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Influence of as-built surfaces on the fatigue behavior of AlSi10Mg parts obtained by laser powder bed fusion

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Abstract

In the recent years the industrial expectations about metal additive manufacturing technology have exploded with an increasing focus on materials and components qualification. Qualification and certification of L-PBF components for structural application require an understanding of the links among technology, materials and fatigue performance. One dominating factor affecting fatigue strength is the as-built surface quality of the -PBF parts because surface modification would add unacceptable high costs is impossible due to geometrical complexity. The present contribution, being aimed at L-PBF applications for the automotive and aerospace sectors, deals with the AlSi10Mg alloy, the most relevant and studied Al-alloy, produced with an industrial grade L-PBF system operated by an established AM service provider. The overall objective was the determination of the link between the as-built surface quality, i.e. technology-dependent, and the fatigue data required for the structural integrity assessment of L-PBF parts. An innovative fatigue test methodology using a miniature specimen geometry was applied to the efficient investigation of L-PBF technology-dependent factors on the fatigue behavior of AlSi10Mg alloy.

Keywords: Part integrity, fatigue, test method, powder bed fusion, AlSi10Mg

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1. Introduction

Metal additive manufacturing technologies have been available to industry for many years, although interest, investments and expectations of especially the powder-bed-fusion (PBF) technology have escalated in demanding sectors, such as aerospace, motorsport, biomedical, energy production etc. during the last 5 years.

However, the level of acceptance of a new technology is different in dependence of the specific requirements of the sector considered. Technology Readiness Levels (TRLs) are typically used to measure the levels of technology implementation in industry. Fig. 1 shows the TRL of metal additive manufacturing in four industrial sectors, Roland Berger (2013). The dental sector and mold production sector are characterized by a full acceptance for serial production deployment (TLR 9-10) where the well-known application drivers of part customization and production of small lots of high-value parts are fully exploited. The level of penetration of metal additive manufacturing in two other critical industrial sectors, such as aerospace and automotive, is considerably lower (TLR 4-7) because of a number of application challenges such as high part cost, low productivity, lack of standardization, insufficient technical knowledge and design skills equivalent to what is available for traditional metals, etc. are hampering its full implementation.

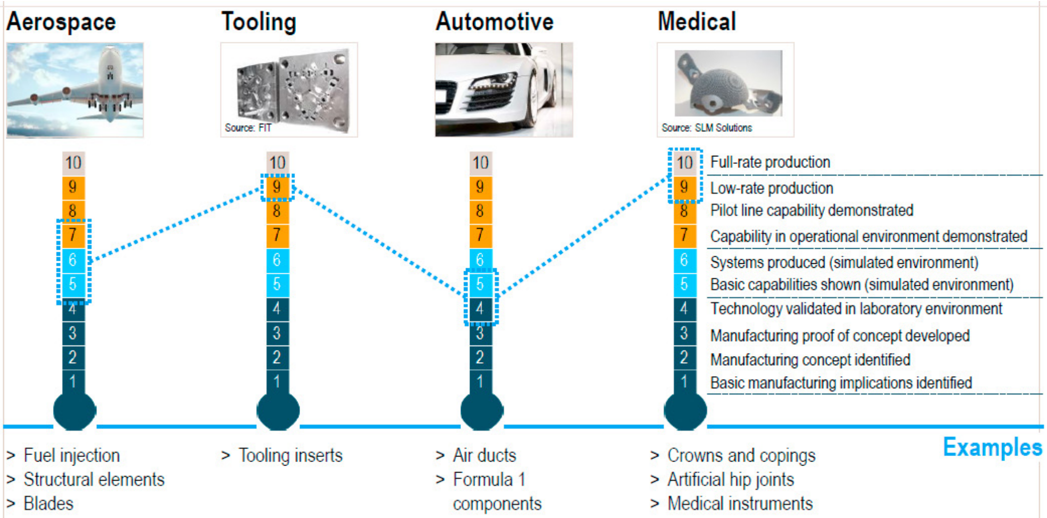

Fig. 1 – Technology Readiness Levels of different industrial sectors for serial production (according to Roland Berger)

A key aspect of interest for this contribution is the technical knowledge for the design and qualification of critical load-bearing metal PBF parts for the automotive and aerospace sectors. Therefore, the established AlSi10Mg alloy produced with an industrial grade L-PBF system operated by an experienced AM service provider is studied. The overall objective is the determination of the link between the as-built surface quality, i.e. technology-dependent, and the fatigue data required for the structural integrity assessment of L-PBF AlSi10Mg parts. Therefore, an innovative fatigue test methodology using a miniature specimen geometry is applied to the efficient investigation of L-PBF technology-dependent factors on fatigue behavior.

2. On the qualification of PBF aluminum parts

Design of structural parts in the automotive and aerospace is especially concerned with fatigue. In addition, actual parts may have as-built surfaces for two important reasons: i) unacceptable high cost of finishing; ii) geometrical complexity preventing surface modification. Therefore, qualification of L-PBF parts for structural application in industry requires an understanding of their fatigue performance in the presence of the realistic as-built surface quality, Yadollahi and Shamsaei (2017). This section initially points out specific features affecting the fatigue behavior of a typical PBF part. Then a literature review focused L-PBF ALSi10Mg will describe the complex interrelation between surface quality and fatigue behavior.

2.1. Peculiar features of PBF parts

The features of a metal part that are distinctive of the PBF manufacturing system are examined considering an actual part (i.e. the scaled version of a lower suspension arm) after a preliminary optimization phase that arrived to the complex geometry show in Fig. 2. Actual parts were built in an SLM Solution system using high quality AlSi10Mg powder of controlled granulometry. The printing parameters were those defined by the experienced service provider Beam-It. After fabrication, the parts were left in the as-built state (i.e. no heat treatment). The part has a structural function as it is connected through two pins and a spherical seat to the adjacent parts of a vehicle suspension. Therefore, a scheme of the loading condition and restraints is also shown in Fig. 2. The service loads in a suspension are typically variable in time. Therefore, its fatigue response is critical for the part integrity assessment. Finally, Fig. 2 shows also the part on the build plate of the L-PBF system. The fabrication phase was preliminarily investigated using a process simulation software. It led to a tilted fabrication in order to optimize the required supports and control the part distortions. After fabrication supports are eliminated and the surfaces are left in the as-built quality.

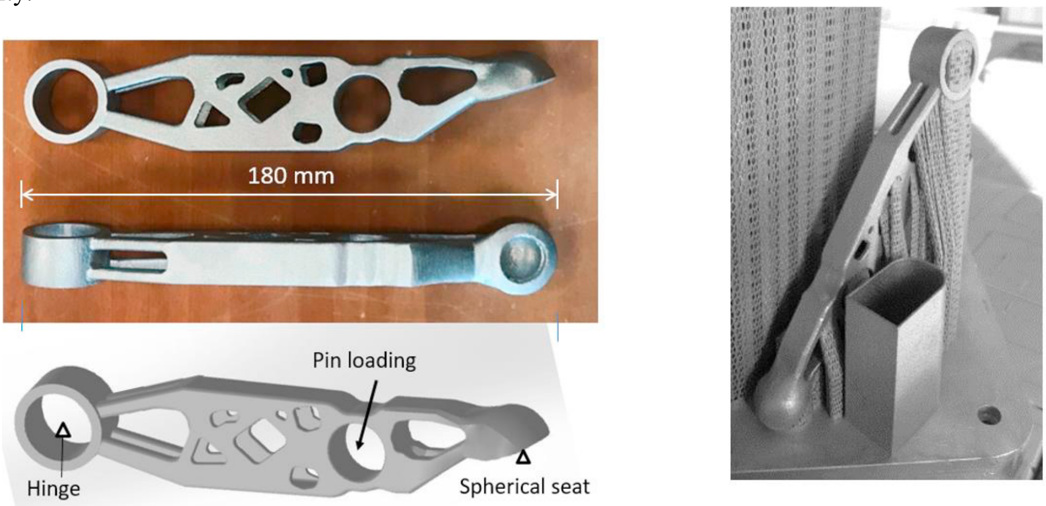

Fig. 2 – (Top left) Scaled lower suspension arm, (Bottom left) structural loading scheme, (Right) L-PBF fabricated part (curtesy of Beam-It)

Having clarified the part geometry, loading and fabrication process, Fig. 3 shows peculiar features affecting the structural integrity of the L-PBF part. These features should be of concern when generating fatigue data to support the design phase. However, most published fatigue studies of PBF metals involve machined specimens, Tang and Pistorius (2019). First of all, Fig. 3a shows the part with traces of the layered structure. Five part details are identified, each introducing a specific feature, namely: 1) surface at an angle with respect to the build direction. The orientation defines an up-skin surface; 2) tilted surface oriented down-skin; 3) and 4) identify geometrical notches, up-skin and down-skin respectively, where stress concentration develops under load; 5) curved surface that for its radius of curvature and orientation need supports (see Fig. 2). After fabrication, supports are removed but locally the material structure may be affected.

Fig. 3b and 3c schematically define the interaction of the L-PBF technology and the part surface quality. Fig.3b shows a nominally flat (i.e. broken line) tilted up-skin surface. The layer-thickness-dependent segmentation inherently induces a surface roughness that affects fatigue crack initiation. In addition, shown in dark gray, layer contouring contributes on near-surface material heterogeneity. Near-surface defects observed in parts may occur at the hatch-contour interface. The curved part surface of Fig. 3c is obtained by layer-wise approximation with geometrical accuracy that depends on the position along the nominal contour. This effect could be further affected by the surface orientation: in Fig. 3c the surface is up-skin but it could be also down-skin with an associated increase in roughness and loss in geometrical accuracy. Down-skin surfaces with a large radius of curvature are typically supported.

The peculiar part features described in Fig. 3 are dependent of the L-PBF printing strategy and process parameters. Together with the as-built roughness, they all affect the part surface and therefore strongly influence the part integrity when subjected to fatigue loading.

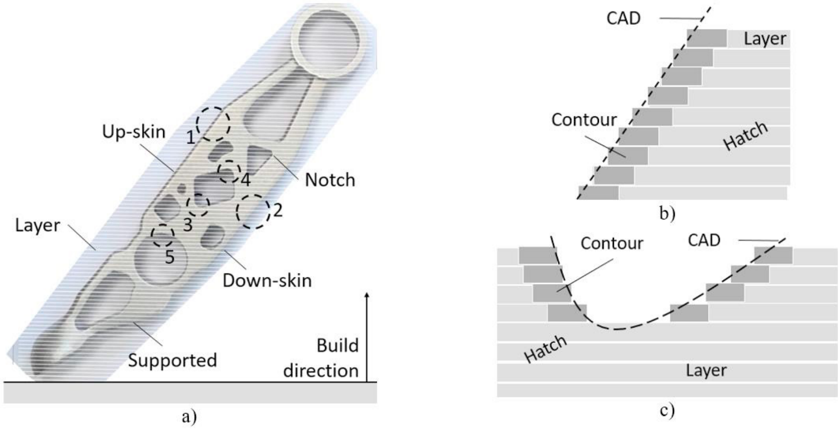

Fig. 3 – a) Details of the L-PBF part b) scheme of tilted up-skin surface c) scheme of a curved up-skin notch

2.2. Fatigue behavior of L-PBF AlSi10Mg

The traditional material qualification approach used with standard manufacturing processes (i.e. forging, casting etc.) where the material is assumed homogeneous in space (within the part) and time (from batch to batch). So material and process is examined and qualified separately and independently of the part. The influence of actual part surface quality on fatigue is then included via a roughness-based influence factor originated for historical testing of steels, Juvinall and Marshek (2011).

Implicitly adopting the traditional approach, fatigue testing of L-PBF metals have been using standard smooth specimens with machined and polishes surfaces. This traditional approach is evidently inadequate when part integrity assessment should deal the peculiar features characterizing a L-PBF part listed above. An original experimental approach has been proposed by Nicoletto (2016) to address these technologically-specific issues and is applied to L-PBF AlSi10Mg in a subsequent section.

Before presenting the original data generated in this study, a brief overview of selected literature is given to assess the current knowledge of the fatigue behaviour of L-PBF AlSi10Mg. Fatigue resistance in these metals is influenced by the presence of internal defects, such as porous, un-melted regions and surface roughness because they activate stress concentrations that promote crack formation and ultimately failure, Abdulkhair et al (2019). The hot isostatic pressing (HIP) treatment (for example 2 h @ 520 °C and 100 MPa) was proposed to eliminate the influence internal defects. In the case of L-PBF parts with extremely fine microstructure, high temperature HIP treatment may lead to microstructure coarsening and significantly decreased mechanical properties.

On the other hand, a post fabrication heat treatment of L-PBF parts as the classical T6 is proposed to increase the mechanical properties. Aboulkhair et al. (2016) considered the effect of surface roughness and thermal treatment on the fatigue life of AlSi10Mg alloy reporting that the effect of T6 heat treatment was more significant than surface machining. Brandl et al. (2012) also concluded that the fatigue resistance of L-PBF AlSi10Mg specimens was positively affected by the T6 heat treatment especially when combined with a final surface finishing. The effects of the build plate temperature and building direction were significantly lower. However, other studies showed that the as-built AlSi10Mg outperformed the HIPed and heat treated counterpart, Uzan et al (2017).

Since the present study investigates the fatigue behaviour of L-PBF AlSi10Mg in the as-built state (i.e. no HIPing, no post fabrication heat treatment) with the as-built surface, two contributions are especially relevant for the subsequent discussion. Mower and Long (2016) adopted rotating bending testing of vertically built specimens and determined significantly lower fatigue resistance of as-built PBF AlSi10Mg compared to conventional machined Al6061 alloy specimens. The fatigue behavior was not sensibly improved by surface finishing as their metallographic observation revealed the existence of pores and microstructural faults distributed throughout the material volume. As a consequence, the surface finishing improved the surface roughness but revealed the sub-superficial defects that became new surface notches. Uzan et al (2017) investigated the fatigue resistance, hardness and tensile stress of L-PBF AlSi10Mg specimens printed in the Z direction and heat treated under various conditions. The highest fatigue resistance was obtained for as-built machined and polished specimens tested in rotating bending. Specimens after stress-relieved and HIP treatment at 500 °C displayed the lowest fatigue resistance due to microstructure coarsening and reduced mechanical properties. Fig. 2 collects fatigue data extracted by Mower and Long (2016) and Uzan et al. (2017) and Tab. 1 links trend lines to material and surface conditions. Fig. 2 show the wide fatigue performance range L-PBF AlSi10Mg. The upper-limit in fatigue performance is represented by the wrought 6061-T6 alloy tested with polished surfaces.

Table 1 Information about fatigue curves of Fig. 4

	Material	State	Specimen surfaces	Ref.
U1	L-PBF AlSi10Mg	Stress relieved	Machined & polished	Uzan et al (2017)
U2	L-PBF AlSi10Mg	As-built	Machined	Uzan et al (2017)
U3	L-PBF AlSi10Mg	As-built	Machined & polished	Uzan et al (2017)
U4	Al 6061	Wrought T6	Machined & polished	Uzan et al (2017)
M1	L-PBF AlSi10Mg	As-built	As-built	Mower and Long (2016)
M2	L-PBF AlSi10Mg	As-built	Polished	Mower and Long (2016)
M3	Al 6061	Wrought T6	Machined	Mower and Long (2016)

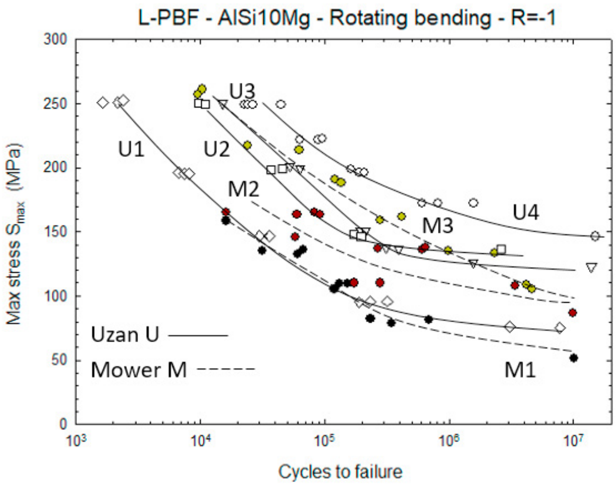

Fig. 4 –Fatigue data of L-PBF AlSi10Mg in different conditions from literature

3. Experimental program

3.1 Innovative fatigue testing using miniature specimens

Fatigue performance is a critical parameter in material selection and part design for structural applications and it typically requires extensive testing and long testing times. In the case of the PBF technology, 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. All these factors negatively affecting fatigue testing costs motivated the author's proposal of a new test methodology based on the use of the miniature specimen geometry shown in Fig. 3 along with the standard rotating bending and standard push/pull specimens. They have comparable reference cross sectional area properties but production cost is drastically reduced. Therefore, batches of miniature specimens can be conveniently built in L-PBF systems in a short time. A validation of the mini specimen geometry for fatigue testing was initially reported by Nicoletto (2016) and it now routinely used, see for example Nicoletto (2019). An additional advantage of the mini specimen geometry compared to the standard geometries of Fig. 5 is that the directional fatigue response with respect to the build direction can be investigated orienting the specimens as desired. Fig. 5b shows three specimens with the long dimension oriented perpendicular and parallel to the build direction.

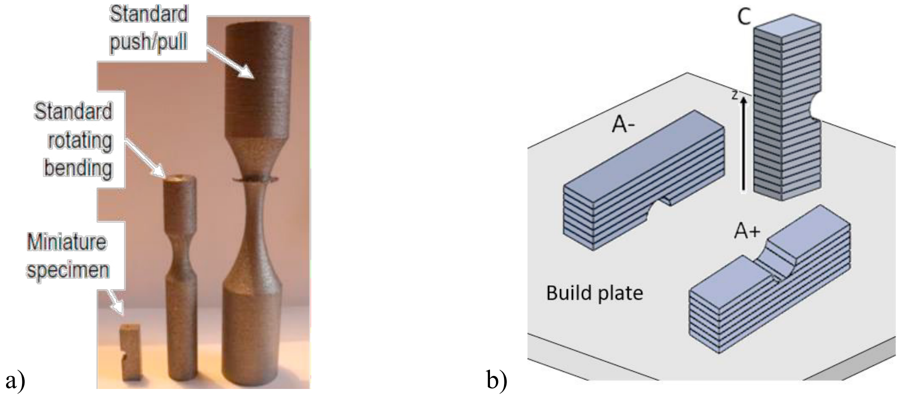

Fig. 5 – a) Size comparison of miniature vs. standard specimen geometries; b) vertical (type C) and two types of horizontal (Type A- and Type A+) miniature specimens on the build plate.

The mini specimen is typically tested in a electromechanical machine applying a plane cyclic bending with a load ratio R=0 at 25 Hz, Nicoletto (2016). Tests are interrupted when the continuously monitored load decreases 10% below its initial value or when 2 10^6 cycles are reached. So the number of cycles to failure are related to the crack initiation stage. Further, the original specimen geometry of Fig. 5b allows the investigation of either the unnotched fatigue behavior (i.e. flat surface under cyclic tensile stress) or the notched fatigue behavior (i.e. notch root under cyclic tensile stress) depending on the direction of applied bending moment.

3.2 Material and specimen fabrication

The AlSi10Mg alloy powder used to fabricate the specimens was characterized by spherical powder particles of predominant diameter range from 25 to 45 µm. All fatigue specimens were fabricated using the Selective Laser Melting technology with layer thickness of 50 µm in a SLM Solutions 280^{HL} system, (SLM Solutions. Germany). This system uses a 400 W Yb-fiber laser unit with a wavelength of 1075 nm. Metal processing was in a protective Argon atmosphere and a chamber temperature of 80 °C. Process parameters used were according to system producer recommendation and system operator validation (Beam-It, Fornovo Taro, Italy). Three sets of fatigue specimens oriented as in Fig. 5b for a total of about 50 specimens were fabricated to investigate both the smooth and the notched fatigue behavior of L-PBF AlSi10Mg. After removal from the build plate, most specimens were tested in the as-built surfaces. However, a small group of Type C specimens were post-processed removing about 200 µm by grinding and polishing from the three flat surfaces (not the notched surface) to investigate surface modification.

4. Results and discussion

This section is organized as follows: the directional smooth and notched fatigue data of L-PBF AlSi10Mg are presented first, the influence of test methodology and surface finish on the fatigue results is discussed next.

4.1. Smooth fatigue behavior

Fig. 6 shows the significant directionality of the smooth fatigue behavior of the present as-built SLM AlSi10Mg without heat treatment and with as-built surfaces. Material scatter appears limited in all cases and the trend curves are well defined. If the Type C orientation (i.e. long axis parallel to build) is considered as reference, Type A+ orientation (i.e. long axis perpendicular to build) demonstrates a similar behavior. On the other hand, Type A- orientation is characterized by a much higher fatigue performance. Fatigue strength at 2 10^6 cycles can be estimated in about 100 MPa for Type A+ and C and about 160MPa for Type A-.

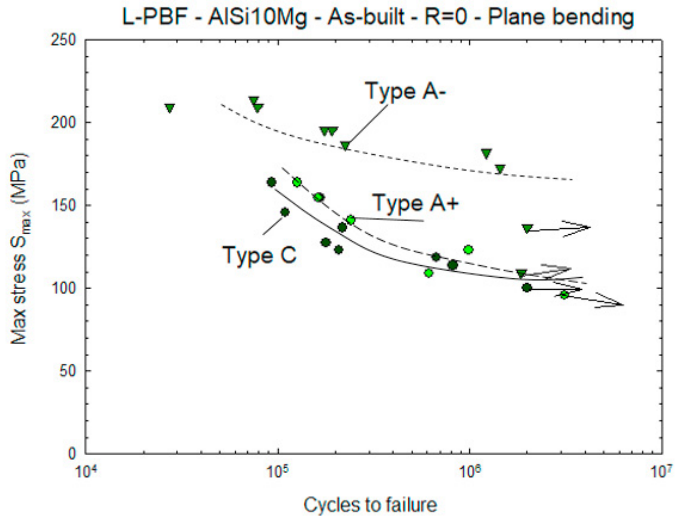

Fig. 6 – Smooth fatigue behaviour of as-built L-PBF AlSI10Mg when miniature specimens are oriented according to Fig. 5b

While the flat surface quality of the three specimen types is different, unpublished studies on T6-heat-treated SLM AlSi10Mg of the same specimen geometry and orientations and with as-built surfaces showed a much reduced difference in fatigue response between Type C and Type A- specimens. Therefore, this novel evidence of strong directional fatigue behavior is attributed to SLM-generated residual stresses: the evidence of Fig. 6 suggests i) strong compression in the top layer of Type A- specimens ii) limited longitudinal residual stresses in Type C specimens. Process simulation tools are currently used to gain support for this hypothesis.

4.2. Notch fatigue behavior

The notch fatigue behaviour of as-built SLM AlSi10Mg without heat treatment is shown in Fig. 7. The nominal stress of the miniature specimen which is characterized by a stress concentration factor K_t = 1.63 is used to plot the fatigue data. The lowest fatigue strength is determined for the Type C specimens. However, the fatigue response of the other two specimen types is inverted compared to the smooth test results of Fig. 6.

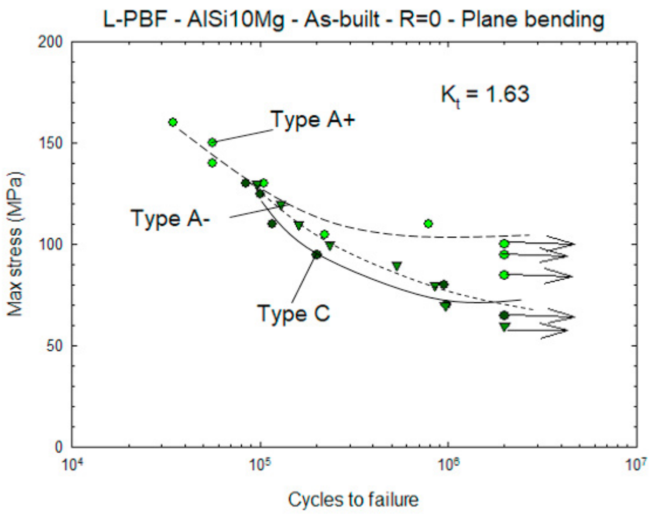

Fig. 7 –Notched fatigue behaviour of as-built L-PBF AlSi10Mg when miniature specimens are oriented according to Fig. 5b

Namely, Type A- specimens characterized by a down-skin notch show significantly lower fatigue strength than the Type A+ specimens with an up-skin notch while behaving similarly to Type C specimens. Notched fatigue strength at 2 10^6 cycles can be estimated in about 65 MPa for Type A- and Type C specimens and about 100 MPa for Type A+ specimens.

Therefore the notch fatigue factor K_f (i.e. ratio of the unnotched/notched fatigue strengths, Juvinall and Marshek (2011)), can be estimated as $K_{f,C}$=1.54 for Type C. A notch sensitivity q = ($K_{f,C}$ - 1)/ (K_t - 1) = 0.86 is thus determined, a value for an as-built vertical semi-circular notch with a 2-mm-radius. On the other hand, application of the same definition to other notch orientations would give the following estimates: $K_{f,A-}$ = 2.46 and $K_{f,A+} \cong 1$, respectively. These values cannot be predicted using the classical notch fatigue approach and are related to the complex interaction of residual stresses and notch surface quality of the L-PBF fabrication of AlSi10Mg. These results demonstrate that complex part details such as those of Fig. 3 cannot be checked against fatigue failure using conventional approaches and tools. Original experimental evidence as that presented here may support the development of suitable fatigue assessment methods.

4.3. Influence of test method and surface finish on fatigue behavior

The novel fatigue test methodology using the miniature specimen geometry under the cyclic plane bending has been validated before by direct comparison against standard test results from the literature. Materials considered were Ti6Al4V in Nicoletto, (2016) and Inconel 718 in Nicoletto (2019). The same type of direct correlation is carried out here for as-built SLM AlSi10Mg. The valuable data by Mower and Long (2016) obtained using a standard smooth geometry under rotating bending (i.e. stress ratio R = -1) and specimen axis parallel to build are presented in Fig. 8.

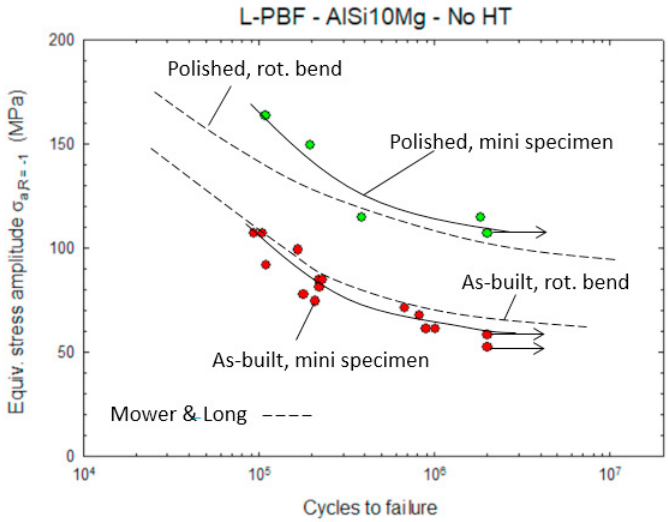

Fig. 8 –Fatigue behaviour of L-PBF AlSi10Mg with as-built and with polished surfaces. Data obtained with the present test method and with a standard test method (Mower & Long 2017) are compared.

The present fatigue test method is characterized by specimens under cyclic bending with a stress ratio R= 0. Therefore, a conversion to an equivalent stress amplitude at R=-1 based on the Haigh linear formula was adopted. It was already proved successful in Ti alloys. The equivalent stress amplitude at R=-1 $\sigma_{a,R=-1}$ is readily determined from stress amplitude at R=0 using the following equation

$$\sigma_{a,R=-1} = \sigma_{a,R=0} /(1-\sigma_{m,R=0})/R_m \quad (1)$$

where $\sigma_{a,R=0} = \sigma_{m,R=0} = 0.5\ \sigma_{max,R=0}$ and ultimate strength R_m = 440 MPa was determined with tensile teste of standard specimens. Fig. 9 shows the good comparison of the present data for the Type C specimens (also with long axis parallel to build) after conversion according to Eq. 1, and Mower's data. A reference fatigue strength at 2 10^6 cycles $\sigma_{a,R=-1} \cong 60$ MPa is determined

Surface finish of the as-built L-PBF parts is known to significantly improve their fatigue performance because fatigue crack initiation is very sensitive to surface quality. Therefore, Type C specimens were polished and tested in fatigue in the same test apparatus and under the same R=0 ratio. Fig. 8 shows the fatigue trend obtained experimentally: the fatigue strength at 2 10^6 cycles increases from $\sigma_{a,R=-1} \cong 60$ MPa to $\sigma_{a,R=-1} \cong 110$ MPa. The fatigue strength increase is not unexpected. Interesting here is the comparison of the data obtained with polished miniature specimens vs. polished standard specimens reported by Mower and Long (2016): Fig. 8 confirms that the novel test methodology yields coherent fatigue results with standard test methods even after surface modification.

5. Conclusions

The interaction of complex part geometry, L-PBF technology and constraints in post fabrication surface finishing generates new problems for the design and qualification of critical load-bearing metal PBF parts for the automotive and aerospace sectors. The fatigue behavior of L-PBF AlSi10Mg was originally investigated to contribute to the development of specific know-how. The following conclusions were reached:

- L-PBF AlSi10Mg without post fabrication heat treatment and with as-built surfaces shows a directionality of the smooth fatigue behavior that is attributed to residual stresses.
- The notch fatigue behavior of L-PBF AlSi10Mg shows direction-dependent trends that cannot be explained with conventional concepts and models
- The positive influence of surface polishing was demonstrated to increase significantly the fatigue strength (about 100%) with respect to the as-built surfaces.
- When applied to L-PBF materials, the new test method using miniature specimens provides useful information at a fraction of the cost of standard test methods.

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