Simulation-based investigation of statistical fatigue strength of selective laser melted lightweight alloys

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1. Abstract

Selective laser melting (SLM) which belongs to powder bed fusion of additive layer manufacturing is investigated for application to structural components in aerospace and automotive industries. The process is said able to produce high-relative-density (> 99%) titanium and aluminum alloys, as well as steels. An attractive feature of SLM to the aerospace industry is the ability to manufacture high-topology-optimized functional components at a high fly-to-buy ratio. Concerning properties, SLM deposited alloys can reach quasistatic and fatigue strength equivalent to wrought alloys and superior to cast alloys. High cooling gradients, during the consolidation of microlayers of powder, constitute finely featured microstructure which is supersaturated with secondary alloying elements.

The strength of SLM components is reported to be a monotonic function of relative density that is dependent on void volume fraction. Porosity originates in SLM parts from improper application of energy density. In addition to remnant porosity, surface roughness induced by the staircase effect is a typical feature of SLM parts. Both types of defects, as well as surface roughness, have an adverse effect on fatigue properties of SLM structures. Remnant pores in the component are stress raisers, thus, crack initiation sites. Coalescence of multi-crack initiations at several defect sites accelerates damage and failure. The effect on fatigue strength is high-property scatter and uncertain repeatability of the manufactured components.

In this study, the aim was to design an algorithm to calculate a confidence interval of fatigue strength. Several techniques were combined including experimental investigation of cyclic flow behavior, as well as failure analysis, numerical modeling, and Monte-Carlo simulation. The phase-field method is applied to simulate the crack initiation process and detect critical propagation loads. Two SLM-manufactured batches of AlSi12, built at 90°, were investigated with one of them subjected to base plate heating (BPH) up to ~200°C. Two further batches of AlSi10Mg were added to the study, without BPH, one of them is built at 0°. The experimental study included quasistatic and load increase testing (LIT) to monitor material response and flow behavior. Micro-computed tomography (µ-CT) was applied for defect characterization and building real-time finite-element (FE) model. Computation of stable cyclic response was carried out in Abaqus FE analysis software using a Fourier-series-based representation of the boundary conditions and solution residual. The calculated distributions of the cyclically-developed stresses and strains were post-processed in a self-developed Matlab code.

The advantage of this concept is not only an evaluation of fatigue life but also evaluation of the repeatability of the process using statistical interpretation for quality control. Setup of an SLM process producing components with a wide range of fatigue strength is unreliable since repeatability of properties is not ensured, and the process is not stable. A further advantage is the possibility to evaluate fatigue life for components with non-standard geometries such as dynamically loaded components of the aerospace industry.

2. Graphical abstract