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Computed tomography for characterization of fatigue performance of selective laser melted parts

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ABSTRACT

Components manufactured by maturing additive manufacturing techniques like selective laser melting (SLM) find potential competence in several applications especially in automotive and aerospace industries as well as in medical applications like customized implants. The manufactured parts possess better, or at least comparable, yield strength and tensile strength values accompanied with a reduced fracture strain. Though their fatigue performance in the as-built condition is impaired due to surface roughness, it can be sufficiently improved by post-process surface treatments. Even then, there exists a high fatigue scatter due to remnant porosity. Characterization of remnant porosity is necessary for a reliable component design to be employed for cyclic applications. Computed tomography has been used in this study to evaluate the influence of porosity-incited stress concentration on the corresponding fatigue scatter. Microscopic analysis, tensile tests, fatigue tests with continuous load increase and constant amplitudes as well as finite element analysis have been used for this purpose. Critical pore characteristics and a modification in the process scanning strategy have been recommended so that the components can be reliably used in fatigue-loaded applications.

1. Introduction

Additive manufacturing (AM) is now an established technology offering ample opportunities for product optimization and is being targeted for designing and manufacturing light-weight components. Selective laser melting (SLM) is one of the maturing AM techniques which directly manufactures three-dimensional parts employing laser energy to melt the powder material. The powder material is selectively scanned and melt, according to the desired component geometry given to the SLM system in the form of a three-dimensional geometrical design, in a layer-wise fashion; the thickness of layers being appropriately thin to let the powder material melt by laser energy in that layer. The scanned section represents the two-dimensional cross-section of the sliced model of the CAD geometry. This manufacturing procedure gives the benefits of freedom of design and individualization of products while maintaining the quasistatic product properties, yield strength and ultimate tensile strength, compared to the properties of conventionally manufactured parts [1–3]. Airbus industry projects a possibility of 30% weight-reduction if an aircraft is completely manufactured using additive manufacturing [4].

Several alloys, including steel, titanium and aluminum, manufactured by SLM have been studied regarding their processing as well as mechanical performance. Titanium alloy Ti–6Al–4V is the most investigated alloy due to its pertinence in aerospace as well as biomedical applications [5–8]. These studies have reported quasistatic tensile strength of SLM manufactured Ti–6Al–4V as comparable, and in cases better, to those of conventionally manufactured alloy [6,8]. Similar behavior has been observed for Al alloys AlSi10Mg [9] and AlSi12 [10,11]. Fatigue performance of the as-built alloys is usually impaired due to surface roughness as well as process-induced porosity. This can be improved by post-processing like polishing and heat treatment, however, even then there is a high fatigue scatter associated with the Woehler curve [8]. The process is capable of manufacturing parts with other

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competitive advantages: fabrication of different crystallographic phases, multi-functional manufacturing [7], introduction of part-specific desirable properties and manufacturing of complex heat transfer devices [12].

For the qualification of the SLM process for industrial and medical applications, the process needs to be reliable under cyclic loading, i.e., the fatigue performance of the SLM parts needs to be at par with those of conventionally manufactured materials. There are a number of factors which affect the fatigue performance like microstructure, texture, surface roughness, residual stresses as well as material defects. Several of these factors are relevant for SLM-parts. Surface roughness and internal defects are the most important factors affecting their fatigue performance. Quasistatic mechanical properties are not susceptible to surface roughness, but fatigue performance of parts largely depends upon the surface roughness. Surface roughness usually act as micro-cracks which are a preferred source of fatigue crack initiation, and is the preferred mechanism of fatigue failure in SLM parts. Fatigue crack initiation from rough surfaces, a characteristic of such processes, reduces the fatigue performance significantly [8,13]. However, for determination of the fatigue performance, the specimens are tested in polished condition to generate the reference fatigue data, and reduction factors should then be used when designing a component. Polishing of SLM parts is something contrary to the competitive advantage of the process i.e. manufacturing of complex structures. However, other surface improvement techniques suitable for the process like blasting techniques or chemical techniques are topics of current research [14].

If surfaces are polished, then the next preferred mechanism of fatigue failure in SLM parts is the porosity induced in the part during the manufacturing process. There are many studies which have reported the fatigue failure due to pores. Chan et al. [15] have reported surface crack initiation in Ti–6Al–4V for as-built samples and crack initiation from internal pores for the polished samples. Pores act as source of stress concentration which then cause crack initiation. Similar observations have been reported by Edward and Ramulu [13]. Brandl et al. [16] have studied the fracture behavior of AlSi10Mg alloy and both surface and sub-surface cracks are reported. Aboulkhair et al. [17] have also studied porosity in AlSi10Mg samples and report that two reasons exist for the pore formation: un-melted particles due to the bonding deficiency i.e.; less laser energy is imparted at some spot, and the gas porosity which is due to the entrapped gas bubbles. They have recommended lower scan speeds to reduce the pores. However, all the researchers have reported the relative density of SLM parts above 99.5%. Even then the remnant pores have been found critical in fatigue performance. This less than 0.5% remnant porosity causes fatigue scatter due to crack formation at the internal pores. Therefore, after achieving this threshold value of relative density, double scanning for the complete part is not cost-competitive, and identification of the critical locations is required.

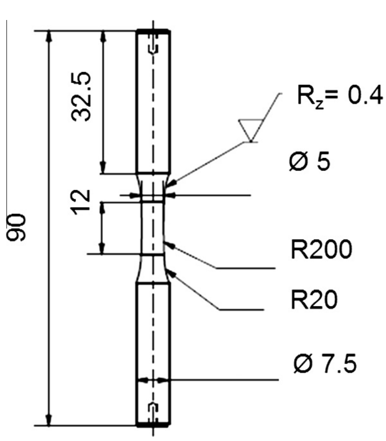

Fig. 1. Geometry of test specimen.

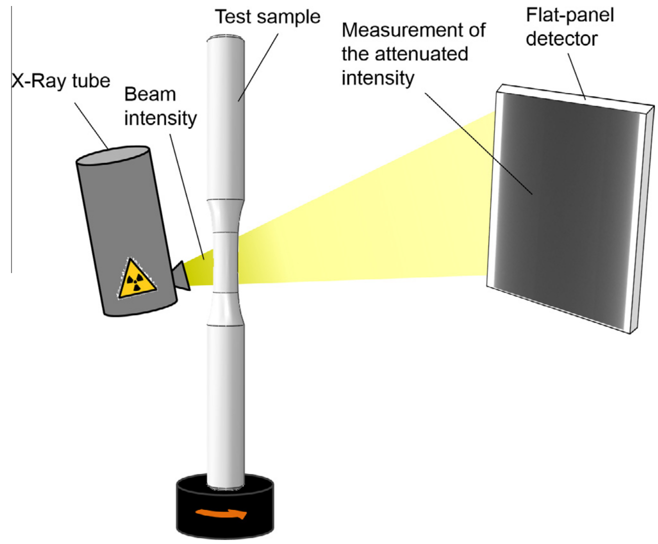

Fig. 2. Setup of X-ray computed tomography.

Residual stresses and microstructure are other important factors which influence the mechanical performance of SLM manufactured parts. Thermal gradients are induced in the process due to high cooling rates which develop residual stresses. Stress-relieving heat treatment is recommended to eliminate these stresses. Heating the base plate also reduces the induced residual stresses significantly [18,19]. Microstructure of the resulting SLM part can be controlled by controlling the process parameters. Low cooling rates coarsen the microstructure which reduces the mechanical strength accompanied by an increase in fracture strain. Microstructural features are usually not the dominant factor in fatigue performance of aluminum alloys in the presence of porosity. After removing the porosity, the next important factor i.e.; microstructural features come into play [20,21].

Along with the design enrichment and weight-reduction advantages, there are some challenges in the metrology of the additive manufactured parts. Fatigue scatter problems characterized by post-fracture microscopy can only be used as a critical analysis tool for exploring the fracture behavior and cannot be used as a prediction tool. The size of crack-initiating pore is usually over-estimated by such post-fracture techniques. Causes of fatigue scatter need to be determined, qualified and formulated such that a reliable prediction of fatigue life can be made. Traditional characterization techniques become difficult to be employed for complex structures due to design complexities. Mapping techniques, e.g. coordinate measuring machines (CMM), have been used as a reliable quality control tool, but the determination of internal features can be achieved only after destructively cutting the part. X-ray computed

Table 1
Scanning parameters of the computed tomography for the two batches.

CT parameter	Batch I	Batch II
X-ray voltage (kV)	130	130
Current (μA)	61	61
Filter	None	2 mm Al.
Number of projections	1020	1140
Integration time (s)	0.7	1.3
Voxel resolution (μm)	4.8	5.3