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Advanced fatigue analysis of metal lattice structures produced by Selective Laser Melting

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A R T I C L E I N F O

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A B S T R A C T

Additive manufacturing techniques such as Selective Laser Melting (SLM) are highly suitable for producing lattice structures with complex unit cell designs. These structures can be designed and built in such a way that their properties match the needs for both medical and structural parts. This paper presents a novel local stress method for fatigue analysis of such SLM lattice structures. The fatigue performance of Ti6Al4V and CoCr structures produced by SLM is assessed with this method. In addition, life-prolonging post-SLM heat and surface treatments are studied. The resulting methods and treatments can be extended to other types of AM structures.

1. Introduction

Selective Laser Melting (SLM) is a layer-wise material addition technique which allows production of complex three-dimensional parts by selectively melting successive layers of metal powder onto each other, using the thermal energy supplied by a focused and computer controller laser beam [1]. Except for enabling the production of complex geometries, SLM also offers the advantage of low material waste and relatively high accuracy compared to other laser based AM techniques such as direct energy deposition.

Additive manufacturing techniques such as SLM can be used for efficiently producing metal lattice structures with complex unit cell designs. These advanced structures can offer interesting advantages over more traditionally produced solid parts. The properties of lattice structures are not only depending on the material, but also on the design of the unit cell [2]. Hence they can be designed and produced in such a way that their properties match the needs for both medical and structural applications.

During the last years, the quasi-static compression behaviour of metal lattice structures produced by SLM was studied and documented for samples with different relative densities and unit cells [3,4]. The fatigue behaviour, on the other hand, is not yet fully understood. In most studies, a global stress approach is used to study fatigue behaviour of lattice structures [3,5]. Global stresses act on the whole lattice structure and are as such straightforward to calculate from the applied load and from the cross section of the lattice structure. These global stresses are, however, dependent of unit cell type, size and relative density and as such they do not facilitate an improved understanding of the actual material fatigue behaviour. This makes it difficult to quantify the influence of SLM process variations and/or the effect of post-build treatments.

In this paper, a local stress method is described in which the stresses in the struts of the unit cells are calculated and used to analyse fatigue behaviour of Ti6Al4V and CoCr lattice structures produced by SLM. The results show that this local stress method is a suitable tool to analyse fatigue behaviour of metal SLM lattice structures as well as to study the influence of different influencing factors such as post-build heat and surface treatments.

2. Materials and methods

2.1. Sample production by SLM

Selective Laser Melting was used to manufacture metal lattice structures from Ti6Al4V and CoCr powder using a ProX320 machine from 3DSystems. Two materials are studied in this work to verify if the developed local stress based method for fatigue analysis is applicable for two different metals that are widely used in biomedical (CoCr and Ti6Al4V) and structural (Ti6Al4V) applications. Standard processing parameters and a layer thickness of 30 μm were used. The build chamber was flushed with Ar to create an inert atmosphere with an oxygen level <25 ppm. The samples were built on top of a solid titanium build plate from which they were subsequently removed using wire EDM. After this, all samples were ultrasonically cleaned using demineralized water to remove unmolten powder particles.

Fig. 1 shows the cylindrical sample geometry with height H and diameter D containing interconnected pores resulting from the use of diamond unit cells with cell size a, strut length L and strut diameter d. This geometry is in line with related work [3–7]. Diamond unit cells are used since they are strongly isotropic and well-suited for production by SLM [8]. All samples were produced with their longitudinal axis perpendicular to the building plate. Special attention was made to have a D/a and H/a ratio of at least 10 so that at least 10 unit cells are present in all

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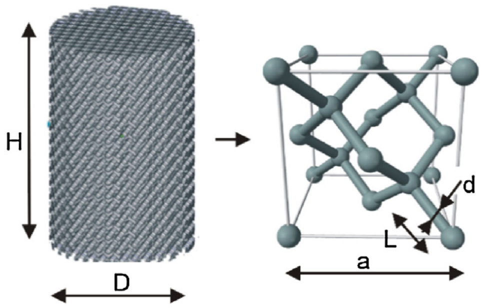

Fig. 1. Test sample (left) and diamond unit cell (right).

directions. This is important to avoid the size-effect in porous structures [9].

2.2. Post SLM treatments

For each material, as-built samples with low (AB_L) and high (AB_H) relative density are produced to demonstrate the ability of the local stress method to account for differences in the structural relative density of lattice structures. After SLM, a heat treatment and/or a surface treatment is used to improve the fatigue resistance of the as-built (AB_H) samples and to demonstrate the potential of the local stress based fatigue method. Hot isostatic pressing (HIP) is applied on the Ti6Al4V samples to reduce material porosity, to relieve any residual stress and to improve the ductility of the material by changing the microstructure. Chemical etching (CE) is applied on both Ti6Al4V and CoCr samples to smoothen the rough surface caused by SLM. Details of these post-SLM treatments can be found in Refs. [6,7,10,11]. This leads to 4 sample conditions for titanium structures and 3 sample conditions for cobalt–chromium structures:

- SLM-Ti6Al4V: AB_L, AB_H, HIP, HIP + CE
- SLM-CoCr: AB_L, AB_H, CE

2.3. Sample characterization

The relative density of a lattice structure RD_L is equal to the ratio of the volume of solid material V_s to the volume of the total sample V_t, as shown in Eq. (1). This sample characteristic is a crucial input parameter for the local stress method and is hence calculated for all samples before starting the fatigue experiments. The volume V_t of every sample was accurately determined by measuring diameter D and height H with a calliper with 0.01 mm resolution. The mass m of every sample was also measured using a balance with 0.1 mg resolution. Based on the theoretical density of Ti6Al4V $\rho_{Ti} = 4.42$ g/cm^3, the volume of solid material V_s could then be calculated as shown in Eq. (1).

$$RD_L = \frac{V_s}{V_t} = \frac{m/\rho_{Ti}}{H\pi D^2/4} \qquad (1)$$

The relative density of the solid material RD_M is related to the porosity in the struts and was measured on five samples for every batch using Archimedes' principle in pure ethanol.

2.4. Mechanical testing and fatigue data analysis

Fatigue tests were performed on an Instron Electropuls E10.000 with 10 kN force cell at room temperature (20 ± 2 °C) and at relative humidity of 50 ± 5%. All fatigue samples were subjected to constant amplitude load controlled sinusoidal loading in compression–compression (R = 0.1) at fixed test frequency of f = 15 Hz.

For each of the sample conditions described in Section 2.2, a stress-cycle (SN) curve was constructed using approximately 12 samples and by testing at least two identical samples at one stress amplitude until failure. The applied loading was chosen such that data were gathered over the fatigue life spectrum between 10^3–10^6 cycles. The failure criterion was defined as the moment when a sudden decrease in displacement (1 mm/s) occurred. To allow lateral expansion of the samples during loading in compression, a PTFE (polytetrafluorethylene) foil of 0.3 mm thickness was placed between the sample and the hardened compression plates.

SN-curves were first constructed by plotting the global stress as function of the number of cycles to failure. In a next step, the local stress method as derived and explained in Section 2.5 was used for fatigue life analysis.

2.5. Local stress method for fatigue analysis

Fig. 2 shows an illustration of a lattice structure loaded in compression and consisting of small diamond unit cells that contain struts which are all connected and hence statically overdetermined. For the widely used global stress method, the global load F_{tot} acting on the sample with diameter D and area A_{tot} is considered. For the local stress method, the force F acting under an angle θ of 35,26° on one hyperstatic strut with diameter d and area A is considered, as illustrated in Fig. 2.

For the global method, compressive stress is straightforward to calculate as F_{tot}/A. For the local method, it becomes clear that, due to the orientation of the struts with respect to the load, normal stress occurs both due to compression and due to bending of the strut. The maximum values of these stresses, S_A and S_B respectively, can be calculated as shown in Eqs. (2) and (3) using conventional strength of materials theory for hyperstatic beams with local strut force F, strut length L, strut diameter d, strut angle θ, bending moment M and moment of inertia I. It is interesting to note that, although the lattice structure is loaded in compression–compression, the struts are actually subjected to compression and bending and hence compressive and tensile stresses occur. Euler calculations also indicate that the failure mechanism of the struts in the diamond unit cell is dominated by bending and not by buckling.

$$S_A = \frac{F\sin\theta}{A} \qquad (2)$$

$$S_B = \frac{My}{I} = \frac{FLd\cos\theta}{4I} \qquad (3)$$

$$\text{with}\, A = \frac{\pi d^2}{4}, \qquad (4)$$

$$I = \frac{\pi d^4}{64}, \qquad (5)$$

$$y = \frac{d}{2} \qquad (6)$$

$$\text{and}\, M = \frac{1}{2}FL\cos\theta \qquad (7)$$

For mechanical fatigue in general, it is well known that it is the tensile stress component S_T rather than the compressive stress component S_C that usually leads to failure. This tensile component S_T is shown in Fig. 2. As fatigue usually initiated as the surface, the maximum value of this stress is calculated in Eq. (8) based on the stresses calculated by Eqs. (2) and (3). The local stress value $S_{T,\max}$ will be used to express a local state of stress of which the authors believe that it is relevant to study fatigue failure of lattice

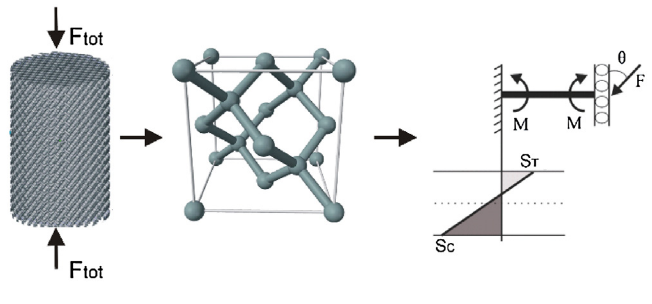

Fig. 2. From cylindrical lattice structure (left) to diamond unit cell (middle) to hyperstatic strut (right).

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