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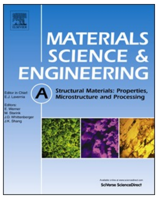

# Anisotropic multiaxial plasticity model for laser powder bed fusion additively manufactured Ti-6Al-4V

Alexander E. Wilson-Heid[a], Shipin Qin[a], Allison M. Beese[a,b,*]

[a] *Department of Materials Science and Engineering, Pennsylvania State University, University Park, PA 16802, United States*
[b] *Department of Mechanical Engineering, Pennsylvania State University, University Park, PA 16802, United States*

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## ABSTRACT

The multiaxial yield and plastic flow behavior of Ti-6Al-4V manufactured in two orientations via laser powder bed fusion (L-PBF) additive manufacturing was investigated. The mechanical properties of L-PBF Ti-6Al-4V were evaluated under uniaxial tension, plane strain tension, pure shear, and combined tension/shear loading. The mechanical behavior was found to be stress state dependent and slightly anisotropic. A plasticity model, consisting of a Hill 1948 anisotropic yield criterion, associated flow rule, and an isotropic hardening law was calibrated and used to describe the yield and plasticity behavior of this material. Validation of the plasticity model under multiaxial stress states demonstrated that the model was able to predict the stress state dependent anisotropic plasticity behavior of this material.

## 1. Introduction

Additive manufacturing (AM) is the process of building a 3-dimensional (3D) component layer-by-layer [1]. In laser powder bed fusion (L-PBF) AM, a thin layer of metal powder is spread on top of a baseplate, and a laser scans the 2D layer pattern, melting the powder and allowing it to fuse to the material below. This process is repeated as the baseplate is lowered, powder is spread on the previous layer, and a new layer is scanned until the 3D component is fabricated. The most commonly adjusted processing parameters in L-PBF include laser power, scanning speed, layer height, and scan pattern. Altering these parameters results in varying morphology and size of both grains and defects in a fabricated component [2].

The microstructures in AM are different from traditionally processed counterparts due the rapid solidification and thermal cycling of the material during processing [3,4]. Material in L-PBF can undergo cooling rates of up to $10^6$ K/s at the solidification front [5], and after solidification undergoes thermal cycles as material is added above or adjacent to the previously solidified material. The unique microstructures in materials made by AM influence the mechanical properties of the completed parts.

The present study focuses on Ti-6Al-4V, an α-β titanium alloy that exhibits high strength, stiffness, and corrosion resistance [6]. This alloy has been widely studied in the AM field, both because of its suitability for building complex part geometries for use in the aerospace and biomedical industries [7,8] and because of the high cost associated with traditional subtractive machining of this material [9].

The strength of Ti-6Al-4V fabricated via L-PBF has been investigated previously. In Ti-6Al-4V, both the yield and ultimate tensile strengths have been reported as greater than those values seen in traditionally manufactured material [2,10–13]. This result can be explained by the rapid cooling in AM leading to the formation of fine acicular α and α’ laths in the L-PBF material, which are stronger than the lamellar α + β structure seen in as-cast and annealed versions of this alloy [14].

Additionally, the elongation to failure under uniaxial tension (UT) of Ti-6Al-4V fabricated via AM has been experimentally measured [15,16]. When compared to their traditionally manufactured counterparts, Ti-6Al-4V that has been fabricated via L-PBF has lower ductility, which can be explained by microstructural differences [12]. In the L-PBF condition, lack-of-fusion (LoF) defects between laser passes can result from non-optimal processing parameters, laser power or beam size fluctuations, or recoating errors [17,18]. The elongated, irregularly shaped LoF defects are detrimental to the ductility of the bulk material as the sharp corners in these defects act as stress concentration sites that lead to early failure [19]. Furthermore, α and α’ phases, which are the primary phases in Ti-6Al-4V made by L-PBF, have limited plastic deformability compared to the β phase typically present in the conventionally processed material [20]. Together, these features result in a decrease in the macroscopic ductility of additively manufactured Ti-6Al-4V compared to conventionally processed Ti-6Al-4V.

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[*] Corresponding author.
*E-mail address:* beese@matse.psu.edu (A.M. Beese).

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The mechanical properties of additively manufactured Ti-6Al-4V have been predominantly assessed under uniaxial tension as described above. These tests provide information about mechanical behavior, including elongation, strain hardening behavior, and yield stress under uniaxial tension. However, these properties only define the mechanical behavior under the single stress state of uniaxial tension, which is not sufficient to completely describe how additively manufactured components will behave under realistic loading, which will subject the material to multiaxial stress states. An investigation into materials under multiaxial stress states is critical because the plasticity and fracture behavior of a ductile metal may be stress state dependent [21–24]. Since a well-defined plasticity model is required for quantitatively investigating fracture, it is critical to first experimentally determine and model the plasticity behavior of the material under different stress states, even if the plasticity behavior of the material is stress state independent, before fracture properties can be assessed. In the current work, the stress state and orientation dependent plasticity behavior was investigated through multiaxial loading tests.

The mechanical behavior of conventionally processed Ti-6Al-4V has been studied under multiaxial loading states, with an emphasis on studying the effects of temperature and strain rate on properties, which are relevant to the applications and forming processes of conventional Ti-6Al-4V. Studies on conventionally processed Ti-6Al-4V have found that the mechanical properties of this material are often anisotropic and stress state dependent. Tuninetti and co-workers found that a Ti-6Al-4V ingot exhibited tension/compression asymmetry, anisotropic yield behavior, and anisotropic strain hardening [25]. An orthotropic yield criterion for hexagonal close packed metals, developed by Cazacu and co-workers [26], was used to describe the initial yield behavior. Hammer and co-workers, found that the mechanical behavior of aerospace grade Ti-6Al-4V plate was dependent on loading condition [27] and was anisotropic [28].

A plasticity and fracture model for wire-based directed energy deposition additively manufactured Ti-6Al-4V was proposed by Gorji and co-workers using analogies to crystal plasticity finite element analysis [29]. The microstructure of this material consisted of large prior-β grains that were several millimeters wide and several centimeters in length, which contained α needles. Their model incorporates statistical variations in the properties of single prior-β grains, based on tension and shear tests, and determines macroscopic mechanical properties by incorporating a random sampling of these statistical properties to account for many prior-β grains within a material.

In the present paper, we experimentally characterized and computationally modeled the plasticity behavior of L-PBF fabricated Ti-6Al-4V, considering both uniaxial and multiaxial stress states. An accurate plasticity model that predicts the mechanical response of complex-shaped additively manufactured Ti-6Al-4V components under loading is required for the adoption of these components in structural applications. Here, L-PBF Ti-6Al-4V was studied under uniaxial tension, pure shear (PS), plane strain tension (PST), and combined tension/shear loading conditions, and the initial yield and strain hardening behavior were measured. A plasticity model that captures the anisotropic and stress state dependent mechanical behavior of this material under multiaxial loading was calibrated based on experimental results and validated using finite element simulations.

## 2. Experimental procedures

### 2.1. Sample fabrication

Ti-6Al-4V walls were fabricated using L-PBF AM (EOSINT M280). The pre-alloyed Ti-6Al-4V powder was manufactured by EOS Gmbh via argon gas atomization and had a chemical composition in accordance with ASTM F1472 and F2924 [30,31]. Standard EOS processing parameters for Ti-6Al-4V with a 60 μm layer thickness were used, resulting in a linear heat input of 0.27 J/mm and a volumetric heat input of 32.4 J/mm$^3$ [1].

**Table 1**
As-built wall sample dimensions and number of samples tested in each orientation.

| Sample description | As-built wall dimensions: width × thickness × height (mm) | Number of Samples |
|---|---|---|
| UT: BD | 12 × 4 × 65.5 | 2 |
| UT: ⊥ BD | 65.5 × 4 × 12 | 2 |
| Multiaxial Loading: BD | 70 × 3.5 × 27.4 | 8 |
| Multiaxial Loading: ⊥ BD | 27.4 × 3.5 × 70 | 8 |

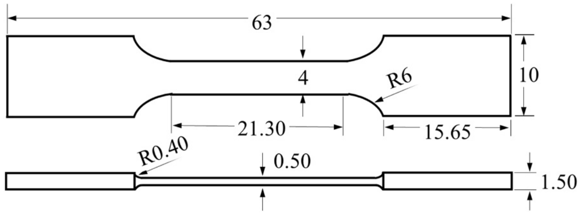

**Fig. 1.** Geometry of tensile samples extracted from as-built walls. Dimensions are in mm.

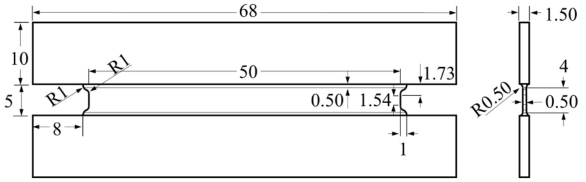

**Fig. 2.** Geometry of multiaxial loading samples extracted from as-built walls. Dimensions are in mm. Adapted from [33].

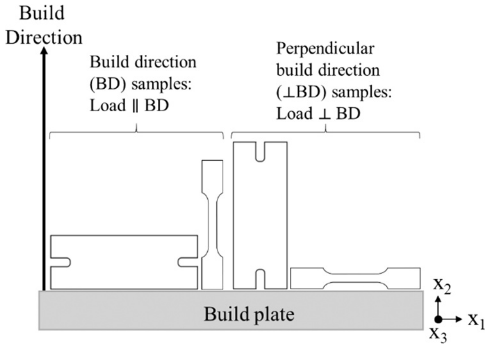

**Fig. 3.** Schematic of sample orientation nomenclature with respect to vertical build direction (BD) where the outlines correspond to sample geometries in Figs. 1 and 2. All of the specimens were extracted from the $x_1$-$x_2$ plane.

All specimens used for mechanical testing were extracted from the thin walls, which had the dimensions given in Table 1. Prior to machining the walls off of the build plate, or machining test specimens out of the walls, the entire build plate was subjected to a standard stress relief heat treatment of 650 °C for 3 h in an argon environment. Uniaxial tension, in accordance with ASTM E8 [32], (Fig. 1) and multiaxial loading (Fig. 2) specimens were extracted from the walls in the build direction (BD) and perpendicular to the build direction (⊥ BD) using wire electrical discharge machining. The gauge thickness of both uniaxial tension and multiaxial loading specimens was 0.5 mm to remove any potential size effects in the mechanical property measurements. A schematic of the orientation nomenclature is given in Fig. 3. Note that all the specimens were extracted from the $x_1$-$x_2$ plane. All specimens are under plane stress