Experimental report

24/02/2022

Proposal: **1-02-338**

Council: 4/2021

Title: Effect of as-built residual stressstate on the fatigue response of aLPBF AlSi10Mg alloy

Research area: Materials

This proposal is a new proposal

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Samples: ALSi10Mg HCF specimen
AlSi10Mg SENB specimen

Instrument	Requested days	Allocated days	From	To
SALSA	3	3	01/09/2021	05/09/2021

Abstract:

Laser Powder Bed Fused (LPBF) AlSi10Mg materials exhibit increased as-built yield strength when compared to conventional as-built cast products due to the fine silicon network and small grain size resulting from the very fast cooling rates occurring after the laser-induced melting. These fast cooling rates also induce high tensile residual stress (RS) at the surface of as-built specimens, which are reported to lead to a reduction in the fatigue life and crack porpagation behaviour of LPBF alloys such as Ti6Al4V. Literature report contradictory fatigue results for the as-built condition of LPBF AlSi10Mg materials, where the deleterious/favourable effect of RS is usually hypothesised. This is because compared to other popular LPBF alloys like Ti6Al4V, the RS state of LPBF AlSi10Mg alloys is poorly studied. So far, it has been observed that the processing parameters significantly alter the surface RS state. Thus, a thorough determination of the surface and bulk RS within fatigue samples is required to further elucidate the influence of RS on the as-built fatigue life and crack propagation behaviour of LPBF AlSi10Mg materials.

Report Proposal 1-02-338

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Local contact	Thilo PIRLING, Sandra CABEZA
Instrument(s)	**Name Requested days / Allocated days** SALSA 3 / 3

Introduction

One of the key strengths of Additive Manufacturing (AM) is the fabrication of near net-shape, economically attractive metallic components with complex geometries, otherwise not achievable with conventional production methods. Al-Si alloys are typically used in the production of lightweight components for applications in fields such as space and automotive. Laser Powder Bed Fused (LPBF) AlSi10Mg materials exhibit increased as-built yield strength when compared to conventional as-built cast products due to the fine silicon network and small grain size resulting from the very fast cooling rates occurring after the laser-induced melting. These fast cooling rates also induce high tensile residual stress (RS) at the surface of as-built specimens, which are reported to lead to a reduction in the fatigue life. It is also reported that the as-built RS state influences the crack propagation behaviour [1][2]. Regarding LPBF AlSi10Mg materials, literature reports contradictory fatigue results for the as-built condition, where the deleterious/favourable effect of RS is usually hypothesised [3]. This is because the RS state of LPBF AlSi10Mg alloys is poorly studied. So far, it has been observed that the processing parameters significantly alter the surface RS state, which can be high compressive (about -100 MPa) in samples produced without external contour [4], moderate compressive (about -30 MPa) when using contour layer [4], and other authors report even tensile RS (about 50 MPa) [5]. Furthermore, the beneficial or detrimental effect of a heat treatment is not evaluated. Thus, a thorough determination of the surface and bulk RS within fatigue samples is required to further elucidate the influence of RS on the fatigue behaviour of LPBF AlSi10Mg materials.
Prior EBSD and X-ray µCT analysis on sister specimens show a mild <100> texture parallel to the building direction (BD), a grain size of 11 µm of equivalent diameter and the presence of gas porosity (Øeq = 50 µm) predominately located at the chessboard island boundaries. The near-surface RS state was investigated using a MetalJet X-ray source at HZB (equipped with a high-flux liquid anode) that allowed measurements to a depth of 350 µm.

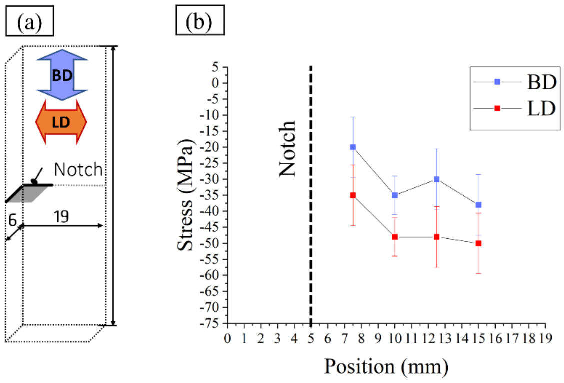

Figure 1: Preliminary near-surface analysis of RS at a depth of 350 µm on the notch line. (a) Position of the measured line and (b) results for the BD (blue) and LD (red).

The results show lower compressive RS values for the BD (Figure 1, blue points) and the LD component (Figure 1, red points). The MetalJet results [6] also show low oscillations in the lattice-spacing/sin2ψ relation, indicating that the grain size and texture permit the use of small sampling gauge volumes.

Methods and material, initial experimental plan and deviations

In the initial experimental plan, two different geometries in the as-built condition were planned: (1) SENB specimen for crack propagation tests and (2) HCF hourglass specimen for High Cycle Fatigue tests. It was decided to focus on the SENB geometry and to investigate the effect of an annealing heat treatment on the material. This decision was taken because the effect of the post-processing on the material performances is a central point in the PhD work of the candidate, part of the experimental team (I. Roveda). Furthermore, the SALSA instrument is well suited for the characterization of the full thickness RS. The stress state in the bulk is significant in view of crack propagation tests, since during the test the crack is propagating through the whole thickness and the RS field can accelerate or decelerate the crack growth rate. On the other hand, in high cycle fatigue, surface RS, for which a neutron source is not required, plays the main role. For these reasons it was considered appropriate to readjust the experimental plan as follows.
The LPFB AlSi10Mg specimens analysed were produced in the shape of rectangular 22 × 8 × 112 mm^3 (width × thickness × height) notched plates for testing (Single Edge Notch Bending (SENB) geometry). Both specimens were machined down to the final testing

shape after heat treatment, when carried out. Two conditions were investigated: (SENB12) an as-built specimen and (SENB09) an annealed specimen at 265°C for 1 hour.
The RS were measured along the three principal directions defined by the SENB geometry: building direction (BD), transversal direction (TD) and longitudinal direction (LD) on the lines (a), (b), (c), (d) reported in Figure 2.

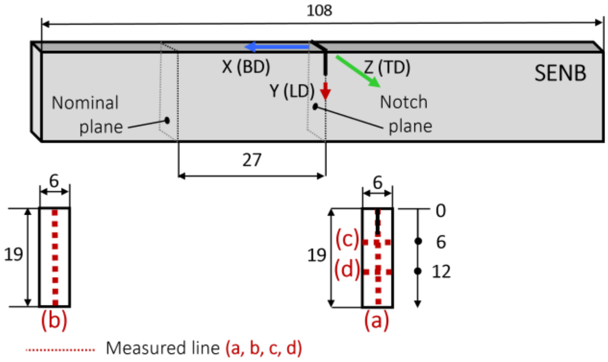

Figure 2: Samples geometry and measured lines.

The wavelength was adjusted to λ = 1.66 Å so that the Al-311 diffraction line was tracked for strain measurement at approximately 2Θ ~ 85.6°. The RS were measured as a function of the position along LD (Y). For the BD and TD directions, 0.6 mm collimators were used for the vertical beam definitions and 2 mm for the horizontal (averaging in TD direction). The optics are rotated of 90° for the LD to ensure that the gradient (present in the LD) is defined by the 0.6 mm optics.
Two strategies were applied to define a stress-free reference. (i) A grid of EDM cut 2 x 2 x 2 mm coupons was extracted by a sister as-built plate, assuming a relaxation of the RS by cutting a small plate from the centre of the specimen. (ii) A line was measured within the notch, where the condition of plane stress is met at the free faces of the notch, and the boundary condition σ_{BD}=0 was applied to calculate a d_0. The (i) method was performed on the as-built material, while the (ii) was performed on both the as-built and heat treated.

Results

Stress-free reference d_0

The d_0 stress-free reference for the as-built condition is measured using 9 coupons, A-D-G-H-K-N-O-R-U, to capture a spatial variation on the cross-section. The LD component is measured only in three coupons (H-K-N). The average d-spacing obtained is d_0 = 1.2135± 0.0005. A variability of d_0-spacing on the cross-section is pointed out: the values vary between 1.2132 and 1.2140 Å, which correspond to a variation in stress of ±40 MPa. An anisotropy between the BD and the other two components is observed: the average d_0 in the BD is equal to 1.21386 ± 0.00006 Å, while is equal to 1.21337 ± 0.00006 Å and 1.21339 ± 0.00006 Å in the TD and LD, respectively. The second strategy (applying a boundary condition at the notch) results in a d_0 is equal to 1.2132 ± 0.0002 for the as-built condition and to 1.2134 ± 0.0007 for the heat-treated. The values of d_0 obtained are compared in Table 1.

Table 1: Results of the stress-free reference d_0 measured with different strategies.

Condition	d_0 strategy	d_0-spacing [Å]			Mean d_0-spacing value [Å]
		BD	TD	LD	
As-built	Coupons	1.21386 ± 0.00006	1.21337 ± 0.00006	1.21339 ± 0.00006	1.2135 ± 0.0005
	Notch	1.21327 ± 0.00006	1.21309 ± 0.00006	1.21330 ± 0.00006	1.2132 ± 0.0002
Heat-treated	Notch	1.21346 ± 0.00006	1.21285 ± 0.00006	1.21365 ± 0.00006	1.2134 ± 0.0007

Bulk RS on the SENB sample

The notch and nominal profiles (lines (a) and (b) in Figure 2) of the absolute components for both the as-built (black) and heat-treated (red) condition are reported in Figure 3. The RS trend in the as-built condition is tensile, with values close to 20 MPa in the notch field and to 0 MPa in the nominal plane. Some marked fluctuations (e.g., at Y =15 mm) are observed. The heat treatment mainly results in a change of sign: positive tensile values become negative, with an average value of -10 MPa. The through thickness profiles, in absence of a reference d_0 deemed appropriate, are shown in Figure 4 as Von Mises stresses. The heat treatment does not have an evident effect on the overall RS.

Conclusion

Two different strategies for assessing the stress-free reference were compared. The method evaluated more consistent with the boundary conditions expected (i.e., the LD component close to the surface, points at 0.5 and 19.5 mm in Figure 3, should approach zero as at the surface the plane stress condition must be met) is measuring the d-spacing in the notch applying the plane stress condition. The results for the as-built condition are in tension in the bulk (~30 MPa) and compressive at the surface (~ - 40 MPa, previously measured at HZB, Berlin). After the heat treatment the bulk RS are brought in compression (~ - 30 MPa). Surface measurements for the heat treated condition will follow. In addition, the strain measurements exhibit considerable scatter. While the absolute RS in the bulk are shifting from tension to compression, the global stress state is not changed by the heat treatment: when the Von Mises stresses are calculated no differences are found between the two conditions.

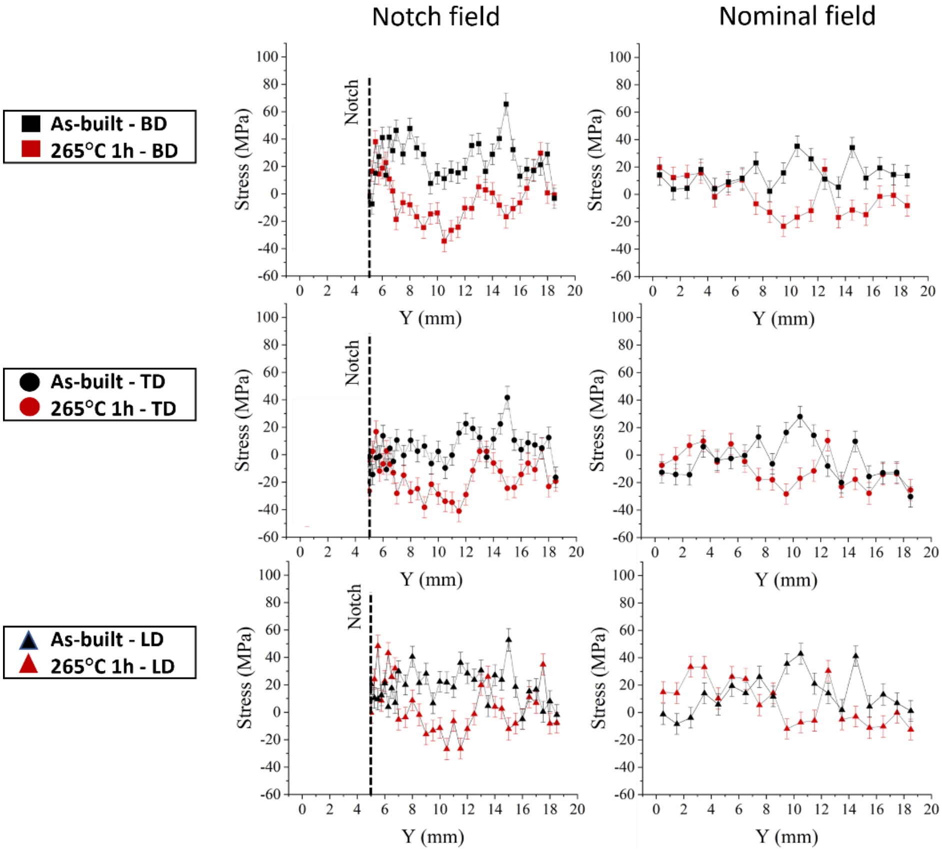

Figure 3: RS absolute profiles for the as-built and heat treated sample. Notch (a) and nominal (b) lines of Figure 2

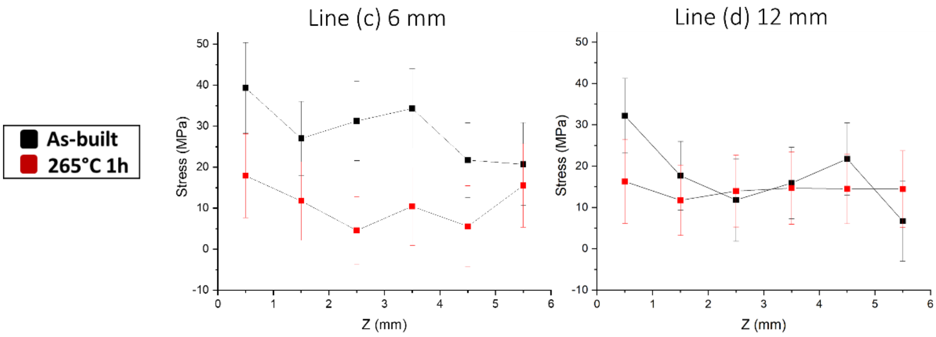

Figure 4: RS Von Mises for the as-built and heat-treated SENB sample. Through thickness lines: (c) and (d) of Figure 2.

Reference

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[6] Laboratory x-rays residual stress measurements were carried out at the LIMAX-160 instrument at the X-Ray Corelab operated by the Helmholtz-Zentrum Berlin für Materialien und Energie (proposal CXR-20-00071-ST).