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Staged thermomechanical testing of nickel superalloys produced by selective laser melting

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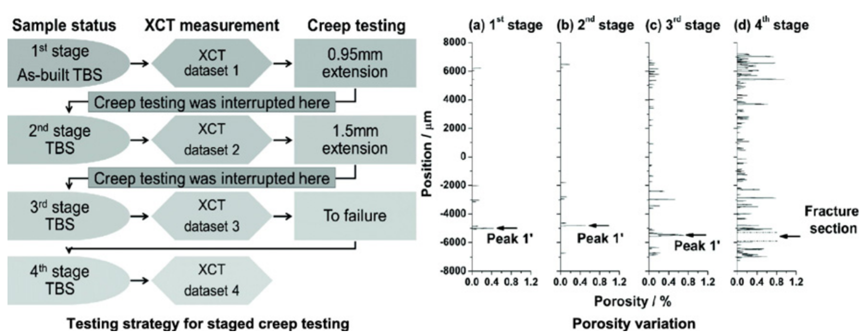
HIGHLIGHTS

- A staged testing method is proposed to study the defects evolving during thermomechanical testing.
- X-ray computed tomography measurement is applied to examine the defects in a selective laser melting manufactured sample.
- The spatial porosity distributions and their changes during the testing become visualisation and comparable.
- Defect evolution during the testing also becomes visualisation and the fracture origin of the sample is accurately predicted.

GRAPHICAL ABSTRACT



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ABSTRACT

The creep performance of additively manufactured components remains an issue before additive manufacturing can be put fully implemented. In this study, Inconel 718 two-bar specimens are produced by selective laser melting and subjected to a 'staged' creep test. Creep test was interrupted at critical junctures and X-ray computed tomography measurements performed at various extensions of the specimen. Periodic X-ray computed tomography measurements allow, for the first time, examination of the specimens during creep testing. Evaluation of specimen performance shows the number and size of pores within the specimen increasing over time as a result of classical creep mechanisms. Location and tracking over time of weak points are performed, allowing early estimation of sample failure points. This information is valuable to selective laser melting practitioners who seek to optimise the build strategy in order to minimise in-built defects.

1. Introduction

Selective laser melting (SLM) is a powder bed fusion based additive manufacturing (AM) technique. It is a near-net-shape technique which provides a high flexibility in producing complex geometrical features in high value components such as turbine blades. However, when considering the mechanical testing of nickel superalloys processed by SLM, the published work is limited to relatively simple tests, e.g. hardness and tensile testing. For example, Amato et al. [1] studied the effects of the build orientation and post-treatments on the hardness and tensile properties of Inconel 718 samples built in two different atmospheres. They confirmed that variations in the mechanical properties were mainly caused by the γ'' precipitates. Jia and Gu [2] investigated the effects of changing SLM build parameters on Inconel 718 samples with an examination of densification, hardness and wear performance. An optimum energy density which resulted in improved mechanical properties was determined. However, fewer researchers have examined the more

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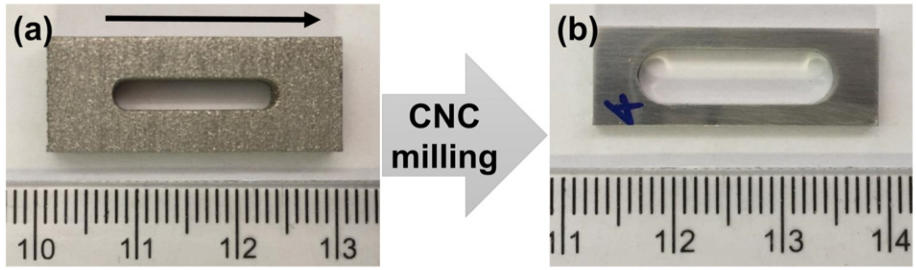

Fig. 1. (a) Raw TBS block (arrow indicates the SLM building direction); (b) CNC machined as-built TBS (dimensions in mm).

complex failure mechanisms of SLM samples, such as creep or fatigue behaviour. Rickenbacher et al. [3], for example, not only studied tensile properties of SLM fabricated IN738LC, but also demonstrated that the creep performance of that material was inferior compared to conventionally manufactured samples. In the study performed by Pröbstle et al. [4], however, Inconel 718 SLM samples were found to possess improved creep strength over cast and wrought samples. Pröbstle et al. also showed that post-process heat treatment further improved the creep performance of Inconel 718, although fracture results were not included.

Of the aforementioned mechanical properties, creep resistance is a key mechanical property for components deployed in high-temperature applications [5], and the use of additively manufactured parts here has so far been limited by the poor creep performance. This is largely based upon the assumptions on the evolution of 'in-built' defects at high temperatures. Analysis of the response of AM components to creep is therefore of critical importance, particularly the response of common defects produced during the AM processes, which are expected to evolve under creep conditions. It is well known that creep is a time-dependent phenomenon, but current conventional testing methods do not examine the entire sample or provide direct evidence of defect evolution during creep testing. In this paper, a staged testing (interrupted testing) method for studying such defect evolution is presented. The destructive interruption (take out the sample and slice) of creep testing before rupture was usually applied to check samples' microstructures in the corresponding testing stages [6]. Through the use of X-ray computed tomography (XCT) [7], defects can be non-destructively detected allowing the measurement procedure to continue. In a previously reported study [8], XCT measurement was applied to detect defects in a sample before and after fracture. Babout et al. [9] studied the damage mechanisms of room temperature tensile testing of powder metallurgy fabricated samples, the entire testing procedure was divided into seven deformation stages and XCT measurement was performed in each stage. In another study [10], an in-situ XCT measurement was applied to study a high-temperature tensile testing, the evolution of samples' deformation was clearly demonstrated. In this study, XCT measurement is undertaken at periodic stages of the creep test. Through comparison of different XCT datasets, the evolution of the defects can be characterised. XCT has so far been used for non-destructive testing to measure the spatial distribution of pores in SLM structures in recent research, and a review of such studies is presented by Thompson et al. [11]. Specifically, Maskery et al. [12] successfully quantified and characterised the porosity in SLM built structures. Maskery et al. demonstrated the feasibility of using XCT to give a sufficient description of part porosity, pore size and pore shape. In another study [13], XCT was applied to locate and measure the defects in samples built by selective electron beam melting (SEBM). The size, volume fraction and spatial distribution of these defects were well recognised and characterised. Particularly, a voxel size of 9.9 μm, which gives a minimum detectable pore equivalent diameter of approximately 25 μm, was found adequate to locate all large-scale defects in the sample.

The novel approach presented in this work combines staged creep testing with XCT and provides new information regarding time-dependent creep phenomena. This approach also provides a new understanding of the creep performance of SLM processed Inconel 718.

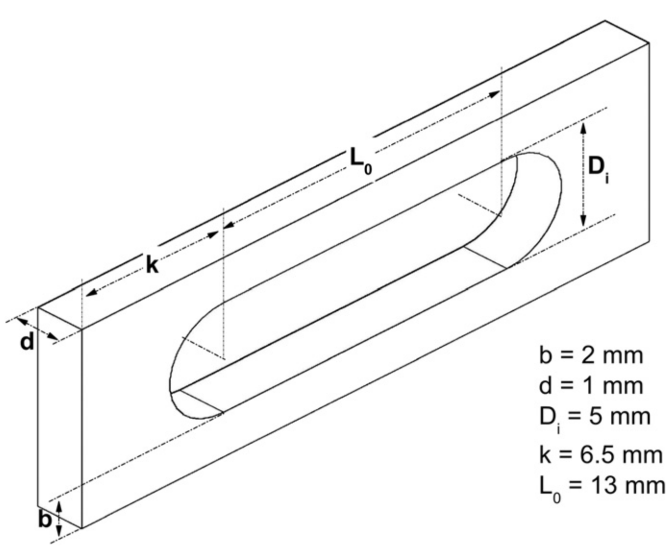

Fig. 2. Dimensions of the TBS used in this study [14].

2. Experimental methodology

Inconel 718 two-bar specimens (TBSs) were subject to creep testing in this study. A TBS (as shown in Fig. 1(b)) is a specimen which designed to obtain information about both uniaxial creep strain rate and fracture life [14]. The raw TBS block (as shown in Fig. 1(a), in which the arrow indicates the SLM building direction) was built in a Renishaw AM250 laser melting system. The raw block was post-processed using a computer numerical controlled (CNC) milling machine to the specified dimensions (as shown in Fig. 2), defined by Hyde et al. [14]. Testing was carried out under a uniform tensile stress of 747.45 MPa at a temperature of 650 °C. These parameters were chosen to match a creep study made by Sugahara et al. [15] on standard wrought Inconel 718 samples.

Preliminary, uninterrupted, creep testing was carried out under the aforementioned conditions to estimate the extension range of the TBS. The extension and lifetime of four repeat samples obtained during preliminary testing are shown in Table 1.

Table 1
The extension and lifetime results of the preliminary testing.

Sample	Initial elastic extension/mm	Failure extension/mm	Lifetime/s
Sample A	0.999	2.014	24,240
Sample B	0.470	1.829	32,880
Sample C	0.729	2.074	47,760
Sample D	0.640	1.856	21,960
Average	0.710	1.943	31,710