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Efficient determination of influence factors in fatigue of additive manufactured metals

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Abstract

The additive manufacturing (AM) technology transforms metal powder, layer by layer, into structural components. Sectors such as aerospace and motor racing require: i) in-depth knowledge of mechanical behavior, especially fatigue, of these metals; ii) fatigue data for component design. In the recent years the industrial expectations about metal AM technology have exploded with a focus now on materials and components qualification. Material and AM process qualification costs are high because metal powder and AM system processing time are expensive. The approach adopted in this paper to efficiently generate knowledge on influencing factors of the fatigue behavior of DMLS Ti-6Al4V alloy utilizes non-standard (i.e. miniature) specimens and simple plane bending test machines. After validation of the proposed methodology against test results for the same material obtained with standard specimens, the merit of the innovative approach is demonstrated by presenting original data on the influence of surface quality, heat treatment, coupled material directionality and notch effects on fatigue behaviour of DMLS Ti-6Al4V.

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Keywords: Fatigue; Test method; Infuence factors on fatigue; Selective laser melting; Ti-6Al-4V

1. Introduction

Additive manufacturing (AM) involves a number of different processes and materials. The common link is the possibility of producing functional parts of complex geometry directly from a CAD file with minimum material and

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energy waste. Metal alloys, such as Titanium, Ni-based super alloys, Cr-Co alloys and Al/Si alloys, are mainly processed by selective laser melting (SLM), where a laser is the concentrated thermal energy source that selectively fuses thin regions of a powder bed that quickly solidify. After recoating, another layer is selectively melted. The process is repeated until the entire part is built layer-by-layer.

Metal AM technologies have been industrially available for more than 15 years, but it is in the last 5 years that the expectations of SLM technology have exploded in demanding sectors, such as aerospace, biomedical, energy production etc., where the fatigue performance is a critical selection and design parameter. The widespread adoption of the SLM technology is hampered by insufficient technical knowledge and design skills equivalent to what is available for traditional metals.

One major challenge of the SLM technology is the high costs and long times involved in the material and process qualification for load-bearing applications, Seifi et al. (2016). Metal powders are remarkably expensive, the SLM production process requires expensive systems and fatigue testing requires multiple specimens (depending the required degree of confidence) to characterize a single material/process combination.

In this paper the high costs of fatigue testing of SLM metals and the many material factors to be investigated in fatigue to promote enhanced use of SLM technology are initially discussed. The approach proposed to efficiently generate knowledge on influencing factors of the fatigue behavior utilizes non-standard (i.e. miniature) specimens and simple plane bending test machines.

The material investigated here is the SLM Ti6Al4V alloy. Although this Ti alloy is possibly the most studied SLM alloy, see Edwards and Ramulu (2014) and Mower and Long (2016), nonetheless a recent review of the fatigue test data available in the literature by Li et al (2016) demonstrated the variability of SLM metal response in fatigue as a function of process parameters, heat treatment and surface quality.

2. Issues with the fatigue characterization of AM metals

2.1. Specific aspects affecting the fatigue behavior of AM metals

The current qualification or certification procedures of aerospace industry rely on a ‘‘building block” concept and a statistical approach based on extensive mechanical test data to quantify uncertainty with respect to material and process variations, Li et al (2016). The expensive and time consuming building block design process involves many stages based on physical testing at each stage, starting from material property evaluation testing and ending with full-scale verification testing. This approach is not practical for qualifying AM parts that are known for drastic variability in processes and processing parameter within each process. Therefore, quicker and more cost effective qualification and certification approaches may need to be developed to fully utilize AM parts.

The alternative model-based qualification, see Seifi et al. (2016), requires a smaller number of tests to validate the model. However, the rapid and complicated SLM process adds many challenges to developing physics-based models with repeatability and reproducibility of predictions across varying processes and process parameters.

An effective qualification and certification approach requires a good understanding of the large number of machine-to-machine and process parameter variabilities, and their impact on fatigue performance. There are currently more than 100 process parameters reported in the literature, see Bandyopadhyay and Bose (2016), which affect SLM material performance, only a few of which are considered and discussed in the literature data. SLM parameters include: layer thickness, laser power, build direction, hatch spacing, scan speed, etc., Rafi et al (2013). The scan strategy used to produce SLM specimens can have a significant influence on attributes, such as the produced residual stresses, Shiomi et al. (2004) or subsurface defect creation, Simonelli et al. (2012) and Wycisk et al (2014), which in turn significantly affect fatigue performance for the data presented in the literature is typically not reported.

Recently Li et al (2016) have attempted to catalog and analyze the published fatigue performance data of an additively manufactured Ti–6Al–4V alloy for technological significance. He focused on uniaxial fatigue performance and compared SLM data to traditionally manufactured Ti–6Al–4V, discussing failure mechanisms, defects, microstructure, and processing parameters. Fig. 1 taken from Li et al. (2016) shows the wide variability of fatigue performance of SLM Ti–6Al–4V. While all data are for un-notched uniaxially loaded specimens in load