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Surface roughness of Ti-6Al-4V parts obtained by SLM and EBM: Effect on the High Cycle Fatigue life.

Bastien Vayssette[a], Nicolas Saintier[a], Charles Brugger[a], Mohamed Elmay[a], Etienne Pessard[b]

[a]Arts et Metiers Paristech, I2M, CNRS, Talence 33400, France
[b]Arts et Metiers Paristech, LAMPA, Angers 49035, France

Abstract

Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are powder bed fusion processing which allows to build-up parts by successive addition of layers using 3D-CAD models. Among the advantages, are the high degree of freedom for part design and the small loss of material, which explain the increase of Ti-6Al-4V parts obtained by these processes. However, Ti-6Al-4V parts produced by SLM and EBM contain defects (surface roughness, porosity, tensile residual stresses) which decrease significantly the High Cycle Fatigue (HCF) life. In order to minimize the porosity and tensile residual stresses, post-processing treatments like Hot Isostatic Pressing (HIP) and Stress Relieving are often conducted. But the modification of the surface roughness by machining is very costly and not always possible, especially for parts with complex design. The aim of this work is to evaluate the effect of the surface roughness and microstructure of Ti-6Al-4V parts produced by SLM and EBM on the HCF life. Five sets of specimens were tested in tension-compression (R=-1 ; f=120Hz): Hot-Rolled (reference) ; SLM HIP machined ; SLM HIP As-Built ; EBM HIP machined ; EBM HIP As-Built . For each condition, microstructure characterization, observation of the fracture surface of broken specimens and surface analysis were carried out respectively by Optical Microscope (OM), Scanning Electron Microscope (SEM) and 3D optical profilometer. Results of fatigue testing show a significant decrease of the HCF life mainly due to the surface roughness. Along with experimental testing, numerical simulations using FEM were conducted using the surface scans obtained by profilometry. Based on extreme values statistics of the crossland equivalent stress averaged on a critical distance, a methodology is proposed to take into account the effect of the surface roughness on the HCF life.

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Keywords: HCF; SLM; EBM; Surface Roughness; Ti-6Al-4V; FEM.

1. Introduction

In order to make the most of the additive manufacturing technologies, the fatigue behavior of additively manufactured materials has to be understood. Due to the quick developement of this technology, a limited, yet fast evolving literature exists on this topic. Specimens obtained by SLM and EBM contain many defects that are inherent to the process and impossible to eliminate even with the best process parameters monitoring. Among these defects, porosity, surface roughness and in addition the residual stresses are also the critical factors regarding the HCF strength. Table 1 summarises the morphology of the as-built specimens.

*Corresponding author. Tel: +003306271739

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Table 1. Morphology of as-built specimens

	Microstructure	Porosity	Roughness	Residual stresses
SLM	Martensitic[1, 2]	0,1%-0,5% [3, 4]	5μm≤Ra≤40μm [5]	100≤ σ ≤500 MPa
EBM	Fine Lamellar [1, 6]	0,1%-0,3% [3, 7]	25μm≤Ra≤130μm[8]	very low

These defects lead to an early initiation of the fatigue cracks and it is well known that, before any post-treatment, the HCF strength of the as-built specimens is not suitable for aircraft loadbearing applications [9]. It is also hard to quantify and understand the respective influence of these defects since in many studies, the early crack initiation is mostly due to a combination of the porosity, surface roughness, residual stresses and brittle microstructure [3, 9, 10]. Moreover the additively manufactured specimens used for aircraft applications are almost systematically stress-relieved and HIP.On the other hand, the surface roughness is not always removable since the parts may have a very complex shape. It is then very important to understand its effect on the HCF strength.

This study compares results of HCF tests on SLM and EBM stress-relieved HIP specimens with either machined or as-built surfaces. This procedure allows eliminating both residual stresses and porosity, homogenizes the microstructure of the samples and to highlight the effect of the surface roughness. Along with experimental testing, numerical simulations using FEM were conducted using the surface scans obtained by profilometry.

There are many existing models accounting for the effect of the surface roughness on the HCF strength [11–14] but only for periodic roughness obtained by machining.

Other models take into account an isolated surface defect using the area of the defect [15] or the distribution of local stresses around defects [16, 17]. Taylor proposed three approches to link the fatigue strength to the stress distribution: Point based (PB); Line based (LB); Volume based (VB). The PB and LB methods require to know the direction where the considered criterion is maximum and then are difficult to apply when the morphology of the surface defect is complex. Since the VB method is easily applicable to any type of defect and allows taking into account complex multiaxial loadings, it will be used in this study. The Taylor methods have proved being interesting for fatigue prediction through FEM calculations [18, 19] but a critical distance having no physical meaning has to be introduced.

In order to take into account the role of the microstructural heterogeneities in multiaxial fatigue life prediction, models have been developed in a probabilistic framework [20]. Recent models based on the extrem values (EV) distributions have given interesting results to establish a relationship between the microstructure characteristics and the variability of the fatigue behavior [21, 22]. The number of micronotches at the surface being important, it is suitable in this study to use the distribution of the EV of the considered fatigue criterion. The proposed approach will combine the Taylor VB method and the EV distribution in order to predict the fatigue strength of specimens produced by SLM.

2. Materials and Methods

2.1. Studied Materials

Five sets of materials were studied: Hot-rolled (HR); SLM HIP machined (SLM machined); SLM HIP As-built (SLM As-built); EBM HIP machined (EBM machined); EBM HIP As-built (EBM As-built). The HIP treatment consists in applying an isostatic pressure of 120MPa at a temperature of 920°C during two hours. All the materials are made of TA6V titanium alloy (Chemical composition in Table 2).

The HR material, used as a reference, shows a fine equiaxed microstructure where the nodules are elongated along the rolling direction (RD). The SLM HIP and EBM HIP materials show a very similar lamellar microstructure where the colomnar ex-beta grains are still slightly distinguishable along the build direction. The α-lamellae thickness is between 1 and 2μm (Figure 2).

2.2. HCF testing

Fully reverse uniaxial tension/compression fatigue tests were conducted in load control using a sinusoidal waveforme, with a load ratio R=-1. Tension tests were carried out at room temperature in air. These