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Creep behaviour of inconel 718 processed by laser powder bed fusion

Zhengkai Xu, C.J. Hyde*, C. Tuck, A.T. Clare

Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, University Park, NG7 2RD, United Kingdom

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ABSTRACT

Additive manufacturing lends itself well to the manufacture of aerospace parts due to the high complexity and small volume of many components found in modern aero engines. By exploiting additive manufacturing design freedoms, enhanced part functionality can be achieved and lead time can be reduced. However, the integrity of these parts is a primary concern which often cannot be guaranteed with current generation additive manufacturing methods and materials. Studies on the performance of additively manufactured parts under service conditions are therefore required.

In this study, laser powder bed fusion is used to produce specimens for creep testing. To allow this a novel specimen design, i.e. Two Bar Specimen, was applied for creep testing. The performance of these specimens, in the as-build condition, is showed to be largely poor because of surface integrity defects and unfavourable microstructure formation. These are clearly highlighted and explored. Further specimens, subjected to heat treatments, have also been tested. These showed a marked improvement of the microstructure. The lifetime of the heat-treated sample prepared with milling + wire electrical discharge machining was enhanced by as much as four times compared to the as-build specimens. However, this lifetime performance remains 33% below that of samples machined from the equivalent wrought material. This work then proposes manufacturing strategies to significantly enhance the performance of Inconel 718 when processed via laser powder bed fusion and post-heat-treatments.

1. Introduction

Laser powder bed fusion (LPBF) selectively melts the powder bed according to a 3D CAD model with a focused laser beam and builds components layer by layer (Gibson et al., 2010). Since LPBF is a process that can produce dense metal components directly from CAD data without the need for tooling, it offers great advantages for fabricating complex components, such as those made from superalloys for aerospace applications (Wang, 2011). However, the high-temperature performance of LPBF components, in terms of, microstructures and mechanical properties compared to traditionally manufactured equivalent has not been fully studied (Song et al., 2015).

Inconel 718 is one of the most popular materials applied in modern aero engines (Schafrik et al., 2001). Multiple strengthening mechanisms, such as precipitation hardening and solid solution hardening, make it possible for Inconel 718 superalloy to retain high strength and fatigue resistance at elevated temperatures as high as 650 °C (Diltemiz and Zhang et al., 2013). But, the mechanical properties sought for such engineering application inevitably leads to poor machinability. Special tools and carefully selected machining parameters are required (Qi et al., 2009). However, in the LPBF process, a material's "machinability" is no longer an issue. In the LPBF manufactured components, the microstructure is normally columnar dendrites which grow epitaxially along the building direction (Liu et al., 2011). LPBF of Inconel 718 has also been investigated by Amato et al. (2012) who studied the microstructure and basic mechanical properties, such as hardness and tensile properties, of LPBF fabricated Inconel 718 structures. However, the high temperature creep performance of LPBF made Inconel 718 specimens, has not been evaluated. Processing parameters were found have influences on the mechanical properties of LPBF manufactured components. Li et al. (2015) applied a simple bidirection scan strategy to manufacture Inconel 625 components. 'V' morphology was reported to exist on the as-built top surfaces, where the angle highly depends on the scanning speed. 'Scale shape' was found in the plane parallel to the building direction. Both features are controlled by the shape of molten pool. They also announced the 'scale shape' can turn into keyhole form with the increase of input energy density and improve the connection between adjacent layers. Lu et al. (2015) demonstrated that different island scanning strategies can lead to different relative density, ductility and residual stress. Both Xia et al. (2016) and Nadammal et al. (2017) studied the effects of hatch spacing. Xia et al. (2016) modelled the mass and heat transfer in the molten pool, found

* Corresponding author.
E-mail address: Christopher.hyde@nottingham.ac.uk (C.J. Hyde).

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hatch spacing played a critical role in determining structures' surface quality. A hatch spacing of 60 μm was applied in their study and result in an average surface roughness of 2.23 μm. Nadammal et al. (2017) noticed ten times increase of the hatch spacing can lead to a texture intensity decrease by a factor of two. They also concluded that the thermal gradient influenced by the hatch spacing is one of the main factors that lead to the residual stress variation. Yadollahi et al. (2017) investigated the effects of building direction on the fatigue performance of LPBF manufactured components. Specimens possess the highest fatigue strength when building direction perpendicular to the loading direction. Since defects between layers are more detrimental when loading direction and building direction are the same. Do and Li (2016) considered the effects of multi-processing parameters as a whole, i.e. the laser energy density, which includes laser power, scanning speed, hatch spacing and layer thickness. With the increase of laser energy density, the LPBF manufactured parts will become denser and possess more martensitic lath with larger size, and therefore increased hardness. Simultaneously, there exists an 'optimum laser energy density' for obtaining the lowest surface roughness. Criales et al. (2016) simulated the effects of a series of materials and LPBF process related parameters on the variation of peak temperature at a fixed position within a laser track and melt pool dynamics. The simulation results showed that the two subjects investigated are most sensitive to the reflectivity of the powders and laser power. Another study on direct metal laser sintering of 316 stainless steel, by Fatemi et al. (2017) focused on the effects of laser-related parameters on layer thickness and density. The results showed that these are proportional to apparent laser power and laser pulse duration and inversely proportional to laser scan speed. LPBF is not only applied to fabricate simple structures, but also complex ones. Sing et al. (2018) manufactured complex cellular lattice structures with LPBF and identified the most sensitive factors to the dimensional and mechanical properties. Structure dimensions in the horizontal direction are most sensitive to layer thickness, while those in the vertical and diagonal directions are mostly influenced by laser power. Laser power is the main reason for the variation of porosity and Young's modulus of a material. Yield strength is strongly affected by both laser power and scanning speed. The reuse of the metal powder is a big issue in the LPBF process. Hann (2016) proved the reuse of powder in LPBF of Inconel 718 can slightly increase oxygen content in powders but has little influence on the mechanical properties. Due to the fast heating and cooling process in the LPBF, residual stress is an important issue which have effects on components' quality and their mechanical properties. As mentioned by Mercelis and Kruth (2006), residual stress generated in the LPBF process is controlled by a variety of aspects such as the building height of samples. Higher building height can lead to higher positive residual stress to the top layer of the samples. While the base plate removal with Wire EDM can release the residual stress. With regard to the post-processing of LPBF manufactured components, Heat treatment (HT) and Hot Isostatic Pressing (HIP) are the most commonly used techniques. The effects of stress relief (SR) heat treatment, HT and HIP were studied by Prater et al. (2015). SR specimens possess the worst ultimate tensile stress and yield stress. As built and SR + HIP specimens possess similar ultimate tensile stress and yield stress. Specimens treated with SR + HIP + HT are the best. Tucho et al. (2017) analysed the microstructure and hardness of as-machined and solution heat treated Inconel 718 specimens. Laves phases are the main precipitates on the grain boundaries and sub-grain boundaries of as-machined specimens. While after solution heat treatment, (Nb,Ti)C carbides become more common, Laves phases which precipitated along intergranular boundaries can be fully dissolved when solution heat treated at 1250℃. Material's hardness was found decrease after heat treatment.

Creep resistance is one of the major life-limiting properties for high-temperature components in aero engines. It is affected by both working environment and the microstructure of the components (Diboine and Pineau, 1987). According to Kassner (2009), the nucleation of cavities in commercial alloys are usually observed on grain boundaries and associated with the existence of second-phase particles. Grain-boundary sliding and dislocation pile-ups are two of the main mechanisms that control the nucleation of cavities. Liu et al. (1991) demonstrated that grain size and carbide structure strongly influence creep crack growth in Inconel 718. The function of these carbide precipitates is twofold, for example, δ phase, as discussed by Parimi et al. (2014), can improve creep resistance, while some other types of precipitates (e.g. Laves phase) are detrimental. Based on the mechanism of creep (Ashby and Jones, 2012), large grain sizes and strengthening precipitates, such as δ phase, on grain boundaries are preferred in order to improve creep resistance.

Surface integrity is a key issue that needs to be considered in specimen preparation. Surface integrity includes many aspects such as basic surface finish, macro-structures, microstructures and even more complicated data sets such as residual stress conditions and other mechanical defects (M'Saoubi et al., 2008). In the study made by Wen et al. (2016), surface roughness was found to have some effect upon creep performance in a stress range smaller than 150 MPa. Their analytical results also showed that the effects of surface roughness on damage will decrease when the stress is higher than 150 MPa. This was because the surface of the sample tends to get flattened under high stress. However, there are few studies with respect to the effects of other surface finish conditions on creep performance. Many studies have also reported the detrimental effects of "white layers" on fatigue resistance, however, no studies considered white layers effects on creep resistance.

As part of a wider study, the main purpose of this paper is to discover key issues in the creep testing of LPBF manufactured Inconel 718 TBS specimens, but important issues such as the effects of LPBF building direction and the role of residual stress in the creep testing, are not yet considered in this paper. Here, the creep behaviour of LPBF manufactured Inconel 718 specimens is evaluated by using a newly developed two-bar specimen (TBS) creep testing method (Hyde et al., 2013). The main mechanisms that lead to specimen failure and the effects of heat treatments on the creep resistance of LPBF built specimens is explored. It is also made clear in this study that the surface integrity of LPBF produced components is critical in determining the creep performance of these specimens. This serves to identify key consideration for manufacturing chains which make use of laser-based additive manufacture.

2. Methodology and materials

Creep testing using two bar specimens (TBS) was undertaken by Hyde et al. (2013) and Ali et al. (2015) to investigate the creep behaviour of Grade P91 steel at 650 °C. This test arrangement allows for scaled and relatively rapid creep testing. The results obtained agreed with those obtained in standard uniaxial specimen creep testing. The dimensions of the two bar specimens applied in this study are showed in Fig. 1.

Eq. (1) has been used to convert the stress applied to the TBS creep testing into a corresponding equivalent uniaxial stress so that the data obtained in two bar specimen creep testing can be compared with those obtained in standard uniaxial specimen creep testing. This method was discussed in the study made by Ali et al. (2015).

$$\sigma_{ref} = \eta\sigma_{nom} \tag{1}$$

(Ali et al., 2015)

Where σ_{ref} is the stress applied in two bar specimen and σ_{nom} is the nominal stress applied in the corresponding standard uniaxial specimen. η is a constant which relates to the geometry of specimen and for which the calculation method and value (η = 0.9966) for the geometry applied in this study can be found in the study made by Hyde et al. (2013).

Eq. (2) has been used to convert the TBS creep extension to the