Received: 21 March 2019 | Revised: 18 April 2019 | Accepted: 13 May 2019
DOI: 10.1002/mdp2.84

LETTER

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What is going on with fatigue of additively manufactured metals?

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Abstract
This brief communication gives an overview of fatigue behaviour and assessment of additively manufactured metals. The high cycle fatigue behaviour of as-built and post-processed additively manufactured superalloy 718, stainless steel (316L and 17-4PH), and Ti-6Al-4 V is compared with their wrought counterparts. Further, different approaches used for assessment of the fatigue behaviour are presented.

KEYWORDS
fatigue, additive manufacturing, defects, Inconel 718, Ti-6Al-4 V, 316L, 17-4 PH

Recently, an increasing effort is put into developing understanding and confidence of additively manufactured (AM) metals for load-bearing applications.[1-4] AM is based on adding material, by, *eg*, fusing powder particles, as shown in Figure 1A, where powder particles are fused to a solid, layer-by-layer using a laser beam. Materials can be manufactured in a new way, opening up possibilities in terms of geometrical complexity never possible before. However, materials produced by AM exhibit unfavourable properties in their as-built state, such as reduction in fatigue life, reduced strength, reduced elongation at failure, high surface roughness, defects, anisotropic microstructure, and residual stresses.[1-4] By various post-treatments, the fatigue strength of AM materials can be increased to the level of wrought materials. This is because post-processing can alleviate the defects that influence the fatigue life of AM material but typically cannot neutralise those completely.[4] The idea of producing components made by high strength materials such as superalloys, titanium alloys, or steel alloys by AM is tempting, because it may reduce the need for machining, *ie*, saving cost. However, the fatigue strength is reduced by defects and high surface roughness, especially for high strength materials.[2] Figure 1B shows the typical test specimens for fatigue; Figure 1C shows a fracture surface with a rough surface, surface defect, and subsurface defects, and Figure 1D shows the as-built microstructure with visible melt pools and elongated grains in build direction, deriving from the temperature gradient from the cooling during manufacturing. The main two results seen in almost all cases when AM (as-built) specimens are compared to conventional materials are that (1) for static loading, elongation at failure and strength is reduced and (2) fatigue life is reduced.[1-4] The reason for the reduction in strength and fatigue life in the as-built state is typically due to defects as shown in Figure 1C.

In order to compare the fatigue performance of AM metals to their wrought counterparts fatigue data reported in the literature are compared in S-N diagrams. High cycle fatigue data for Superalloy Inconel 718[5-9], Ti-6A-l4 V,[10-16] stainless steel 316L,[17-20] and 17-4PH[19,21,22] are shown in Figure 2A to C, respectively. All data are corrected for mean stress employing the Smith-Watson-Topper (SWT) correction.[23]

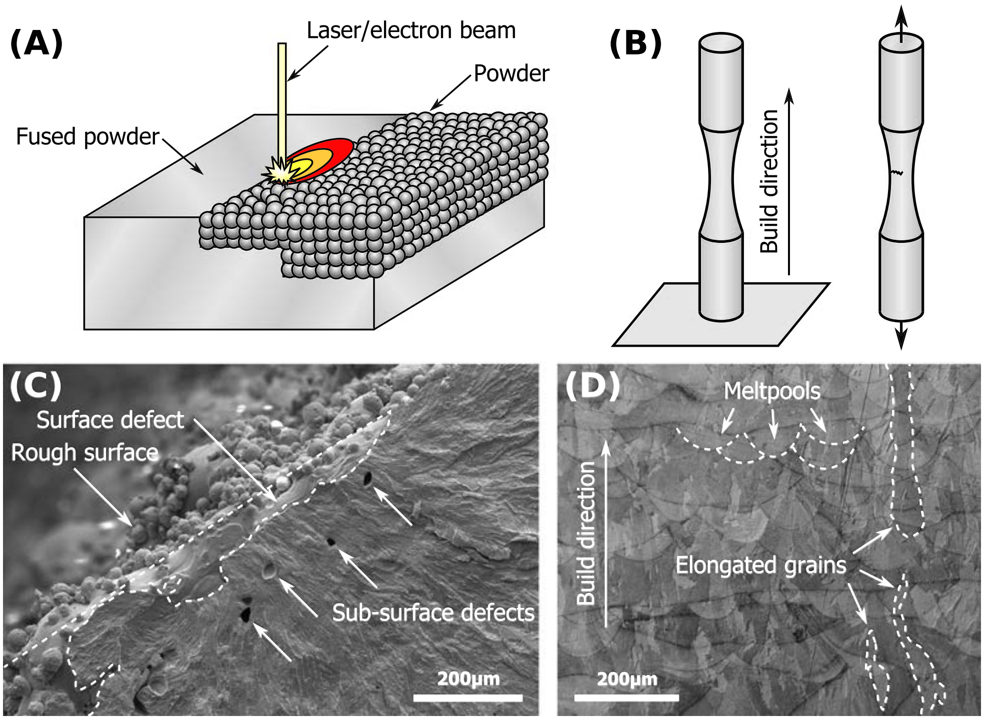

FIGURE 1 (A) Schematic illustration of powder bed fusion process. (B) Schematic illustration of as-built specimen and fatigue loading. (C) Example of SEM image of a fatigue initiation site in AM 316 L (D) Example of microstructure in AM Inconel 718 obtained by means of optical microscope

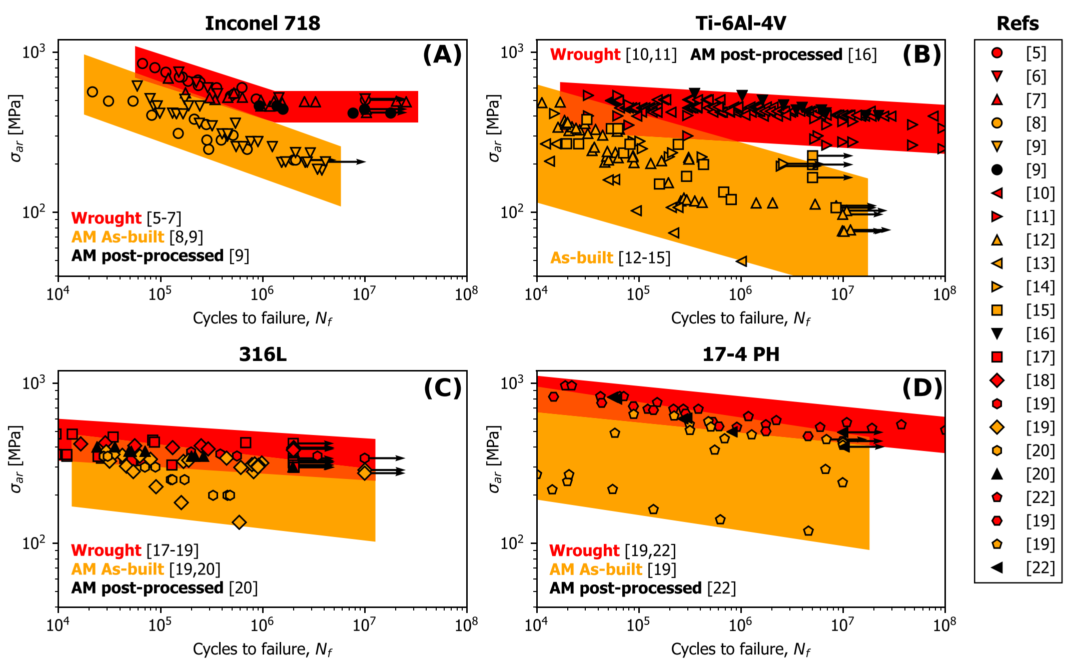

FIGURE 2 Comparison of fatigue data for wrought and AM materials. The data are presented in S-N curves given in stress amplitude (corrected by SWT) versus number of cycles to failure: (A) Inconel 718, (B) Ti-6Al-4V, (C) 316L SS, and (D) 17-4PH SS. (Arrows indicate discontinued tests)

$$\sigma_{ar} = \sigma_{max}\sqrt{\frac{1-R}{2}}.$$

From Figure 2A to D, the general trend is that the fatigue life is reduced when comparing AM as-built with the wrought material. These two cases are the two extremes in terms of fatigue life. The fatigue performance of AM materials can be improved by various post-processing methods, typically involving machining and heat treatments. Machining removes rough surface and defects in the surface region (defects and rough surface can be seen in Figure 1C). Heat treatments can remove residual stresses, alter the microstructure of the material; make the microstructure isotropic and introduce, *eg*, precipitation hardening or hot isostatic pressing (HIP) can close internal pores by applying a combination of pressure and heat.[3] For each material presented in Figure 2 one set of AM materials subjected to post-processing is shown.[9,16,20,22] These materials are post-processed by combinations of the methods mentioned above and achieve the same fatigue strength as wrought materials.

Assessment of the fatigue behaviour of materials containing residual stresses, geometrical defects and anisotropic microstructure is a complicated task. As the geometrical defects are usually reported as the main mechanism for fatigue and fracture, most works dealing with fatigue assessment are aiming to take critical defects into account. There are three main approaches when dealing with fatigue assessment of AM metals: (1) Considering the effects of defects as statistical scatter. This is done by only designing according to the statistics of the fatigue life curve without taking into account the various defects. (2) Taking into account the defects utilising analytically approaches, *eg*, employing fracture mechanics. Here, several works are considering the defect as a crack by assuming the crack size is equal to the $\sqrt{area}$ of the defect and further correlates this value to the hardness in order to predict the fatigue limit.[24-26] (3) Modelling the material with the geometrical defects, usually by means of finite element software. This method can be done based on, *eg*, computed tomography 3D image or surface profile from a confocal microscope, obtaining the geometry, then importing it as a 3D model into a finite element software and applying loads.[27]

The fatigue strength is reduced when comparing as-built AM metals to their wrought counterparts. Post-processing AM metals can give similar fatigue life as wrought materials. Fatigue of AM metals usually initiates from defects deriving for the AM process. When assessing the fatigue behaviour, these defects are taken into account by different methods.

ACKNOWLEDGEMENT

There is no funding to report for the current investigation.

CONFLICT OF INTEREST

The authors of this paper declare that there is no conflict of interest.

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How to cite this article: Solberg K., and Berto F. What is going on with fatigue of additively manufactured metals?, *Mat Design Process Comm*. 2019;1:e84 https://doi.org/10.1002/mdp2.84