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Fatigue behaviour of additive manufactured Ti6Al4V, with as-built surfaces, exposed to variable amplitude loading

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Abstract

Additive Manufacturing (AM) allows for great design freedom compared to conventional manufacturing. This is very attractive for the aerospace industry in which AM could contribute to lightweight designs and thereby reduce fuel consumption, increase payload and extend flight range. The fatigue behaviour for rough as-built AM surfaces has previously been characterized with constant amplitude testing but in aerospace applications, most parts are exposed to variable amplitude loading. The fatigue behaviour for variable amplitude is not always consistent with the behaviour for constant amplitude due to effects of overloads and local plastic deformations. Therefore, variable amplitude loading behaviour of laser sintered and electron beam melted Ti6Al4V, with rough as-built surfaces have been investigated in this study using the Short-FALSTAFF (Fighter Aircraft Loading STandard For Fatigue) load sequence. The predicted and the experimental fatigue life was overall consistent even though most experimental results exceeded the predicted life, especially for the laser sintered

material. These findings show that conventional cumulative damage fatigue life predictions give reliable predictions for AM materials with rough as-built surfaces for the type of tension dominated load sequence used.

1. Introduction

Additive manufacturing (AM), also referred to as 3D-printing, in metal is a group of manufacturing processes that has gained increased interest in recent years. In AM, a small amount of material is added layer-by-layer to create the final geometry of a part which allows for greater design freedom for such parts compared to parts that are restricted to the constraints of conventional subtracting processes. For industrial applications, the design freedom of AM can contribute to parts with improved performance and reduced costs [1,2]. Improved performance can for example include lightweight designs for aerospace applications, in which a reduced weight would contribute to reduced fuel consumption, increased payload and extended flight range.

The material properties of the AM titanium alloy Ti6Al4V can, however, be different compared to the same alloy produced from conventional product forms. This can be attributed to both microstructural differences [3–5] but also to the rough as-built surface, that is a result of the AM process, which affects both static strength [5–7] and fatigue properties [4,5,7–9]. There are to date several techniques for metal AM that are used for industrial purposes and each technique can give slightly different material characteristics [10]. The three main techniques are powder bed fusion (PBF), directed energy deposition (DED) with wire and DED with blown powder [1]. Moreover, for each technique there are a number of different AM equipment available that can also affect the final material quality.

This study has focused on the PBF technique with material produced with both Electron Beam Melting (EBM) and Laser Sintering (LS) equipment. During a PBF process, the part is

manufactured layer-by-layer and a computer model of the part to be manufactured is therefore sliced into thin layers. A thin layer of powder material is spread out onto a build platform followed by a melting procedure in which a laser or electron beam melts the powder that are located in the pre-defined bottom slice of the computer model. The powder surrounding the melted slice is left un-melted. The built platform is thereafter lowered and a new layer of powder is spread out and the next slice of the computer model is melted, fusing the new layer of powder to the previous one. The layer-by-layer process is then repeated until the whole geometry of the part is completed [2].

The LS and the EBM processes are very similar but there are two major differences between the processes that affect the material quality and material properties. First, while the EBM is performed in vacuum with pre-heating of the entire powder bed, the LS is generally performed in argon gas with non-heated build chambers [4]. The non-heated build chamber process for LS generates high residual stresses in the material and post stress relieving heat treatment is therefore needed. The other important difference is that the EBM process use thicker build layers and larger size powder particles, compared to LS, which contributes to a coarser surface roughness of the EBM material [3].

AM, is generally considered to have great possibilities for aerospace application. However, there are some challenges yet to be solved before AM can be used in critical aerospace components and the poor fatigue strength of AM material with rough un-machined, as-built, surface is one of the major challenges. The fatigue properties of rough un-machined surface of AM parts are dominated by the surface roughness rather than by internal defects or microstructure [11] and the fatigue strength for un-machined AM material can be 65 - 75 % lower than for conventional manufactured materials [9].

Constant amplitude fatigue behaviour for AM Ti6Al4V have been widely investigated in previous studies [3,5,7,9,12–15] but few aerospace components are loaded with constant amplitude cycles. Most structural components are subjected to variable amplitude fatigue loading [16] which does not always give the same material response as constant amplitude loading do due to the effect of overloads, load sequence order and local plastic deformations [17]. Generally, the fatigue life of components subjected to variable amplitude loading are estimated with fatigue data from constant amplitude fatigue testing using, for example, Palmgren-Miner's rule for cumulating damage [18]. To our knowledge, there has been no study to date that has investigated the variable amplitude fatigue behaviour for additive manufactured metals parts.

In the present study, fatigue investigations have been performed in several steps in order to evaluate how AM material with rough as-built surfaces behave during variable amplitude fatigue loading and if a conventional cumulative damage approach could be used to predict the fatigue life. Constant amplitude test results were used to produce fatigue design data that in turn were used for cumulative damage prediction of the fatigue behaviour for an aircraft spectrum of variable amplitude loading. Variable amplitude fatigue testing was then performed with maximum net section peak stresses that, according to the cumulative damage predictions, would correspond to 15 000 simulated flights and the results were compared to the predictions. An overview of the evaluation process is schematically illustrated in Figure 1.

Figure 1. Schematic overview of the evaluation process of this study. CA = constant amplitude, VA = variable amplitude

2. Materials, Computational and Experimental Methods

2.1. Materials and Test Specimens

Test material was manufactured using EOS M 290 LS equipment and Arcam A2 EBM equipment with standard parameter settings for Ti6Al4V for each process. Different parameters were used for bulk material and contours. The LS samples were produced with powder with an average size of 50 μm and with 30 μm build layers in which the laser scanning direction was rotated 67 ° between each layer. The EBM used 50 μm build layers and had a powder size range of 45-100 μm . The LS samples were stress relieved (SR) by heat treatment at 650 °C for 3 h in argon gas. To remove loosely bound powder, the LS samples were sandblasted while the EBM samples were blasted with titanium powder. As a final post process, the samples were subjected to Hot Isostatic Pressing (HIP) at 920 °C and 1000 bar for 2 h in an argon gas environment. Two EBM test series were excluded from the HIP heat treatment, to be used as references. All AM samples used for this study were manufactured in one single LS and EBM build cycle, respectively, to avoid batch-to-batch variations when comparing different test series.

The LS and EBM fatigue test specimens were produced with the loading direction in the process build direction, the Z-direction [1]. A wrought Ø30 mm Ti6Al4V bar, in mill

annealed condition, was used to produce reference test specimens. The fatigue test series used for this study are presented in Table 1. Light optical microscopy was performed on polished cut-up samples for the different AM material variants EBM+HIP, EBM (non-HIP) and LS+HIP to determine the presence of internal defects.

The fatigue specimens were manufactured with two different geometries, type 1 and type 2, which is illustrated in Figure 2. The type 1 specimens had an un-notched surface with a theoretical stress concentration factor (K_t) of 1 while the type 2 had a notch with a 0.85 mm radius and a stress concentration factor of $K_t=2.5$, see Figure 3. The geometry of the LS and EBM fatigue specimens were directly produced by AM including the notch for the type 2 specimens. All LS and EBM fatigue test specimens therefore had un-machined rough as-built surfaces while the wrought bar specimens had machined and polished (longitudinal grinding) surfaces. Even though post processing through blasting and heat treatment were performed on the LS and EBM material, the rough AM surfaces will be called rough as-built surfaces in this paper.

Figure 2. Type 1 (left) and 2 (right) fatigue test specimens with both rough as-build surfaces and machined surfaces.

Tensile specimens with $\varnothing 6.0$ mm cross section, in accordance with the ASTM E8 standard, were machined from vertically built bars for the LS+HIP, EBM+HIP and EBM without HIP material conditions. Additional tensile specimens were machined from a $\varnothing 30$ mm wrought

bar in mill annealed condition. Both the AM and the wrought tensile specimens were manufactured from material from the same builds respectively bar as the fatigue specimens.

Figure 3. Geometrical notch (type 2 specimens) with stress concentration $K_t=2.5$. Machined notch (left), LS AM-built notch (middle) and EBM AM-built notch (right).

Light optical microscopy was performed on longitudinal sections of cylindrical specimens, $\varnothing 6.5$ mm, in the Z-direction to determine the presence of internal defects. Samples of different AM material conditions, EBM+HIP, EBM (non-HIP) and LS+HIP, were mechanically polished down to 3 μm diamond paste and finished with oxide polishing (3 % H_2O_2).

2.2. Tensile Tests

Room temperature tensile testing was performed on machined specimens from the four material conditions; wrought bar, EBM with HIP, EBM without HIP and LS with HIP. The tests were performed in a servo hydraulic test rig with an Instron 8800 control system. An extensometer was used during the first stage of the test to determine yield strength at 0.2 % offset and elastic modulus. The test specimens were loaded with a rate corresponding to 0.006 mm/mm/min up to the yield strength and 0.043 mm/mm/min to fracture. Two tests per test material condition were performed.

2.3. Constant Amplitude Fatigue Design Data

The high cycle fatigue behaviour of AM Ti6Al4V with rough as-built surfaces were investigated in a previous study with constant amplitude loading and a stress ratio $R=0.1$ [9]. The test material in that study was produced in the same AM builds as the test material used

for the present study. Moreover, the specimen geometries in this study, type 1 and 2, are the same as for the previous study which means that the material properties could be expected to be the same in the two studies.

In order to apply the Palmgren-Miners rule, see Eq. 1, for variable amplitude calculations, the constant amplitude fatigue data from Kahlin *et al.* [9] were manually curve-fitted to produce Wöhler curves. Existing fatigue Wöhler curves for cast Ti6Al4V, from the Saab Aeronautics company material database, were scaled with a stress amplitude (σ_a) linear adjustment function, that depends on the fatigue life (N), to fit to the constant amplitude data for the AM test series. This procedure is schematically illustrated in Figure 4.

A full Haigh diagram for cast Ti6Al4V [19] was then used as a template to derive a Haigh diagram for the investigated material in this study. This was achieved by applying the same adjustment function to the complete Haigh diagram. All reducing safety factors for fatigue scatter and material batch variations were removed to produce Haigh diagrams that could be used to predict the variable amplitude fatigue life for the tests performed in the present study.

Figure 4. Schematic illustration of the adjustment procedure to fit the Wöhler curves for cast Ti6Al4V to the investigated material in this study. A and B are constants.

2.4. Aircraft Spectrum for Fatigue Loading

Fatigue life prediction and fatigue testing were performed using variable amplitude loading with a fighter aircraft wing bending spectrum FALSTAFF (Fighter Aircraft Loading STandard For Fatigue) [20]. A modified version, Short-FALSTAFF, of the standard

FALSTAFF test sequence was used in order to reduce fatigue test times. Short-FALSTAFF was developed by CEAT in Toulouse [21] and the numbers of cycles is reduced with about 50 % compared to FALSTAFF. However, the Short-FALSTAFF load sequence contributes to almost all of the cumulative damage of the original FALSTAFF load sequence [22]. The load sequence of Short-FALSTAFF and the distributions peaks and troughs are presented in Figure 5 and Figure 6 in which the maximum tensile peak (100) correspond to the maximum net section peak stress used for variable amplitude tests. The sequence runs then repeatedly during a fatigue test until the specimen fails. One sequence consists of 18 012 turning points, 9 006 rain-flow counted cycles, which corresponds to 200 simulated flights.

Figure 5. One sequence of the short-FALSTAFF load spectrum.

Figure 6. Distribution of peaks and troughs for one short-FALSTAFF load sequence.

2.5. Cumulative Damage Approach for Fatigue Life Prediction

Constant amplitude fatigue data were produced at a fixed value of stress ratio R equals to 0.1 [9]. However, since a Short-FALSTAFF variable amplitude spectrum consists of several R -values, an interpolation procedure is necessary for cumulative fatigue damage calculations. A complete Haigh diagram for cast Ti6Al4V has therefore been used as a template for constructing a diagram for the investigated material in this study, as described in section 2.3. The derived Haigh diagram and the rain-flow counted cycles in the load sequence have been used in cumulative fatigue damage calculations according to the Palmgren-Miner rule [23,24], see Eq. 1, in which D is the cumulative damage, n_i is the number of applied load cycles of type i and N_i is the number of type i cycles that equals fatigue failure.

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \quad (\text{Eq. 1})$$

The rain-flow counted cycles for a Short-FALSTAFF test sequence is shown in Figure 7 in a Haigh diagram format with schematic constant life curves. The number of cycles to failure for each spectrum data point is obtained by interpolation in amplitude stress σ_a in extracted Wöhler curves defined for each individual R -value when $-1 \leq R \leq 0$ and for constant minimum stress $\sigma_{\min}$ when $R > 0$ and for constant mean stress σ_m when $R < -1$.

Figure 7. A Short-FALSTAFF test sequence shown as a schematic Haigh diagram with rain-flow counted cycle data points and interpolation procedure. The size of the Short-FALSTAFF data points is proportional to the logarithmic number of cycles, i.e. larger points correspond to a larger numbers of data points in the load sequence.

2.6. Fatigue Tests with Variable Amplitude Loading

Fatigue testing with variable amplitude loading were performed with a maximum net section peak stress, predicted by cumulative damage calculation, that correspond to 15 000 simulated flights. Two (2) fatigue tests were performed for each test series, see Table 1. The fatigue testing was performed at 10 Hz loading in a servo hydraulic fatigue test rig with an Instron ± 50 kN load cell and an Instron 8800 control system. The Short-FALSTAFF load sequence presented in Figure 5 was scaled for each test series so that the maximum net section peak stress corresponded to the values presented in Table 1. The load sequence was then applied repeatedly until the specimen failed. The tests were performed at room temperature using load control. The fatigue crack initiation locations were investigated for each fatigue test specimen by both stereomicroscopy, for an overview, and by scanning electron microscope (SEM), for a more detailed view. The SEM investigations were performed with a HITACHI SU-70 field emission gun operating at 15 kV.

Table 1. Fatigue test series for variable amplitude loading. The maximum load was predicted using the cumulative damage approach. Two (2) tests per test series were performed. HIP=Hot Isostatic Pressing, SR=Stress relieving

Material	Heat treatment	Surface	Specimen type	Maximum net section peak stress, predicted for 15 000 flights
Wrought bar	Mill annealed	Machined and polished by longitudinal grinding	1 (un-notched)	970 MPa
EBM	HIP	Rough as-built	1	505 MPa
EBM	none	Rough as-built	1	505 MPa
LS	SR+HIP	Rough as-built	1	575 MPa
Wrought bar	Mill annealed	Machined	2 (notched)	735 MPa
EBM	HIP	Rough as-built	2	310 MPa
EBM	none	Rough as-built	2	310 MPa
LS	SR+HIP	Rough as-built	2	310 MPa

3. Results

3.1. Tensile Strength

Tensile tests of machined specimens were performed for the four material conditions;

EBM+HIP, EBM without HIP, LS+HIP and reference wrought material. The LS+HIP

material showed the lowest strength while the overall tensile behaviour was similar for tested series, see Table 2.

Table 2. Average results from tensile testing. Two tests per test series with loading in the build direction, Z, for AM specimens and longitudinal direction for wrought material. HIP = Hot Isostatic Pressure, UTS= Ultimate Tensile Strength, $R_{p0.2}$ = Yield strength at 0.2% offset.

Test series	UTS [MPa]	$R_{p0.2}$ [MPa]	Elongation to fracture [%]	Elastic modulus [GPa]
Wrought bar	1002	910	17	112
LS+HIP	968	870	14	117
EBM+HIP	1005	895	16	119
EBM, no HIP	1067	989	12	118

3.2. Internal Defects

Light optical microscopy of cut out samples showed a large amount of internal defects, Lack of Fusion (LOF) and gas pores, for the non-HIP EBM samples. Moreover, the LS and EBM samples subjected to HIP were generally free of internal defects in the bulk material but had occasional small LOF located just below the as-built surface. The difference in material quality is illustrated by Figure 8.

Figure 8. Light optical microscopy of cut out samples. a.) EBM sample with HIP, b.) EBM sample without HIP, c.) LS sample with HIP. b.d.=Building direction (Z-direction). HIP = Hot Isostatic Pressing

3.3. Fatigue

3.3.1. Predicted Fatigue Life

The predicted fatigue life for the Short-FALSTAFF load spectrum with a critical cumulative damage sum $D=1$ are presented in Figure 9 for the different test series. The predicted maximum net section peak stress that correspond to 15 000 simulated flights, as illustrated by Figure 9, were then used for the variable amplitude fatigue testing to confirm the predicted fatigue life.

Figure 9. Predicted fatigue life for Short-FALSTAFF loading with cumulative damage $D=1$. AB= as-built, HIP=Hot Isostatic Pressing.

3.3.2. Variable Amplitude Fatigue Life

The experimental fatigue behaviour for Ti6Al4V subjected to Short-FALSTAFF variable load sequence is presented in Figure 10 for un-notched (type 1) specimens and in Figure 11 for notched specimens (type 2). The experimental fatigue life corresponds well with the predicted fatigue life for all test series. There is no distinct difference between the EBM material with or without HIP, even though there are tendencies that the non-HIP samples had somewhat shorter fatigue life. There is also somewhat higher tendency for LS samples to exceed the predicted fatigue life, compared to EBM material.

Figure 10. Variable amplitude fatigue life for un-notched samples, type 1. AB= as-built, HIP=Hot Isostatic Pressing.

Figure 11. Variable amplitude fatigue life prediction vs test results. Notched samples, type 2. AB= as-built, HIP=Hot Isostatic Pressing.

3.3.3. Crack Initiations and Fracture Surfaces

All LS and EBM fatigue specimens, in this study, showed multiple crack initiations, which is illustrated in Figure 12 b, with between 3 - 25 observed crack initiations locations. The amount of observed crack initiations at the fracture surfaces is presented in Table 3. Notched (type 2) specimens generally had larger numbers of initiations compared to the un-notched (type 1) specimens. All specimens showed a clearly visible striation pattern, originating from the peak loads, close to the final failure, see Figure 12 h.

Table 3. Numbers of crack initiation locations observed.

Test series	Un-notched (type 1)	Notched (type 2)	Position of initiations
Wrought bar, machined-and-polished	1	2 - 4	Surface
LS + HIP, rough as-built surface	3 – 7	10 – 15	Surface
EBM + HIP, rough as-built surface	4 – 9	13 – 15	Surface
EBM, no HIP, rough as-built surface	8 – 25	17 – 19	Surface

Figure 12. Crack initiations and fracture surfaces. a-b.) LS + HIP, un-notched (type 1) specimen, multiple crack initiations, c-d) EBM + HIP, notched (type 2) specimen, crack initiation, e-f) EBM, no HIP, un-notched (type 1), Lack of Fusion (LOF) and multiple crack initiations, g) EBM + HIP, un-notched (type 1) specimen, surface notch, h) LS+ HIP, un-notched (type 1) specimen, striations from peak loading. Dashed red line squares are enlarged in the figure to the right.

4. Discussion

4.1. Tensile

The ultimate tensile strength for LS material subjected to HIP was approximate 3 % lower compared to material from wrought bar while the HIP:ed EBM material had similar strength to the wrought material. In a previous investigation [9] test material from the same builds, as for the present study, showed similar differences for Vickers hardness testing which indicates that hardness testing is a good indicator for tensile strength. The tensile properties from previous studies [5,25–28] show a large scatter of both strength and elongation, see Table 4, which further indicates that the material properties can differ between different builds and different AM equipment. The tensile strength for the EBM samples in this study were high compared to EBM material from previous studies while the LS samples in this study were inferior to material produced by similar equipment.

Table 4. Tensile strength of AM Ti6Al4V from this study compared to previous studies. Specimen orientation is in the build direction. HIP treatment at 915-920 °C for 2 h at 1000 bar. HIP = Hot Isostatic Pressing

AM method / equipment	Ultimate tensile strength, MPa	Ultimate tensile strength, MPa	Elongation to fracture, %	Elongation to fracture, %	Reference
	no HIP	HIP treatment	no HIP	HIP treatment	
EBM / Arcam A2	1067	1005	12	16	This study
LS / EOS M 290	n.a.	968	n.a.	14	This study
LS / Concept Laser M2	1155 / 1115*	973	11 / 11*	19	[5]
LS / SLM 250	1080	1005	2	8	[25]
LS / SLM 250	1315	1089	4	14	[26]
EBM / n.a.	953	942	14	13	[27]
EBM / n.a.	915	870	13	14	[28]

* Stress relieved at 700 °C for 1 h

4.2. Comparison to Fatigue Life Predictions

The fatigue life of the test specimens was generally underestimated which is illustrated in Figure 13 in which the predicted fatigue life is compared to the experimental test results. The evaluated fatigue test specimens were tested at different stress levels, see Table 1, and with different geometry, un-notched (type 1) and notched (type 2). The majority of the tested specimens showed longer fatigue life compared to the predicted 15 000 flights which was calculated to correspond to a cumulative damage of $D=1.0$, according to Eq. 1. The test results ranged from $D=0.8$ to $D=1.6$ in which an experimental fatigue life greater than 15 000 flights generates a $D > 1.0$. The LS samples, both $K_t=1$ and $K_t=2.5$ showed the least scatter while the wrought bar samples had the largest scatter, although the number of specimens in each test series was too few to make any statement regarding variation. The corresponding experimental cumulative damage for each material is presented in Table 5.

Figure 13. Predicted fatigue life compared to test results

Table 5. Average fatigue life and corresponding cumulative damage for $K_t=1$ (type 1) and $K_t=2.5$ (type 2) specimens combined. Predicted fatigue life was 15 000 flights. LS and EBM specimens had rough as-built surface while the wrought specimens had machined surfaces.

Material	Average fatigue life [flights]	Average experimental cumulative damage, D	Range of experimental cumulative damage, D
Wrought bar	17 950	1.2	0.8-1.6
LS (HIP) *	22 320	1.5	1.5
EBM (HIP)	17 124	1.1	1.0-1.3
EBM (no HIP)	14 469	1.0	0.8-1.2
EBM (both HIP and no HIP)	15 797	1.1	0.8-1.3

* All specimens had similar fatigue life, no scatter

4.3. Comparison to Previous Fatigue Investigations

To our knowledge, there are to date no previous publications on variable amplitude fatigue behaviour for any metal AM material, including Ti6Al4V. Even for conventional manufactured titanium, there are very few papers published. This is understandable since a lot of variable amplitude testing is performed in-house at companies, and does not result in publications. Moreover, since AM materials is a quite young field of research, the focus in academia has so far been on fundamental material behaviour at the expense of more applied research like variable amplitude behaviour.

However, Cardrick *et al.* [18] published a paper on wrought Ti6Al4V with the same approach as the present study in which they compared predicted variable amplitude fatigue life to experimental. Constant amplitude test results were used as input to Miner's rule to set a load level for variable amplitude testing that should correspond to a certain numbers of variable amplitude cycles. In that study the variable amplitude fatigue life was overestimated and only $D=0.3$ was achieved during variable amplitude fatigue testing. This is in contrast to the findings in the present study in which the predicted variable fatigue life generally was

underestimated ($D \geq 1$). Cardrick *et al.* used a Gaussian narrow band random load sequence which is a symmetric tensile-compression load sequence in contrast to the Short-FALSTAFF load sequence, that were used in the present study, which is a tensile dominated sequence. It is possible that the larger compressive stresses in the Gaussian sequence will produce tensile residual stresses in the plastic region which would be detrimental to fatigue life. This could be an explanation to why the symmetric Gaussian sequence gave a large overestimation of fatigue life while the fatigue life was underestimated with the tensile dominated Short-FALSTAFF sequence.

4.4 Surface Roughness

The surfaces of EBM and LS samples with rough as-built surface can be very rough, in the Z-direction, and consist of partially melted powder particles that form sharp radii of curvature. These radii of curvature act as micro notches which lead to local stress concentrations which can considerably reduce the fatigue life [4,29]. The surface roughness of material from the same AM build as the test material in this study has been determined in a previous study [9]. The surface roughness in the Z-direction was found to be more than twice as rough for EBM samples with rough as-built surface compared to LS samples as illustrated by Figure 14.

Figure 14. Average values of R_v -surface roughness in Z-direction determined by Kahlin *et al.* [9]. R_v = maximum profile depth

In addition to introducing local stress concentrations, the rough as-built surface will not carry loads in the same way as the bulk material which will lead to a reduction of the load bearing area [30]. This will make the fatigue properties for AM material with rough as-built surfaces thickness dependent since the surface roughness for thin walled structures will be a significant part of the cross section. In this study, however, all fatigue specimens had the same nominal diameter and the difference in load bearing area between the test series should therefore be minor.

4.5. Effect of HIP

Both EBM and LS samples subjected to HIP had occasional small LOF defects located just below the surface. This indicates that these defects have a direct connection to the surface since HIP would need fully enclosed voids to be effective. However, no cracks were observed to have initiated at these subsurface defects which indicates that their effect on fatigue life is limited.

The EBM samples showed, regardless of the difference in amount of internal defects which is illustrated by Figure 8, similar fatigue life when subjected to Short-FALSTAFF variable amplitude fatigue spectrum, see Figure 10 and Figure 11. The experimental fatigue life corresponded to a cumulative damage of $D=1.0$ for non-HIP specimens and $D=1.1$ for HIP specimens which confirms the previous findings for constant amplitude fatigue testing in which it was determined that HIP had a negligible enhancing effect on fatigue strength for AM material with rough as-built surface [9]. For the un-notched (type 1) specimens in the present study, there is, however, a small tendency to a slightly longer fatigue life for the HIP specimens. This small tendency for un-notched (type 1) specimens was also found in the previous study [9]. Moreover, in that study, no difference could be found between notched (type 2) HIP and non-HIP specimens which also corresponds well with the variable amplitude results from the present study. Hence, the overall behaviour for HIP and non-HIP EBM

specimens subjected to variable amplitude loading correspond well with the behaviour for constant amplitude loaded specimens.

Even though it seems like the presence of internal defects does not affect the fatigue strength for AM materials with rough as-built surfaces [7,9], since the crack initiation will occur in the surfaces notches of the rough surface, it is still possible that a large amount of internal defects will reduce the load bearing area of the fatigue specimen cross section and thereby reduce the apparent fatigue strength. The un-notched (type 1) non-HIP specimens in the present study showed a large amount of Lack of Fusion (LOF) defects which were roughly measured to cover 5 % of the fatigue fracture area. The amount was considerably lower within the notched (type 2) non-HIP specimens which could be expected since the fracture is guided to the notched cross section regardless if this is the section with most defects or not. No internal defects was visible in the fracture surface at macro level for any of the HIP:ed samples. If the maximum net section peak stress for the non-HIP un-notched (type 1) fatigue samples is recalculated with a 5 % lower cross section area, the samples will be in line with the HIP:ed samples. This shows that, even though the rough as-built surface mainly determines the fatigue life, the presence of a large amount of internal defects could still have a minor influence on fatigue life.

5. Conclusion

The primary goal of this study was to investigate the variable amplitude fatigue behaviour of additive manufactured Ti6Al4V, with rough as-built surface and geometrical notches.

Moreover, it has been investigated if the variable amplitude fatigue behaviour could be predicted using cumulative damage calculations with constant amplitude fatigue data. The following conclusions can be made by the findings in this study:

- Additive manufactured, both with Laser Sintering (LS) and Electron Beam Melting (EBM), Ti6Al4V material with rough as-built surface has considerably lower fatigue strength compared to conventional manufactured material.
- Hot Isostatic Pressing (HIP) has negligible influence on the fatigue strength for additive manufactured Ti6Al4V material with rough as-built surface.
- Cumulative damage approach for Short-FALSTAFF (Fighter Aircraft Loading STandard For Fatigue) variable amplitude sequence showed good agreement between predicted and experimental fatigue life for both LS and EBM materials. The cumulative damage approach could therefore be used, at least for tensile dominated load sequences, to predict fatigue life for variable amplitude loaded parts in additive manufactured Ti6Al4V using fatigue data from constant amplitude testing.

Further work to improve the surface roughness quality of additive manufactured materials with rough as-built surface would improve the fatigue strength hence increase the scope for the use of AM in aerospace applications.

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