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A novel test method for the fatigue characterization of metal powder bed fused alloys

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Abstract

This research addresses the conflicting factors of high costs of fatigue testing and large number of influencing factors that need to be investigated for PBF material and process qualification. Metal powders are remarkably expensive, the PBF production process requires expensive systems and fatigue testing requires multiple specimens (depending the required degree of confidence) to characterize a single material/process combination. In this paper a novel fatigue test method aimed at the peculiar needs of PBF technology is initially presented and fatigue data obtained on Direct Metal Laser Sintering Ti6Al4V are validated against standard rotating bending test results. Then, the link between microstructure and directional fatigue behavior is demonstrated using the present methodology and SLM Inconel 718: namely, the stress direction parallel to build direction is the most severe. Finally, the new test method is applied to the investigation of the fatigue notch sensitivity of DMLS Ti6Al4V in relation to the notch fabrication process. Round notches in specimens with opposite fabrication orientations (i.e. up-skin vs down-skin) resulted in two notch fatigue factors and the up-skin notch has a better fatigue strength than the down-skin notch.

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Keywords: Fatigue, test method, powder bed fusion, Ti-6Al-4V , IN718, notch

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1. Introduction

Additive manufacturing (AM) embraces a number of different processes and materials. The common link is the possibility of producing functional parts of complex geometry directly from a CAD file with minimum material and energy waste. Powder bed fusion (PBF) is one of the seven AM technologies identified by ISO/ASTM 52921 norm and it is mainly aimed at producing parts using metal alloys such as Titanium, Ni-based super alloys, Cr-Co alloys and Al/Si alloys. Alternative acronyms falling under the same denomination are: SLM (selective laser melting), DMLS (direct metal laser sintering) where a laser is the energy source and EBM (electron beam melting) where the source is an electron beam. In PBF, the concentrated thermal energy source selectively fuses thin regions of a powder bed that quickly solidify. After recoating, another layer is selectively melted. The process is repeated until the entire part is built layer-by-layer, see Bandyopadhyay and Bose (2016). To industrialize the process as well as design and qualify the PBF part, material quality has to be controlled and the mechanical properties determined and guaranteed. The PBF technology is penetrating in high-value-added industrial sectors such as aerospace, medical, energy, motorsport etc., where the fatigue performance is a critical selection and design parameter, see Li et al (2016).

One of the major challenges of the PBF technology is the poor fatigue behavior of the rough as-built surfaces. The fatigue behavior of AM parts is dominated by the rough surface rather than by internal defects. The roughness of the as-built AM surface is the result of several mechanisms, for example, balling, stair-stepping, and partially melted powder grains attached to the as-built surface, Gong et al (2013). When a part has a complex geometry it may be too costly to machine all surfaces considering that some of them may not be accessible. So the link between surface quality and fatigue needs to be further understood.

This research addresses the conflicting factors of high costs of fatigue testing and large number of influencing factors that need to be investigated for PBF material and process qualification. Metal powders are remarkably expensive, the PBF production process requires expensive systems and fatigue testing requires multiple specimens (depending the required degree of confidence) to characterize a single material/process combination.

In this paper the novel fatigue test method of Nicoletto (2016) is initially presented along with consideration cost and time savings that motivates its development and application when applied to the qualification of AM process. The quality of the obtained data is verified using standard rotating bending test specimens oriented in the build direction as reference. The experimental evidence of a directional fatigue behavior is in investigated in SLM Inconel 718. The interaction of the fatigue behavior and notch geometry in as-built Direct Metal Laser Sintering (DMLS) Ti6Al4V is originally studied and discussed.

2. Novel fatigue test method for PDF metals

2.1. Motivation and specimen geometry

Fatigue testing of PBF metals to reach process qualification and design data is a remarkable task considering the large number of influencing factors that need to be investigated being the systems now reaching maturity and stability of process quality. Cost and time are the conflicting factors because metal powders are remarkably expensive, the PBF production process requires expensive systems and fatigue testing requires multiple specimens (depending the required degree of confidence) to characterize a single material/process combination.

Planning a fatigue testing campaign involves selection of a standard, specimen geometry, test equipment, test parameters, etc.. Adoption of the fatigue test standards such ASTM involves the adoption of a push-pull specimen geometry, which is then machined to fit to the test machine. Suitable bulky ends are needed to machine the gripping heads without the risk of failure outside the control section. Fatigue testing involves use of a costly servo hydraulic machine or a resonating test machine.

Alternatively, the rotating bending configuration has been recently adopted for fatigue testing of AM metals, Mower and Long (2016). For a comparable minimum cross-section, the specimen can be relatively smaller than the push-pull specimen as shown in Fig. 1. If the as-built condition is to be investigated only the Z-direction can be explored (i.e. axis of the specimen parallel to build direction) with the rotating and push-pull geometry as the two specimen configurations are self-supporting and the surface can be left unmodified. That means that loading is made in the normal axis to the layers. Other orientations of the specimen axis (in the X-Y axis) with loading in the direction parallel to the layers would require support removal and subsequent surface machining.

Recently, this author proposed a new miniature specimen geometry especially aimed at PBF material and process qualification in Nicoletto (2016). It is shown in Fig. 1 where the direct comparison demonstrates that for a similar cross-section the volume of material to be produced is extremely reduced (i.e. the volume of the mini specimen is approx. 1/7 of the rotating bending specimen and 1/78 of the push-pull geometry). Therefore, batches of numerous specimens can be cheaply built in PBF systems in a short time.

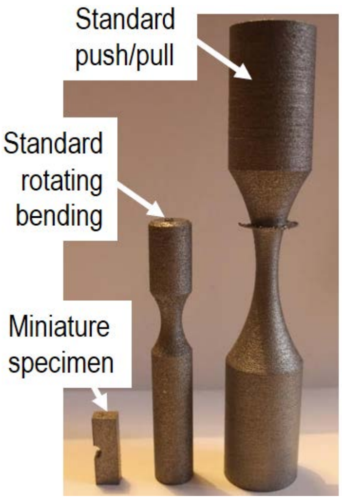

Figure 1 Different specimen geometries used for fatigue testing of AM metals

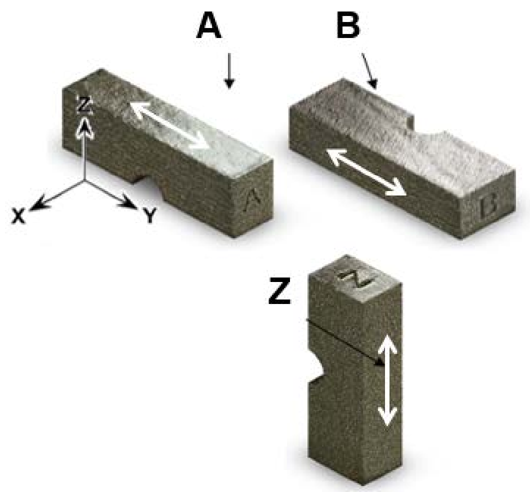

Figure 2 Denomination and positions of the mini specimens on the build plate with evidence of applied cyclic stress on smooth surface

A further advantage of the new specimen geometry compared to the standard geometries is that a a-priori defined material surface is under testing. Therefore, to investigate anisotropic fatigue response, specimens can be oriented and built as desired with respect to the Z-direction as shown in Fig. 2. The specimen loading condition is plane cyclic bending applied by a modified Schenck-type machine, see Fig. 3.

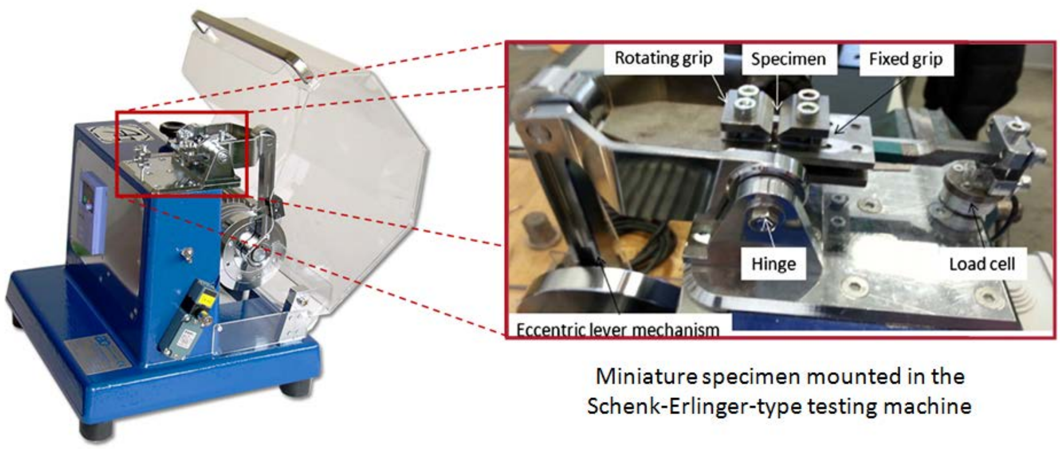

Figure 3 Cyclic plane bending fatigue testing machine with detail of mini specimen in the grips.

In Fig. 2 arrows show the directions of the applied cyclic stress on the smooth as-built surface and how it relates to the layer-wise material microstructure. Three different orientations of the cyclic applied stress can be defined with respect to the PBF material building direction, namely Type A where the stress is on the top surface perpendicular to the build direction, Type Z (or C), where the stress is parallel to build direction and perpendicular to the layer build-up and Type B where the stress perpendicular to the build direction and parallel to the layer build-up.

The role of the three different stress orientations with respect to build were investigate in DMLS Ti-6Al-4V obtained according to two process conditions and post processing heat treatments, Bača et al (2016). It was found that in one case, the directionality was relevant with C specimens showing the lowest fatigue strength and Type A the highest. In the second case, the three orientations were substantially equivalent in terms of fatigue strength. More experimental evidence will be presented in a subsequent section.

2.2. Validation

The new specimen geometry and fatigue testing method has been validated adopting the following approach: first, the rotating bending configuration with an equivalent section modulus of the mini specimen was selected and used to build specimens of DMLS Ti-6Al-4V. A batch of type Z mini specimens was also built in DMLS Ti-6Al-4V. Both sets of specimens were heat treated and their surfaces left as-built.

Second, the fatigue tests on the two types of specimens being conducted under different load ratios (R=0 in mini specimens and R=-1 in the rotating bending specimens) were made comparable using an equivalent stress amplitude $\sigma_{a,eq}$ at R = -1 definition on the basis of the Haigh relationship for mean stress effect on fatigue, see Juvinall and Marshek (2012). When R=0, that is when the stress amplitude σ_a is equal to the mean stress σ_m, the Haigh relation is given by

$$\sigma_{a,eq}=\sigma_a/(1-\sigma_m/R_m) \quad (1)$$

where σ_a is the stress amplitude of the fatigue test at R=0 and R_m is the tensile strength of DMSL Ti6Al4V.

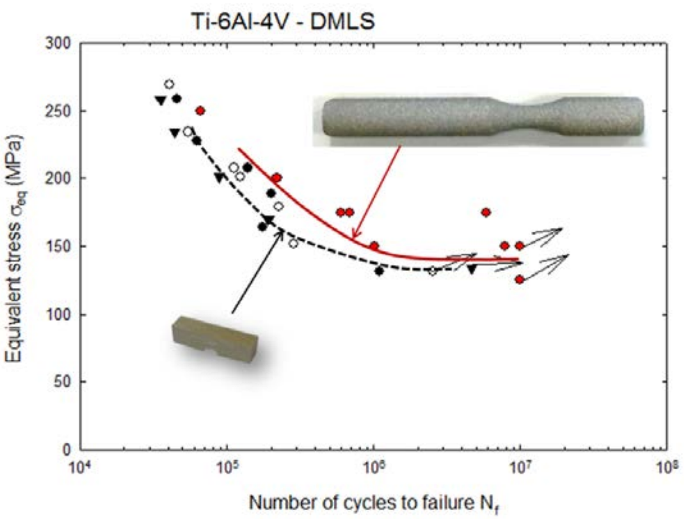

Figure 4 Fatigue curves for DMLS Ti-6Al-4V for two specimen geometries.

Third, the results of the fatigue experiments on the two sets of specimens were directly compared in the same (equivalent stress amplitudes vs number of cycles) plot of Fig. 4, since the material of the two types of specimens was identical, the size effect between the two geometries was very similar by design, the roughness effect was identical as the process parameters and the load direction with respect to the material layup was the same, the loading frequency of the two test machine was similar (20 Hz vs 50 Hz).

Inspection of the plot of Fig. 4 shows that the two sets of specimens have very similar trends with a slight underestimate of the life in the case of the mini specimens. While the motivation behind the test method was the reduction of costs and flexibility of use at the expense of a standardized procedure, the similarity in the results confirm that the new approach yield representative results and can be used for investigating the many process and material and finishing parameters involved in the PBF technology. If a standard test result is then needed for a particular combination of material and process parameters, then the standard procedure can be adopted.

3. Application of the novel fatigue test method

3.1. Directional fatigue behavior of SLM Inconel 718

Three sets of mini specimens with the three orientations specified in Fig. 2 were fabricated using micrometric Inconel 718 powder (particle size range 24-53 μm) and the SLM Renishaw AM250 system (Renishaw, UK). Renishaw-recommended heat treatment was performed in a vacuum furnace at the end of the fabrication phase with the aim of reducing residual stresses and optimizing mechanical performance by precipitation hardening. Information on heat treatment and material microstructure is given in Konečná et al. (2016).

The fatigue tests results of SLM Inconel 718 obtained from specimens oriented in the three directions and with smooth as-built surfaces are shown in Fig. 5. For comparison purposes, note that the data are presented in terms of stress amplitudes σ_a with experiments run under a load ratio R = 0, while fatigue data at this load ratio in the literature are reported in terms of max stress σ_{max} (i.e. $\sigma_{max} = 2\ \sigma_a$).

Inspection of Fig. 5 shows a limited scatter and a well-defined behavior of the three sets of specimens: namely Type A and B specimens are similar with a slight prevalence in strength of the Type A ones. Type Z specimens show the lowest fatigue strength with a reduction of approx. 25-30%. This directional behaviour is similar to previously observed behaviour of DMLS Ti-6Al-4V after low temperature annealing (380°C for 8 hrs) and reported elsewhere, see Nicoletto (2016). The present experiments demonstrate the presence of a directional fatigue behavior of as-built SLM Inconel 718 even after an optimized heat treatment.

The bending loading and rough as-built specimen surface, typical of this test method, tends to activate surface or-near-surface initiation mechanisms in contrast with to cyclic tension of machined specimens may reveal internal defects. Presently under study is the morphology of the surface roughness.

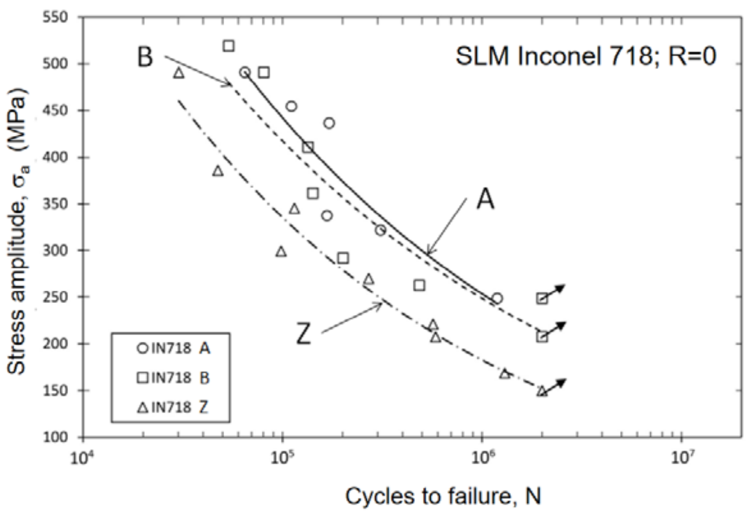

Figure 5 Directional un-notched fatigue behavior of as-built & heat treated SLM Inconel 718 obtained with three sets of mini specimens

3.2. Directional notch effect in fatigue of DMLS Ti6Al4V

The fatigue properties of smooth specimens with rough as-built surfaces of DMLS Ti6Al4V have been recently discussed for example by Wycisk and al (2013), Edwards and Ramulu (2014), Mower and Long (2016), Li at al (2016). In practice, however, few metal AM components are expected to have simple geometries without any corners or radii that would act as stress concentrations. Therefore, the combined effect of a rough as-built surface and a geometrical notch needs to be established to enable relevant fatigue predictions for structural parts.

Very recently Kahlin et al (2017) have presented possibly the first study on the fatigue properties of as-built Ti6Al4V affected by a geometrical notch. A specimen geometry with a semi-circular notch with a 0.85 mm radius and a theoretical stress concentration factor $K_t = 2.5$ was used. The loading was cyclic tension with R = 0.1. Both the laser melting (LM) and electron beam (EB) melting technologies were used to produce specimens with either a rough as-build surface or a machined surface in the Z-direction. The combined effect of a rough as-built surface and a geometrical notch gave a fatigue notch factor, K_f, of 6.15 for LM process and 6.64 for EB process, with K_f defined as the ratio of the fatigue limit of un-notched geometry with polished surface and the fatigue limit of notched geometry with as-built surface.

In parallel to Kahlin et al (2017), this author has been using the mini specimen geometry to investigate the directional notch fatigue effect of as-built DMLS Ti6Al4V. Here the first experimental evidence is presented. Figure 6 shows the specimen type A and the different possible combinations of fabrication and testing conditions. The unnotched Type A specimen configuration means that the mini specimen was oriented with respect to build direction as shown and the cyclic bending loading applied cyclic tensile tests on the top flat surface. Type A-notched specimen configuration shares the same orientation with respect to build as the previous but the bending loading is inverted to apply cyclic tensile tests at the notch root with a stress concentration factor $K_t = 1.56$. Type A+ notched configuration is characterized by the opposite specimen orientation with respect to build compared to the two previous cases and the bending loading applies a cyclic tensile tests at the notch root with a stress concentration factor $K_t = 1.56$. The elastic stress analysis of the size of 90% maximum stressed volume revealed that the volume of the notched specimen is about 4% of the volume of the unnotched specimen, therefore the damage initiation is fundamentally controlled by the surface layer.

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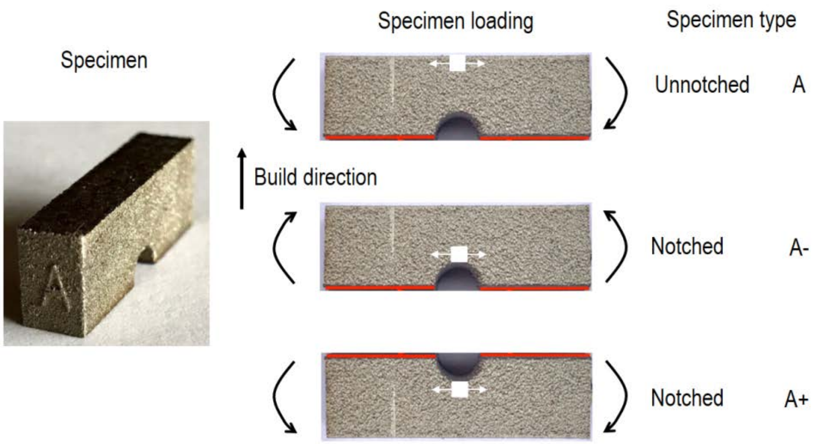

Figure 6 View of a mini specimen and definition of specimen type in dependence of direction of bending loading and build orientation. White arrows show points under tensile cyclic stress where fatigue crack started.

Three sets of as-built DMLS Ti6Al4V mini specimens as defined in Fig. 6 were produced and heat treated and then tested in fatigue under a load ratio R=0. The test results in terms of max nominal bending stress vs number of cycles are plotted in Fig. 7. The data appear well-behaved with a reduced scatter. They define trends which allow the experimental determination of an effective notch factor K_f of the two notched configurations Type A+ and Type A- using the unnotched response of Type A as the reference.

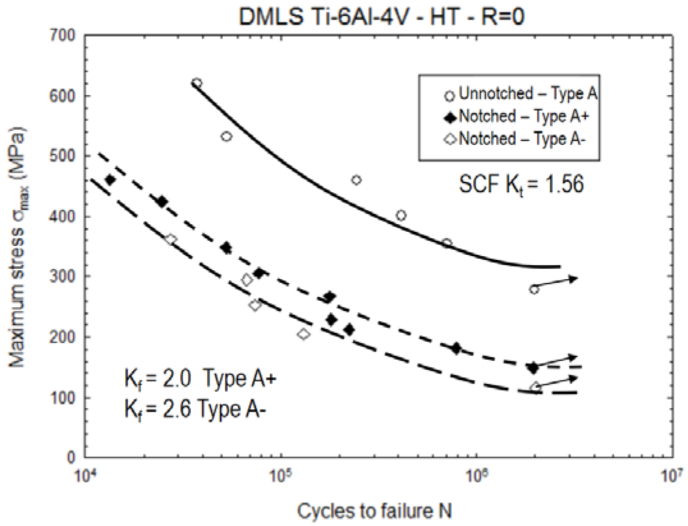

Figure 7 Notch fatigue behavior of the three types of as-built & heat treated DMLS Ti-6Al-4V specimens and bending loading (load ratio R=0; K_t =1.56).

Adopting the classical definition of K_f as the ratio of the smooth fatigue strength and notch fatigue strength, Type A+ configuration is characterized by K_f = 2.0 and the Type A- configuration by K_f =2.6 for the as-build surface condition. These are possibly the first results of this kind where the notch surface quality that depends on specimen orientation is quantified. The surface quality, i.e. roughness, depends on the up-skin vs down-skin generation of the notch and the step-wise generation of the theoretically semicircular notch geometry.

Interestingly, both K_f values are larger than the theoretical K_t value of the notch geometry, in contradiction with classical results for fatigue tests in conventional materials and specimen geometries, see Juvinall and Marshek (2012). A possible motivation is in the difference between the smooth theoretical geometry and the rough PBF surface of the present notches that introduces a technology-dependent contribution to the fatigue notch effect.

Alternatively, Kahlin et al. (2017) estimated a value of K_f = 6.1 for LM and slightly more for EB as he adopted a comprehensive notch effect K_f defined as the ratio of the fatigue strength of the smooth (K_t=1) & polished Ti64 and the fatigue strength of the notched as-built Ti64. If the same smooth & polished fatigue strength of 800 MPa is assumed here, a global K_f = 5.3 for specimen Type A+ and K_f =6.15 for specimen Type A- are determined. They are coherent with Kahlin's K_f = 6.1 considering that his stress concentration factor was K_t = 2.5 and the present is K_t = 1.56. Furthermore, he investigated only the specimen orientation parallel to build while here the orientation of the notch with respect to the fabrication process was of interest.

4. Conclusions

The fatigue behavior of Ti6Al4V alloy produced by the DMLS technology and the Inconel 718 alloy produced with SLM technology was investigated using an innovative test method especially developed for PBF metals. Initially the new test methodology was presented and validated by direct comparison with data on as-built and heat treated Ti6Al4V alloy obtained with standard rotating bending specimens.

The methodology was then applied to heat treated Inconel 718 SLM where the original experimental results showed a directional fatigue behavior that can be attributed to the anisotropic (columnar) grain structure typically produced by the SLM process. The most critical orientation in fatigue is the stress direction parallel to the build direction with a noticeable reduction compared to the other two directions examined.

Finally, the new test methodology was applied to the study of the fatigue notch effect of heat treated DMSL Ti6Al4V in relation to the notch fabrication process. Round notches in specimens with opposite fabrication orientations (i.e. up-skin vs down-skin) were tested and the notch fatigue factor K_f experimentally determined with respect to the as-built smooth fatigue strength. The two notch fabrication orientations resulted in two notch fatigue factors and the up-skin notch has a better fatigue strength than the down-skin notch. To the author's best knowledge, this is the first published result of this kind.

Acknowledgements

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