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Mechanical behavior of additive manufactured, powder-bed laser-fused materials

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A R T I C L E I N F O

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Mechanical behavior of four metallic alloys fabricated with layered, laser-heated methods of additive manufacturing (AM) was compared to that of similar alloys produced with conventional methods (wrought and machined). AM materials were produced by a leading commercial service provider, as opposed to incorporating material specimens produced by unique or specially-adapted equipment. The elastic moduli were measured in flexure, stress–strain characteristics were measured in tensile deformation, and fatigue strengths were measured in fully reversed bending. The effects of fabrication orientation, surface polishing, and hot isostatic pressing upon mechanical behavior were studied.

The fatigue strengths exhibited by SLM AlSi10Mg and DMLS Ti6Al4V in the as-fabricated condition proved to be significantly inferior to that of conventional material. These lower fatigue strengths are a consequence of multiple fatigue cracks initiating at surface defects, internal voids and microcracks, and growing simultaneously during cyclic loading. Measured fatigue strengths of DMLS 316L and 17-4PH approached those of corresponding wrought materials when subjected to principal stresses aligned with the build planes. When cyclic stresses were applied across the build planes of the DMLS stainless steels, fatigue fractures often developed prematurely by separation of material. Post-processing the DMLS Ti6Al4V and SS316L with hot isostatic pressure elevated the fatigue strength significantly. Measurements of surface roughness with an optical profilometer, examinations of the material microstructures, and fractography contribute to an understanding of the mechanical behavior of the additive materials.

1. Introduction

1.1. Background

Developers of aerospace systems are increasingly employing additive manufacturing (AM) technologies to fabricate complex structural components used in fielded systems. Initially used to create models of design concepts and preliminary prototypes, applications of laser sintering to produce metallic components for end-use applications grew exponentially, beginning in the mid-1990s [1]. Introduction of commercial laser-sintering systems used to incrementally fuse layers of metal powder into solid objects generated the shift from "rapid prototyping" to "rapid manufacture" by 2005 [2]. Early selective laser sintering (SLS) systems utilized powders with polymer-coated powders, resulting in low-density products requiring consolidation with hot isostatic pressure (HIP) to achieve near-full density [3]. Parallel innovations enabled the use of metal powders without coatings to be used in a "direct selective laser sintering" method [4]. Refinements of this concept grew into the AM process now referred to as direct metal laser sintering (DMLS), which is technically a special instantiation of SLS [5].

Comprehensive reviews of laser-based AM techniques are available in the literature [1,2,6], and will not be provided here. We note, however, that selective laser melting (SLM) systems achieve melting of the powders and initially were applied only to pure metals [1,2,6]. In contrast, SLS processes historically did not heat the powders above the melting temperature, and produced solids with somewhat less than full (ideal) density. Although we have pointed out the most obvious difference between SLM and SLS systems, the distinction between the two AM processes has become blurred within the community of AM fabricators simply because state-of-the-art DMLS systems are operated at power levels sufficient to achieve full melting of the powders; thus, SLM and DMLS are in practice used interchangeably [7]. These AM techniques have both been termed "powder bed fusion" processes, as defined by ASTM International [8].

Characterization of the mechanical properties of additive, layered materials produced by laser-heating methods has not kept pace with the proliferation of the systems put into service. Only a

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few reports published in the open literature present mechanical properties of AM-produced AlSi10Mg materials. In their review of AM aluminum alloys [9], Manfredi et al. include an example plot of stress–strain data measured with AlSi10Mg produced by DMLS and subjected to different heat treatments [10]. Buchbinder et al. reported measured hardness and tensile strength of AlSi10Mg specimens fabricated with their custom, high power SLM apparatus [11]. Tensile stress–strain curves of AlSi10Mg produced in two orientations with a customized SLM machine were presented by Kempen et al. [12], and the elastic modulus, ultimate strengths and strain to failure were compared to cast AlSi10Mg data measured by others.

Several reports of investigations of the characteristics of Ti6Al4V materials produced with layered AM techniques have been published recently. Early work by Brandl et al. compared the fatigue strength of Ti6Al4V built with a laser-fused, wire-fed process to that built with an electron-beam, powder-bed process [13]. Stress–strain characteristics of Ti6Al4V produced with DMLS and an experimental SLM machine were measured by Facchini et al., but no differentiation of results between the two AM processes were explained [14]. Fatigue properties of notched and unnotched Ti6Al4V specimens generated with an “in-house” SLM were presented by Van Hooreweder [15]. Crack growth rates and monotonic stress–strain behavior were measured by Leuders et al. in Ti6Al4V built with a commercial SLM (SLM250), and were discussed in relation to microstructural features [16]. Liu et al. studied fatigue in Ti6Al4V specimens also produced with an SLM250, attributing poor fatigue behavior to defects created by lack of fusion [17]. A comparison of the “mean fatigue strength” of Ti6Al4V produced with DMLS (EOSINT M270) versus an e-beam system was presented by Chan et al., along with excellent microscopy of crack-initiating defects [18]. Rafi et al. measured tensile and fatigue properties of both Ti6Al4V specimens produced with an EOS M270 (fatigue specimens were post-machined) [19]. Most recently, Edwards and Ramulu studied Ti6Al4V produced with a selective laser meting process (MTT 250), attributing the poor fatigue behavior to porosity present in the AM materials [20]; these authors stated that “while some data on the fatigue performance of AM titanium components is currently available, much more data is still needed.” While all of these published reports furnish data relevant to behavior of AM Ti6Al4V, they do not provide definitive indications of the mechanical behavior of materials built with the most prevalent, state-of-the art AM machines.

Published reports concerning mechanical properties of stainless steels produced with powder-bed fusion techniques are much more limited. Rafi et al. [19] and Spierings et al. [21] both included stainless steel (SS) 15-5 in their studies of mechanical properties of DMLS materials. Investigations of the microstructure [22] and fatigue–crack growth rates [23] in SS316L produced with SLM have been reported. Spierings et al. also measured fatigue strengths of SLM 316L, under tensile loading with load ratio of $R=0.1$. Most recently, Murr et al. have described very detailed studies of the microstructures of 17-4PH materials produced with SLM, relating hardness of the materials to the type of gas used in the SLM chamber, but no other mechanical property measurements were reported [24].

1.2. Scope of the present work

This study was performed to contribute to the understanding of the mechanical behavior of materials produced using additive metal manufacturing processes presently available commercially. Two categories of materials were studied: “light metals” (an aluminum alloy, AlSi10Mg and a titanium alloy, Ti6Al4V) and stainless steels (316L and 17-4PH). Material specimens were fabricated at an experienced facility using their typical process parameters, with specimens produced in both vertical and horizontal orientations. Tensile stress–strain behaviors were measured using flat-plate specimens in a universal test machine, and flexural moduli were measured with a dynamic mechanical analyzer (DMA). Measurements of fatigue strengths were conducted in fully-reversed, rotating bending mode. Reference material behaviors were obtained from specimens produced with conventional techniques, i.e. subtractive machining of wrought materials. The effect of surface polishing was explored and is discussed in relation to corresponding potential improvements of fatigue strength.

Extensive surface characterization was performed to establish correlation between surface roughness and topography, and the resultant mechanical behaviors, in particular fatigue strength. Optical microscopy and profilometry were used to measure surface roughness and to characterize intrinsic surface defects and interior voids. Metallography was performed to reveal the material microstructures and prevalence of interior voids within the additive materials.

Tensile deformation measurements are compared in engineering stress–strain plots, showing the differences in yield and post-yield behaviors between conventional materials and layered AM materials. Measured fatigue-strength data are presented in traditional S–N plots, including wrought and machined specimens to provide a reference or “baseline.” Fatigue behaviors of the AM specimens are compared to those of conventional materials, and are discussed in relation to characteristics observed on the fracture surfaces. Special attention is paid to the fatigue–crack initiation sites, to explain why the AM materials exhibit lower fatigue strengths.

2. Experimental details

2.1. Powder-bed material fabrication

The AlSi10Mg materials used for this study were fabricated using an SLM 280, a selective laser melting system from SLM Solutions GmbH. Raw material powder was obtained from EOS GmbH, and was Nadcap[1] certified with particle sizes ranging from 20 to 63 μm. The build chamber was backfilled with argon gas, while powder melting and fusion was performed with a 100 W laser with a spot size of 100 μm, traveling at 930 mm/s. Specimens were built with layer thickness of approximately 50 μm, while supported on a plate heated to 200 °C. To relieve residual stresses generated by the fabrication process, thermal stress relieving was performed on these specimens at 300 °C for 2 h, prior to removing specimens from the support structures.

Additive Ti6Al4V specimens were fabricated using an EOS M280, a DMLS system, also with argon gas and a laser having spot size of 100 μm. The laser power and travel rate are considered proprietary by the service provider.[2] Powder for Ti6Al4V fabrication was also obtained from EOS GmbH, Nadcap certified with particle sizes ranging from 15 to 45 μm. The resulting specimens had a layer thickness of approximately 30 μm, and the temperature of the build platform during their fabrication was 35 °C. Thermal stress relieving was performed on these specimens at 650 °C for 2 h. A separate lot of Ti6Al4V specimens was similarly fabricated and subjected to hot isostatic pressure (HIP), at a temperature of 900 °C while under pressure of 102 MPa for two hours.

The two SS materials (316L and 17-4PH) studied were fabricated using an EOS M270, with alloy powders obtained from EOS

[1] Nadcap (formerly NADCAP, the National Aerospace and Defense Contractors Accreditation Program).

[2] Linear Mold and Engineering, Livonia, MI.