stochastic nature of mechanical behavior. The current study focuses on stochastic yield strength, ultimate strength, and ductility as measured by strain at failure (elongation). However, this method can be used to capture the statistical nature of many mechanical properties including the full stress-strain constitutive response, elastic modulus, work hardening, and fracture toughness. Moreover, the technique could extend to strain-rate and temperature dependent behavior. As a proof of concept, the technique is demonstrated on a precipitation hardened stainless steel alloy, commonly known as 17-4PH, produced by two commercial AM vendors using a laser powder bed fusion process, also commonly known as selective laser melting. Using two different commercial powder bed platforms, the vendors produced material that exhibited slightly lower strength and markedly lower ductility compared to wrought sheet. Moreover, the properties were much less repeatable in the AM materials as analyzed in the context of a Weibull distribution, and the properties did not consistently meet minimum allowable requirements for the alloy as established by AMS. The diminished, stochastic properties were examined in the context of major contributing factors such as surface roughness and internal lack-of-fusion porosity. This high-throughput capability is expected to be useful for follow-on extensive parametric studies of factors that affect the statistical reliability of AM components.

1. Introduction

One of the key benefits of Additive Manufacturing (AM) is the ability to rapidly produce customized components with complex geometry. However, the full benefit of this rapid production turn-around cannot be fully realized unless all elements of the design-production-qualification route are streamlined. In addition to the development of topological optimization algorithms for efficient requirements-driven design, such as described recently by Gardan (2014), it is necessary to develop qualification pathways that can rapidly assess material quality and performance.

To take advantage of the AM benefit of geometrically complex features, a new high-throughput tensile testing approach was developed. This new approach provides an extensive assessment of stochastic variability in mechanical properties. With this new approach, hundreds of high-fidelity tensile tests can be per-

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formed in a similar time and for similar cost to a few conventional tests. The current study has three primary objectives: (1) demonstrate the efficacy of this high-throughput testing methodology to extract statistical distributions of mechanical properties; (2) employ the high-throughput method to compare the performance of nominally-identical material produced by two independent commercial vendors; and (3) identify the defects associated with lower-tail worst-case performance and statistical outliers.

The AM process of interest in the current study is powder bed fusion, defined in ISO/ASTM 52900 (2016). Variations of powder bed fusion are also known by common names such as Selective Laser Sintering, Direct Metal Laser Sintering, Selective Laser Melting, and Electron Beam Melting. For examples of the usage of these four alternative names in the literature, see works by Beaman and Deckard (1990), Khaing et al. (2001), Kruth et al. (2004), and Cormier et al. (2004), respectively. Powder bed fusion is also known by proprietary names such as Direct Metal Printing (3D Systems, Inc.) or LaserCUSING® (Concept Laser GmbH). In these processes, a layer of unfused powder is placed on the build tray and locally fused through the directed application of an external heat source, typically a laser or electron beam. Sequential layers are built-up and fused together in this layer-by-layer process. The use of a bed of packed powder distinguishes this process from other common metal AM processes such as Laser Engineered Net Shaping employed by Atwood et al. (1998) or Direct Metal Deposition employed by Mazumder et al. (1997) in which the powder is dynamically injected into the focal point of the laser. Some of the most common defects that arise in metal powder bed additive manufacturing which give rise to stochastic performance include voids, channels bridging many layers and partially melted and sintered particles. For example, Bauereiß et al. (2014) observed and simulated the formation of channel-like faults that form due to insufficient heat input. For laser powder bed fusion, several researchers including Shamsaei et al. (2015) and Liu et al. (2016) have described how the type, size, and spatial distribution of defects is dependent on a number of factors, including: powder chemistry, particle size distribution, printer atmosphere, laser power, traverse rate, hatch pattern, part thickness, and build orientation. Many of these parameters can vary within a build, between builds, or from vendor to vendor, leading to a lack of consistency in material performance.

The current study demonstrates the high-throughput testing methodology and ensuing analysis of stochastic mechanical properties in a precipitation hardenable stainless steel, commonly known as alloy 17-4PH produced by laser powder bed fusion. Precipitation-hardening stainless steels such as 17-4PH were developed to provide high toughness and strength while maintaining the benefit of corrosion resistance. Several ferrous metallurgy reference books describe the metallurgical principles of precipitation hardened stainless steel alloys, including the book by Krauss (1990). Precipitation-hardening alloys are particularly amenable to AM because the mechanical properties can be controlled via post-deposition heat-treatment. While some stainless steel alloys made by additive manufacturing have been shown to have average properties that can be comparable to wrought Rafi et al. (2013) or cast Tolosa et al. (2010) product, generally these previous studies involve only a few measurements with very limited detail regarding the *variability* in mechanical properties.

2. Method

2.1. Material and specimen design

Tensile specimens were fabricated from precipitation-hardened 17-4PH, also known as Alloy 630 or AMS 5604 (UNS number S17400). While 17-4PH is the commonly used name for this alloy in wrought form, similar casting variations include CB7Cu-1 (UNS J92180) and AMS 5342–5344 (UNS J92200). This alloy was produced from powder feedstock directly using a powder bed fusion processes at two vendors using different commercial systems. Vendor 1 utilized a ConceptLaser Mlab printer and Vendor 2 utilized a 3DSystems ProX^{TM} 300 printer. Both machines employ a laser-based powder bed fusion process to produce a three-dimensional metallic object. Both vendors produced net-shaped tensile bars with the tensile axis parallel to the vertical build direction. This resulted in the individual print layers arranged in a laminate structure perpendicular to the tensile axis. The layer thickness of parts manufactured by the Concept Laser Mlab printer was 20 μm and by the 3DSystems ProX^{TM} 300 printer was 40 μm. Aside from the build orientation and specimen geometry, no additional constraints were placed on the process parameters such as laser power, traverse rate, powder chemistry, feedstock source, etc. Instead, each vendor utilized their proprietary expertise to select appropriate conditions that would achieve nominal 17-4PH components. In this way, the present study is not intended to be a systematic assessment of process parameter effects on resulting properties, but rather an illustration of the variation that can be observed when requesting nominally identical manufactured components. After printing, the AM tensile specimens were solution treated (1037 °C/1 h/air cool) and subsequently aged to the H900 condition (482 °C/1 h/air cool). To complement the population of AM tensile bars, geometrically-equivalent tensile specimens were also electrodischarge machined from 1 mm thick commercially-produced wrought sheet supplied in Condition A and heat treated to the same nominal H900 condition. Samples were machined with the tensile axis parallel to the rolling direction.

The nominal tensile bar geometry is shown in Fig. 1. The nominal width and thickness of the specimen gauge section were both 1 mm. The nominal gauge length was 4 mm. The geometry deviates from ASTM (2015) E8 standard geometries to eliminate unprintable horizontal overhang features and facilitate a compact, cost-efficient test sample volume. The unusual 45° wedge-shaped end sections of the rectangular dog-bone tensile bars not only eliminated overhang issues, but also facilitated self-alignment in the open-face grips. A layout of 120 tensile samples was recommended to the vendors as shown in Fig. 1. While Vendor 1 produced this exact arrangement (Fig. 1b), Vendor 2 added protective structural sidewalls to prevent the print wiper/roller from bending the vertical tensile bars. The Vendor 1 product was able to avoid bending without the protective barriers, presumably due to differences in the print roller: a rigid roller employed in some 3D printers such as the ProX^{TM} line is more likely to deform high-aspect ratio features.

The chemical composition of each material was measured by inductively coupled plasma mass spectroscopy. Light elements including carbon, nitrogen, oxygen, and sulfur were measured using LECO combustion analysis. Table 1 lists measured compositions. Industrial alloy specification limits for investment cast and wrought sheet 17-4PH are also included for reference. While the composition was generally consistent with the 17-4PH alloy, the AM parts exhibited elevated copper, oxygen, and nitrogen.

The tensile specimens in this study were produced in the final shape by the AM process with no post-process machining. Vendor 1 removed loose particles and improved the surface finish through a bead blasting process whereas Vendor 2 provided as-printed parts. The surface roughness of the tensile bars was measured using a Bruker ContourGT-I 3D Optical Microscope. The surface roughness (R_a) of the samples produced by Vendors 1 and 2 was 5.6 μm and 18 μm ($\pm$0.1 μm) and maximum peak height (R_p) of 36 μm and 82 μm ($\pm$0.6 μm), respectively. The wrought 17-4 samples had a surface roughness (R_a) and maximum peak height (R_p) of 0.05 μm and 6.6 μm, respectively, on the as-rolled surface (top and bottom)