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Fatigue behaviour of additively-manufactured metallic parts

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Abstract

An overview on recent research efforts is presented to obtain an understanding on the fatigue behaviour and failure mechanisms of metallic parts fabricated via powder-based additive manufacturing (AM) processes, including direct energy deposition (DED) and powder bed fusion (PBF) methods, utilizing either laser or electron beam as an energy source. Some challenges inherent to characterizing the mechanical behaviour of AM metals under cyclic loading are discussed, with emphasis on the effects of residual stresses on their fatigue resistance. In addition, an aspect pertaining to the structural integrity of AM parts relating to their fatigue behaviour at very high cycles is presented and compared with those of the conventionally-manufactured counterparts.

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Keywords: Additive manufacturing (AM); Fatigue; Microstructure; Failure mechanisims; Residual stress; Very high cycle fatigue

1. Introduction

Additive manufacturing (AM) is gaining significant attention in various industries, such as aerospace, automotive, and biomedical, due to its many unique advantages specifically the ability to fabricate customized and complex parts that are often unobtainable with conventional manufacturing methods[1-3]. Despite the fact that AM technologies have been continued to demonstrate many potentials, the mechanical behaviour, and in particular the fatigue behaviour, of

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AM parts are not yet fully realized. This lack of understanding creates a barrier against AM technologies to be adopted in many load-bearing, fracture-critical applications[4-5].

The presence of material anomalies (i.e., process-driven defects such as lack of fusion voids, entrapped gas pores, etc.) and microstructural properties and heterogeneity resulted from directional heat transfer during AM process can significantly affect the mechanical behaviour of AM parts especially under cyclic loading[6-9]. For laser-powder bed fusion (L-PBF) and direct laser deposition (DLD) processes, two commons manufacturing-induced defects, including (1) lack of fusion (LOF) voids due to unconsolidated partially-/un-melted powder particles, and (2) pores caused by the entrapped gas, are generally observed[10-14]. Since they can serve as micro-notches that cause stress concentrations and local plastic deformations within the material, fatigue cracks are typically initiated from these process-induced defects, which are considered to be the main contributors to the lower fatigue resistance of AM parts, as compared to their conventionally-built counterparts. By employing the hot isostatic pressing (HIP), a post-manufacturing treatment at combined high pressure and high temperature, process-induced internal defects can be reduced which consequently strengthens the fatigue resistance. Nonetheless, the effectiveness of HIP in removing defects from AM parts greatly depends on the material as well as the chosen HIP parameters[15]. The surface-connected and near surface voids may still exist in HIPed parts as they cannot be removed by this process[16].

Other challenges that may significantly affect the fatigue resistance of AM parts include the condition of surface finish and design parameters (i.e., build orientation, process time interval, size, geometry, etc.), which potentially influence the degree of similitude between the mechanical properties of laboratory specimens and those of actual AM parts. These topics have been comprehensively discussed in some previous reviews[7,13].

Beside the aforementioned factors, other important aspects related to the fatigue performance of AM parts, such as the influence of residual stresses and very high cycle fatigue behaviour, need further discussion. In this paper, the fatigue behaviour and failure mechanisms of AM parts related to these topics are discussed based on the recent publications in the literature.

2. Effect of residual stresses

Residual stresses are commonly classified into three types, namely types I, II, and III, depending on the length scale over which they equilibrate within a material. Type I residual stresses (i.e., stresses in macro-scale) extend over large distances and play a significant role in distortion of material. On the other hand, types II and III residual stresses are those that occur between grains at micro-scale, and inside of a grain around dislocations and crystal surfaces at atomic-scale, respectively, due to different phases in the material[17-18]. In this paper, some recent works involving the influence of type I residual stresses on the fatigue behaviour of AM parts are discussed.

Residual stresses are generally induced throughout AM parts during fabrication due to several factors, including the inherent rapid heating/cooling rates, significant spatially varied thermal distribution, and repeated tempering during subsequent laser-deposition process[3]. The presence of residual stresses often leads to localized deformations that can extensively impact the strength and fatigue resistance of parts[19-21], or possibly resulting in distortion (i.e., loss of near-net shape geometries) and even failure of parts during fabrication[22]. In addition, several studies have indicated that the magnitude and pattern of residual stress within AM parts are commonly affected by various aspects, such as process parameters (e.g., scanning pattern, laser power, beam transverse speed, etc.), part geometry, phase transformation, as well as the material properties (e.g., modulus of elasticity, yield strength, thermal conductivity, and coefficient of thermal expansion)[21,23-24].

In intermediate and long-life fatigue applications, compressive residual stresses in parts are often desired due to beneficial effects in delaying the crack formation and its growth, typically resulting in an enhanced fatigue resistance. On the other hand, tensile residual stresses facilitate crack opening and propagation from the surface, reducing the fatigue strength of the material[25]. Common approaches to weaken the tensile residual stresses in AM parts during fabrication are to lower the local thermal gradient by adjusting the process parameters, maintaining optimal melt pool size, or pre-heating of the build plate[26,18]. Besides optimizing the scan strategies, the residual stress can also be reduced by utilizing post-build heat treatment[27-28], or mechanical treatments such as shot-peening or surface rolling[29,30] to relieve internal stresses in AM parts.