International Journal of Fatigue 116 (2018) 543–552

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

# Surface roughness effects on the fatigue strength of additively manufactured Ti-6Al-4V

Jonathan Pegues[a,b], Michael Roach[c], R. Scott Williamson[c], Nima Shamsaei[a,b,*]

[a] Department of Mechanical Engineering, Auburn University, Auburn, AL 36849, United States
[b] National Center for Additive Manufacturing Excellence (NCAME), Auburn University, Auburn, AL 36849, United States
[c] Department of Biomedical Materials Science, University of Mississippi Medical Center, Jackson, MS 39216, United States

ARTICLE INFO

*Keywords:*
Additive manufacturing
Fatigue behavior
Surface roughness
Size effects
Geometry

ABSTRACT

Additive manufacturing has become an increasingly popular advanced manufacturing technique, however, many questions concerning the reliability of parts fabricated by methods such as laser powder bed fusion must be addressed. In this research, the effect of surface roughness and size is investigated by designing various additively manufactured Ti-6Al-4V specimen geometries. These as-built specimens were designed to specifically determine the effect of surface area and part diameter on the fatigue behavior of specimens fabricated diagonally from the substrate. Results indicate that the fatigue behavior is more sensitive to part diameter than surface area. Parts with diameters of 4.90 mm or less showed higher surface roughness on the down-skin surface. This variation diminished, however, for specimens with diameters larger than 4.90 mm. Additionally, as part diameter decreased, the difference between the load-bearing and nominal stress amplitudes, caused by surface roughness, increased, resulting in significant scatter in the high cycle fatigue data.

## 1. Introduction

Additive manufacturing has become an increasingly popular manufacturing technique offering large design freedoms and a significant potential for fabricating optimized and customized parts with complex geometries. In the aerospace industry, topology optimization can be utilized to create complex geometries that can reduce weight of structural parts, and thus, effectively increasing fuel efficiency. These complex geometries often cannot be fabricated through traditional subtractive methods, however, additive manufacturing has shown the ability to produce such geometries [1]. In the biomedical industry, additive manufacturing promises customized parts, per patient/injury, that can be readily tailored to the patient ensuring a better fit. While titanium alloys such as Ti-6Al-4V are commonly used in both aerospace parts and biomedical implants due to their high strength-to-weight ratio, excellent mechanical properties, and biocompatibility [2–5], they are also compatible with additive manufacturing processes because of their weld-ability. One of the major obstacles facing full implementation of additive manufactured (AM) Ti-6Al-4V parts, however, is the concern with the reliability, especially under cyclic loading conditions. While extensive research has been conducted on the fatigue behavior of traditional wrought Ti-6Al-4V [5–12], there are needs for further investigating the fatigue behavior of AM counterparts due to their structural imperfections such as defects/pores and increased surface roughness [13–16].

The reliability and durability concerns for AM parts have driven a recent surge of research into the fatigue behavior of AM parts [13–15,17,18]. Defects associated with AM parts such as porosity and lack of fusion can reduce the fatigue life leading to lower endurance limits compared to traditional wrought alloys. Additionally, as-built AM parts have been shown to have even lower fatigue limits when compared to parts that underwent post-process machining and polishing [14,15]. This is attributed to the high surface roughness of the as-built parts in which the micro-notches associated with partially melted powders on the surface act as stress concentrators resulting in earlier crack initiation [19]. Parts fabricated diagonally have been shown to have increased surface roughness on the down-skin surface, which can further reduce the fatigue strength of AM parts [20,21].

There have been many investigations that attempt to characterize the effect of surface roughness on the fatigue behavior of both wrought and AM materials with both conditions showing mixed results [22–27]. Removal of the surface roughness through machining and polishing is necessary for AM parts to achieve fatigue limits that are more comparable to wrought materials. However, one of the most beneficial promises of additive manufacturing technology is the ability to manufacture net shape parts without the need of further subtractive

* Corresponding author at: Department of Mechanical Engineering, Auburn University, Auburn, AL 36849, United States.
*E-mail address:* shamsaei@auburn.edu (N. Shamsaei).

https://doi.org/10.1016/j.ijfatigue.2018.07.013
Received 27 April 2018; Received in revised form 3 July 2018; Accepted 7 July 2018
Available online 09 July 2018

**Nomenclature**

| | |
|---|---|
| $N_f$ | cycles to failure |
| $R_a$ | mean roughness value |
| α | primary hexagonal close packed phase |
| α′ | martensitic hexagonal close packed phase |
| β | prior body centered cubic phase |
| $\sigma_a$ | stress amplitude |

machining or polishing. For this reason, it is imperative to better understand the fatigue performance of AM parts fabricated in the net shape condition without any surface enhancements before testing. Additionally, the range of AM part sizes can vary from small medical implants to large structural components in which the fatigue behavior of the net shape parts may differ between these contrasting sizes.

The objective of this research is to investigate the effect of part size in relation to surface roughness, surface area, and gage diameter on the fatigue behavior of laser-based powder bed fusion (L-PBF) specimens in as-built condition. Directly correlating these specimen properties to the corresponding fatigue performance for various part sizes is critical to reliably design AM parts with the ability to withstand the service loadings associated with a given application.

## 2. Materials and methods

A series of five specimen geometries were designed to investigate the effect of part size on the fatigue behavior of L-PBF Ti-6Al-4V. The five specimen geometries are shown in Fig. 1 and can be separated into two distinct groups. The first of these groups maintains constant gage volume while incrementally increasing the gage surface area by 25%. These geometries are referred to as the constant gage volume (CGV) specimens and shown as Geometries 1–3 in Fig. 1. In order to maintain the constant volume between Geometries 1–3 while increasing the surface area, the gage diameter and gage lengths were adjusted accordingly. The second specimen group maintains constant gage diameter while incrementally increasing the gage surface area by 25% as shown for Geometries 4 and 5 in Fig. 1. These specimens are referred to as the constant gage diameter (CGD) and are designed to account for any effect that the change in the gage diameter may have on the fatigue behavior. The sub-sized geometries were chosen to allow each group to be fabricated during the same build to limit variability between tests.

Parts were fabricated on an EOS M290 (EOS, Krailling, Germany) AM machine with a maximum laser power of 400 W. The process parameters used for fabrication were the suggested performance parameters provided by EOS for Ti-6Al-4V components. This set of process parameters include a laser power of 280 W, a scan speed of 1200 mm/s, and a hatch distance of 0.140 mm. The powder was supplied by LPW Technology Inc. (LPW, Runcorn, UK) and had a particle size range of 15–45 µm. All specimens were fabricated at an angle of 45° from the substrate. Before removal from the substrate, the parts were stress relieved at 700 °C for one hour, and air cooled to room temperature. The time and temperature were selected to maintain the as-built microstructure while minimizing the effects of residual stress that arise from the high cooling rates associated with L-PBF.

The surface roughness of the up-skin and down-skin surfaces of each specimen was measured at two areas within the gage section using a Keyence VHX-1000 (Keyence, Osaka, Japan) digital microscope. The down-skin and up-skin surfaces are shown in Fig. 2 (not to scale) and are termed in relation to the build direction. Down-skin refers to surfaces in which the vertical component of the vector normal to the surface is in the opposite direction of the build progression. This occurs in overhangs or, as in this case, surfaces that are diagonal and directed opposite of the build direction. Up-skin refers to surfaces where the vertical component of the vector normal to the surface is in the same direction as the build progression. Representative measurements for a down-skin surface are schematically shown in Fig. 3 where the 3D surface map was collected from each end of the uniform gage section. Triplicate line measurements were taken from each surface map, resulting in six total measurements for each up-skin and down skin

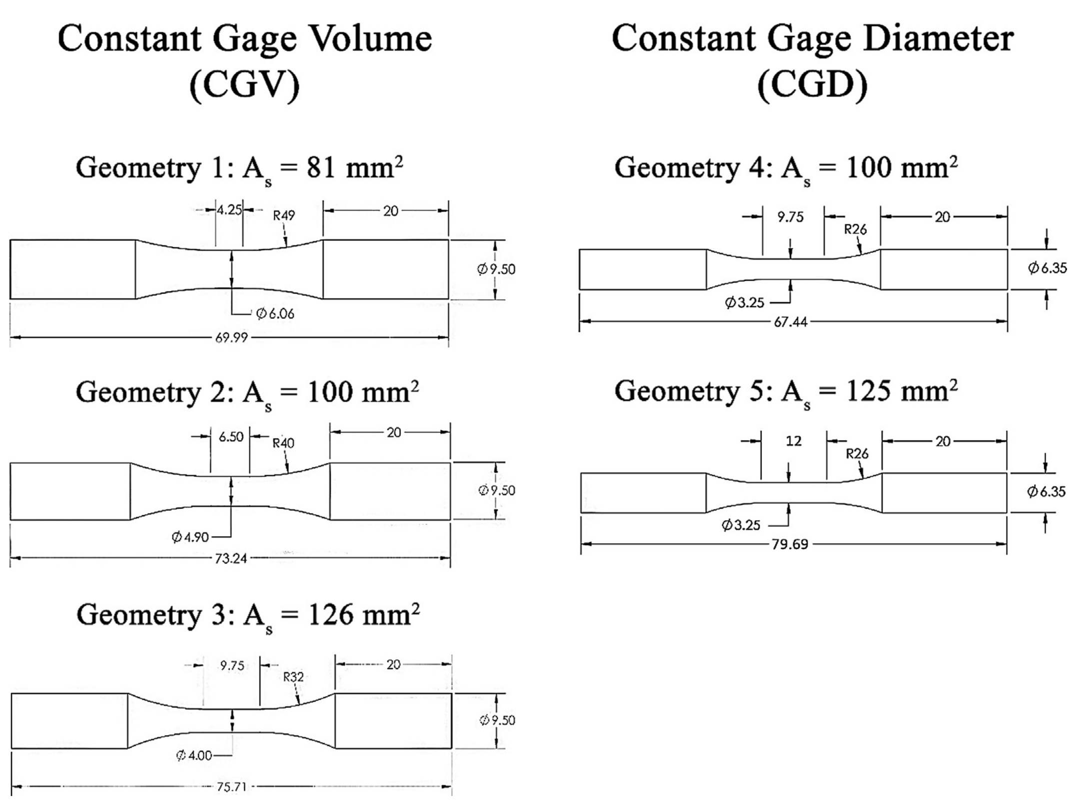


**Fig. 1.** Geometry dimensions (all measurements in mm).