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Fatigue Performance of Additive Manufactured Ti6Al4V in Aerospace Applications

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ABSTRACT

Additive Manufacturing (AM) for metals includes a group of production methods that use a layer-by-layer approach to directly manufacture final parts. In recent years, the production rate and material quality of additive manufactured materials have improved rapidly which has gained increased interest from the industry to use AM not only for prototyping, but for serial production. AM offers a greater design freedom, compared to conventional production methods, which allows for parts with new innovative design. This is very attractive to the aerospace industry, in which parts could be designed to have reduced weight and improved performance contributing to reduced fuel consumption, increased payload and extended flight range. There are, however, challenges yet to solve before the potential of AM could be fully utilized in aerospace applications. One of the major challenges is how to deal with the poor fatigue behaviour of AM material with rough as-built surface.

The aim of this thesis is to increase the knowledge of how AM can be used for high performance industrial parts by investigating the fatigue behaviour of the titanium alloy Ti6Al4V produced with different AM processes. Foremost, the intention is to improve the understanding of how rough as-built AM surfaces in combination with AM built geometrical notches affects the fatigue properties. This was done by performing constant amplitude fatigue testing to compare different combinations of AM material produced by Electron Beam Melting (EBM) and Laser Sintering (LS) with machined or rough as-built surfaces with or without geometrical notches and Hot Isostatic Pressing (HIP) treatment. Furthermore, the material response can be different between constant amplitude and variable amplitude fatigue loading due to effects of overloads and local plastic deformations. The results from constant amplitude testing were used to predict the fatigue life for variable amplitude loading by cumulative damage approach and these predictions were then verified by experimental variable amplitude testing.

The constant amplitude fatigue strength of material with rough as-built surfaces was found to be 65-75 % lower, compared to conventional wrought bar, in which HIP treatments had neglectable influence on the fatigue strength. Furthermore, the fatigue life predictions with cumulative damage calculations showed good agreement with the experimental results which indicates that a cumulative damage approach can be used, at least for a tensile dominated load sequences, to predict the fatigue behaviour of additive manufactured Ti6Al4V.

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I also would like to thank my colleagues at both Saab Aeronautics and Linköping University for support and understanding, an industrial PhD student is torn between industry and academia and can never spend enough time at either place. A special thanks to my colleague Niklas Eriksson at Saab Aeronautics for excellent discussions and for his work with the AM demonstrator part seen on the thesis cover.

I have my parents to thank for many things but for this thesis I especially express my gratitude for the many days of babysitting which made it possible to finish the thesis in time. To my baby boy Oskar, thank you for your encouraging smiles, they mean the world to me. When you will be able to understand this thesis it will be old and probably replaced by new research, since additive manufacturing develops very rapidly, but hopefully it will inspire you to explore science and find out how the world works. Finally, I give all my loving gratitude to my wife Anna, you make the sun rise in the morning and makes me feel special every single day.

LIST OF PAPERS

The following papers have been included in this thesis:

- I.** M. Kahlin, H. Ansell, J.J. Moverare, “Fatigue behaviour of notched additive manufactured Ti6Al4V with as-built surfaces”, *International Journal of Fatigue* 2017, *Accepted for publication*, doi.org/10.1016/j.ijfatigue.2017.04.009.
- II.** M. Kahlin, H. Ansell, J.J. Moverare, “Fatigue behaviour of additive manufactured Ti6Al4V, with as-built surfaces, exposed to variable amplitude loading”, *Submitted for publication* 2017.

Contribution to the papers included:

In the above papers I have been the main contributor, performing all experimental work as well as the manuscript writing. In paper II, however, Hans Ansell has performed the fatigue life predictions using cumulative damage calculations.

Papers not included in this thesis:

- III.** L. Pejryd, P. Karlsson, S. Hällgren, M. Kahlin, ”Non-destructive evaluation of internal defects in additive manufactured aluminium”, *Presented at WorldPM2016, Hamburg (Germany), 2016*.

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ABBREVIATIONS

AM	Additive Manufacturing
BD	Build Direction
EBM	Electron Beam Melting
HIP	Hot Isostatic Pressing
LOF	Lack of fusion
LS	Laser Sintering
SR	Stress Relieving

PART I

BACKGROUND AND THEORY

1. INTRODUCTION

1.1. Introduction to the Research Project

This licentiate thesis is a part of the ongoing industrial PhD project *Additive manufacturing: Performance in aerospace applications*, which began in January 2015. Saab Aeronautics, the European commission and the Swedish Foundation for Strategic Research (SSF), finance the project that is performed in close collaborations with Saab Aeronautics. Synergies have been found with other research projects through Saab Aeronautics, for example OPTIPAM (*Optimized Production Process for Additive Manufacturing/Produktion 2030*) and AddMan (Clean Sky 2/Horizon 2020).

Additive manufacturing (AM) have been referred to as the 3:rd industrial revolution, introducing a technological paradigm shift in which the way industrial products are designed and the way logistics is handled will be very different to the existing procedures [1]. Futuristic designs with improved part performance and on-demand manufacturing could be reality in a not too distant future. Additive manufacturing in metal is, however, a relative young field of research in which there still are many challenges to solve before the full potential of AM can be achieved.

1.2. Aim of the Project

The aim of the project is to increase the understanding of how AM can be used to produce high performance industrial parts by investigating fatigue and damage tolerance behaviour of titanium Ti6Al4V produced with different AM processes.

By the end of the project, the goal is to have an understanding of which factors that influence the current fatigue behaviour and to have improved the fatigue behaviour through post processing. The goal is further to investigate if existing fatigue life and crack propagation prediction methods gives relevant predictions compared to experimental results.

1.3. Hypothesis

AM produced material has different fatigue behaviour compared to wrought material.

1.4. Research Questions

The research questions that are addressed in this licentiate thesis are summarized below:

- What effect have rough as-built AM surfaces, compared to machined surfaces, on fatigue crack initiation properties and what effect has Hot Iso-static Pressing (HIP) on fatigue behaviour for AM material with rough as-built surfaces?
- What effect has geometry (geometrical notches), for parts with rough as-built surface, on fatigue crack initiation properties?
- Can traditional fatigue life prediction methods be used for AM material?
- Is there any difference in the fatigue behaviour for samples subjected to constant amplitude and variable amplitude loading?

1.5. Structure of the thesis

This licentiate thesis consists of two parts:

- Part I: Background and Theory
- Part II: Papers Included

Part I, *Background and Theory*, cover an introduction of the research project, including aims and research questions, followed by an introduction to additive manufacturing and titanium material. After the introduction, the experimental methods and main findings are presented as well as a summary of the included papers. Finally, the conclusion of the licentiate thesis is given.

Part II, *Papers Included*, is based on two journal papers, which describe the main research that has been performed in this project.

2. ADDITIVE MANUFACTURING

Additive manufacturing (AM), 3D-printing, is a group of manufacturing processes that have been evolved from rapid prototyping but. After being initially used only for prototyping, the interest in metal AM for serial production has increased rapidly in recent years. In AM, the manufacturer has the possibility to create final components directly from a computer model by adding material layer-by-layer. Moreover, since AM allows for a greater design freedom, designers are no longer restricted to the geometries that can be manufactured by conventional manufacturing, by for example milling or casting. A component can therefore be designed with a complex geometry that can have improved performance or reduced cost compared to the conventional solution [2,3]. AM is still, however, an expensive manufacturing process which is most suitable for small production series and expensive materials, for example titanium and nickel based alloys [2,4].

All AM processes use the layer-by-layer method, in which a small amount of material is added to an existing layer of material which is in contrast to conventional subtracting processes in which material is removed. There are three main techniques for industrial metal AM; Powder Bed Fusion (PBF), Directed Energy Deposition (DED) using wire-feed and DED using blown powder [2]. In addition to this, there are a number of different manufactures of AM equipment for each AM technique and even though the processes are similar each manufacturing equipment gives slightly different material characteristics for the same alloy [5].

This research project has focused on the titanium alloy Ti6Al4V produced with PBF technique, using both Electron Beam Melting (EBM) and Laser Sintering (LS) equipment. EBM and LS processes have the same basic principles, in which a computer model of the component is sliced into thin layers and each layer is manufactured one at a time. A thin layer of pre-alloyed metal powder is spread out on a build platform as schematically illustrated in Figure 1. The material representing the bottom slice of the computer model is thereafter melted, using a laser or an electron beam, leaving all excess powder surrounding the slice unmelted. The build platform is then lowered and the procedure is repeated, in which a new layer of metal powder is spread out and material for the second computer model slice is melted. Several layers of already solidified material are re-melted during the melting of each new layer, fusing the layers together to a solid bulk material as illustrated by the thermal profile in Figure 2. Additional layers are added until the full geometry of the final component is completed [3].

Figure 1. Schematic illustration of a Powder Bed Fusion process.

Figure 2. Schematic thermal profile of a single layer of Ti6Al4V with repeated heating during AM, adapted from [2]

2.1. AM Material and Equipment

A variety of AM powder bed techniques are available in which, to date, Arcam has the only EBM based systems. Different process parameters are needed for different materials and not all materials are available for all processes. An overview of commercially available alloys and examples of AM powder bed systems are presented in Table 1. New AM techniques and equipment are constantly developed and more materials are added to each process. Therefore, a summary of existing equipment is very fast outdated. The terminology “Laser sintering” refers to any PBF process that use a laser to melt powder particles according ISO/ASTM 52900. Moreover, according to ISO/ASTM 52900, the term “sintering” is used by historical reasons and is a misleading name since the AM process

involves partial or fully melted powder in contrast to the traditional powder metal sintering.

Table 1. Examples of AM powder bed technologies and equipment. EBM= Electron Beam Melting, LS= Laser Sintering

AM Suppliers and Systems	Technique	Build volume (mm)	Materials
ARCAM (A2X) [6]	EBM	200x200x380	Ti6Al4V, Ti6Al4V ELI, CP Ti, CoCr, IN718
ARCAM (Q20plus) [6]		Ø350x380	
EOS (M290) [7]	LS	250x250x325	Ti6Al4V, Ti6Al4V ELI, AlSi10Mg, CoCr, MS1, HX, IN625, IN718, stainless steels
EOS (M400) [7]		400x400x400	
Concept laser LaserCusing (M2) [8]	LS	250x250x280	AlSi10Mg, Ti6Al4V, Ti6Al4V ELI, CP Ti, IN718, IN625, bronze, stainless steels
Concept laser LaserCusing (X line 2000R) [8]		800x400x500	
SLM Solutions (SLM 500) [9]	LS	500x280x365	Ti6Al4V ELI, Ti6Al7Nb, AlSi-alloys, CoCr, HX, IN625, IN718, IN939, stainless steel
SLM Solutions (SLM 280 2.0) [9]		280x280x365	
Renishaw (AM 500M) [10]	LS	250x250x350	Ti6Al4V ELI, AlSi10Mg, CoCr, IN625, IN718, stainless steel
Renishaw (AM 400M) [10]		250x250x300	

2.2. When to Use AM

AM can contribute to industrial parts that are both lighter in weight and cheaper to produce compared to parts produced with conventional manufacturing methods. In addition to this, complex geometries that would be very difficult and expensive to produce with conventional manufacturing methods can be manufactured without increased cost with AM.

AM is not, however, beneficial for all applications and to have the potential advantages, a suitable application must be considered. Frazier [2] has summarized the factors favouring a business case with AM compared to conventional manufacturing presented in Table 2. AM is mostly favoured, according to Frazier, for small production lots with a breakeven point between 90-175 parts as illustrates by Figure 3.

AM is not a low-cost production method so it is not favourable for AM to compare the recurring cost for a part manufactured with AM to the same geometry manufactured with conventional manufacturing. To fully take advantage of the

potential of AM other aspects need to be considered e.g. complex geometries, lower lead times, reduced weight through optimized AM design [11] and reduced assembly through integration of several parts into one. There are also possibilities to increase the customer value by customized products or integrating additional functions in the part.

Table 2. Factors favouring AM vs conventional manufacturing. Source [2]

Favor AM	Favor Conventional Manufacturing
Low production volumes	Large production volumes
High material cost	Low material costs
High machining cost	Easily processed/machined materials
Capital investment	Centralized manufacturing
Logistics costs	
Transportation costs	
Prototyping

Figure 3. Low volume business case for conventional fabrication methods vs AM with two different Recurring Costs (RC), adapted from [2].

2.3. EBM Compared to LS

EBM and LS are both PBF processes with the same basic principles. However, even though the processes are similar, the procedures differ in some important aspects which results in different properties of the AM component depending on which AM equipment that is used. The major differences between EBM and LS processes are presented in Table 3. The EBM process is performed in vacuum using a pre-heated powder bed which effectively reduces the residual stresses in the final part [12]. LS processes are generally performed in non-heated build chambers with argon gas environment [12]. Moreover, the LS non-heated build

chambers generate much higher residual stresses in the material, compared to EBM material, and post stress relieving heat treatment is therefore necessary for LS material [5].

Another important difference between the processes is that LS processes uses smaller size powder particles and thinner build layers, compared to EBM, which result in better surface finish for LS parts, i.e. a lower surface roughness [13].

Table 3. Electron Beam Melting (EBM) process compared to laser sintering (LS) .

	EBM	LS
Environment	Vacuum [6]	Inert gas [7]
Heated powder bed	Yes, approx. 700°C [6]	No* [15]
Layer thickness	50-70µm [6]	20-30µm [7]
Powder size	45-100µm [6]	25-45µm [14]

* Generally, not heated to high temperatures. Powder bed kept at 90°C [16]

2.4. AM for Aerospace Applications

Additive manufactured components are generally considered to have great potential for aerospace applications. The performance of aerospace components can be improved by new innovative design solutions that now are possible with AM. Light weight design is one good example of improved performance that would be appealing to the aerospace industry. A reduced weight could for an aircraft, like for example the Saab JAS 39 Gripen in Figure 4, contribute to extended flight range, increased payload and reduced fuel consumption.

Even though AM is an expensive manufacturing method it could contribute to reduced costs through reducing assembly and machining operations. In addition, welding and other joining operations can be eliminated by integration of several parts into one AM part [17]. Moreover, reduced machining by producing AM parts with final or near-net-shape geometry would considerably reduce the amount of machining which is an expensive for tough materials, like for example titanium and nickel base alloys [4].

Figure 4. The Saab JAS 39 Gripen fighter. Photo Frans Dely. Copyright Saab AB.

There are however still a number of challenges yet to be solved before AM can be fully utilized in aerospace applications, a few of them are listed below [18]:

- The variation in material properties and quality between different AM equipment must be understood and controlled.
- Qualification methods adapted to AM must be established.
- There is a need for new reliable non-destructive testing (NDT) methods to enable inspection of aerospace AM parts for critical flaws and defects.
- Design guide lines for AM need to be established to be able to use innovative AM design to reduce weight
- Improved fatigue properties for AM materials through better surface finish are needed.
- Simulation models are needed to predict properties and microstructure for an AM process.
- New alloys especially adapted for AM processes should be developed

3. TITANIUM Ti6Al4V

This chapter provides general information about the titanium alloy Ti6Al4V addressed in this thesis. Alloy Ti6Al4V is to date the most widely used titanium alloy by far and correspond to more than 50 % of the annual titanium production [19]. Aerospace and medical industry are two of the major customers and in 2006, aerospace used 44% of the world production of titanium in which Ti6Al4V was the most commonly used alloy [20].

When it comes to metal AM, Ti6Al4V is the alloy that have been investigated the most, which can be attributed to a large range of possible business cases of advanced industrial parts with low production volumes [2]. Additive manufactured Ti6Al4V has the same chemical composition, see Table 4, as Ti6Al4V produced from conventional production forms like for example castings, bars or forgings. However, material behaviour for AM Ti6Al4V can still be very different compared to the behaviour of Ti6Al4V from conventional product forms. The different behaviour can both be attributed to differences in microstructure [12,13,21] but also due to effects of the rough as-built AM surface which affects both fatigue behaviour [12,21–23] and static properties [21,22,24].

Table 4. Nominal chemical composition, according to ASTM F2924-14, for Ti6Al4V manufactured by powder bed fusing

	Al	V	Fe	O	C	N	H	Y	Other	Ti
Min, %	5.50	3.50	-	-	-	-	-	-	-	remainder
Max, %	6.75	4.50	0.30	0.20	0.08	0.05	0.015	0.005	0.40	

3.1. Microstructure

The AM PBF production methods are complex and includes both layer-by-layer manufacturing and repeated heating, see Figure 2, of the material [2]. The heat cycle, that includes both heating and cooling, is rapid and grain formation is therefore very fast even though the grains do not have time to grow further due to the quick cooling, in which cooling rates of 10^4 K/s have been reported for LS [2]. During each heat cycle, the laser or electron beam melts simultaneously both a new layer of un-melted powder and several layers of already solidified material. This gives a continuous microstructure across the layers and the growth of columnar grain structure is promoted in the vertical building direction [2].

3.1.1. Conventional Produced Ti6Al4V

The microstructure of Ti6Al4V from conventional product forms is achieved by refinement of the grains during cooling from the β -phase or the $\alpha+\beta$ phase region followed by ageing heat treatment to dissolve the martensite formed at quenching. During slow cooling from the β -region the microstructure start to form α -phase below the β -transus (980°C). The α form as plates and together with the remaining β -phase it forms a Widmanstätten structure which is illustrated in Figure 5 [25].

When cooled quickly from temperatures above the β -transus (980°C) the β -phase could decompose to martensitic α' or α'' structure with only a small amount of remaining β . The β -phase can remain in the structure even after rapid cooling since the end of the martensitic transformation, M_f , is below room temperature (< 25°C) for this alloy and not all β is therefore transformed to α' or α'' . Subsequent heat treatment to achieve a more ductile material is common by, for example mill annealing at 730°C for 4h, which gives a microstructure with globular crystals of β within an α -matrix [25].

Figure 5. Phase diagram for Ti6Al4V and schematic microstructure at intermediate temperatures during slow cooling from a temperature above the β -transus. The final microstructure has plates of α (white) separated by β -phase (dark). Adapted from [25]

3.1.2. EBM Produced Ti6Al4V

Ti6Al4V produced by EBM has a pronounced columnar grain structure in the vertical building direction that is continuous through multiple building layers as illustrated by Figure 6 [11,26]. The microstructure generally consists of α (hcp) + β (bcc) microstructure [12] and has elongated columnar (epitaxial) β -grains with a secondary α -phase that has grown from prior β -grain boundaries [11,26]. The α -phase is acicular (needle like) or plate like and has generally a fine and evenly distributed Widmanstätten (basket weave) structure [26]. The microstructure of EBM material subjected to HIP has been found to be coarser but otherwise similar to the microstructure of EBM without heat treatment which is illustrated in Figure 7 [26]. The rough as-built AM surface consists of partially melted powder grains that are attached to the surface. These grains have a continuous microstructure with the bulk material which can be seen in Figure 8.

Figure 6. Columnar grains of EBM Ti6Al4V material, b.d.= build direction.

Figure 7. Microstructure of EBM Ti6Al4V as-built (left) and HIP:ed (right).

Figure 8. Partially melted grains attached to the surface with continuous microstructure continuing into the bulk material.

3.1.3. LS Produced Ti6Al4V

Ti6Al4V produced with LS show somewhat different microstructure characteristics compared to EBM material. The higher cooling rates of LS give a finer microstructure, compared to EBM material, but the high rate also contributes to considerable higher residual stresses if no post heat treatment is performed [15].

Similar to the EBM microstructure, the LS Ti6Al4V has a pronounced columnar grain structure in the vertical building direction that is continuous through several building layers [15,21,27]. If no post heat treatment is performed for LS material, the microstructure generally consists of α - α' (martensite) microstructure [12]. The columnar grains are filled with 1-2 μ m wide martensitic laths that are transformed from prior β -grain boundaries [13]. LS material that is post heat treated with stress relieving, at 700-730°C for 1-2h, can either have martensitic α' microstructure or a mixture of α + β if the temperature exposure is large enough [21,28]. If the LS material is annealed at higher temperatures (900°C 2h + 700°C 1h), the α' is transformed to α + β microstructure [21].

3.2. Internal Material Defects

3.2.1. Porosity

Spherical microporosity, see Figure 9, in both EBM and LS material originates generally from the gas atomized powder which could contain entrapped microporosity of argon gas bubbles [26,29]. However, if appropriate AM process parameters are used a pore free material is generally achieved with a relative density above 99% [30].

There are different methods for porosity measurements which all can give measurement process induced variations of the results according to Kasperovich *et al.* [21]. Analysis of etched surfaces in 2D can give misleading results due to expansion of the pores by the etchant. Non-etched surface analysis in 2D can give misleading results due to closure of small pores by smearing of material during sample preparation. Computed Tomography (CT) scanning used for 3D analysis can give misleading results with non-detectable pores, if the pores are smaller than the resolution. Moreover, Archimedes technique can greatly overestimates the relative density and give large deviations $\pm 0.4\%$ which is very large when evaluating relative densities of about 99% [21]. Kasperovich *et al.* [21] concluded that the 3D analysis most likely gives the most accurate determination of the internal porosity.

Figure 9. Spherical micro-porosity in as-built EBM Ti6Al4V material.

3.2.2. Lack of Fusion (LOF)

The most severe internal defect in AM materials, from a fatigue point of view, is Lack of Fusion (LOF), see Figure 10, which is primarily formed between the building layers [29]. LOF defects are generally created if there is insufficient energy to properly melt and fuse the new layer with the previous layer during the manufacturing process [29]. Other factors that can promote LOF could be non-optimal focus calibration of the beam, unsuitable parameters of beam current and scan speed, non-optimal settings for powder deposition or powder with to high content of contaminations.

LOF is generally aligned perpendicular to the building direction and forms primarily along the interlayer boundaries in the interface region between the material melted with contour-parameters and material melted with hatching [29].

Three types of LOF have been identified by Liu et al. [29]; Type-I is a “separated” surface with un-melted powder particles, Type-II is a “separated” surface without un-melted powder particles and Type-III is a narrow and long shape with un-melted powder particles. Type-I and Type-II LOF occurs often in vertically built samples while Type-III only occurs in horizontally built samples. The LOF defects act both as stress concentrations and reduces the load-bearing area when samples are loaded in the building direction (perpendicular to the layer). This reduce the fatigue and static strength in building direction as well as the elongation to fracture [31]. For fatigue specimens with machined surfaces the fatigue cracks generally initiated from internal LOF and therefore an elimination of LOF can, through process optimization or HIP treatment, increase the fatigue life [29].

Figure 10. Lack of fusion (LOF), in EBM for Ti6Al4V, located between building layers. Partially melted powder grains are visible.

3.2.3. Effect of Hot Isostatic Pressing (HIP)

The effect of HIP is illustrated in Figure 11, in which material with and without HIP is compared. The EBM material without HIP, investigated in the present study, had a large amount of gas pores and LOF while the non-HIP LS material only had a minor amount of pores and LOF. In contrast, after HIP all internal pores and LOF were eliminated, for both LS and EBM material, and only occasional LOF were visible just below the surface. This indicates that these LOF are directly connected to the surfaces since fully enclosed voids would be needed for HIP to be effective.

Figure 11. a.) EBM with Hot Isostatic Pressing (HIP), b.) EBM without HIP, c.) LS with HIP, d.) LS without HIP, b.d.=Building direction

4. MATERIALS AND EXPERIMENTAL METHODS

4.1. Material

Additive manufactured Ti6Al4V samples were manufactured using both LS and EBM processes. All AM samples that were investigated in the papers included in this thesis were manufactured in one single LS build and one EBM build to avoid batch-to-batch variations. An EOS M 290 equipment was used for LS with 30 μm build layers and an average sized powder of 50 μm . Furthermore, an Arcam A2 equipment was used for EBM with a powder size range of 45-100 μm and 50 μm build layers. A wrought $\varnothing 30\text{mm}$ Ti6Al4V bar, in mill annealed condition, was used for reference tests.

4.1.1. Post Processing

The LS samples were stress relieved (SR) to reduce residual stresses inherent from the process by heat treatment in argon gas at 650°C for 3h. Sandblasting were used to remove loosely bound powder grains from the surface of the LS samples while blasting with titanium powder were used for the EBM samples. To reduce internal porosity, Hot Isostatic Pressing (HIP) heat treatment was performed for the AM samples in an argon gas environment at 920°C and 1000 bar pressure for 2h. Five (5) fatigue test series were excluded from the HIP treatment to be used as references, see Table 5.

4.1.2. Fatigue Test Specimens

The AM fatigue specimens were manufactured with the loading direction in the vertical build direction, the Z-direction, since this orientation generates both the roughest as-built surface [2] and LOF defects oriented perpendicular to the load direction [29]. The fatigue test series are summarized in Table 5.

Two (2) types of fatigue specimen geometries were used, as illustrated in Figure 12 and Figure 13. One (type 1) with an un-notched surface and a theoretical stress concentration factor (K_t) of 1 and one (type 2) with a notch with a radius of 0.85mm and a stress concentration factor of $K_t=2.5$. The LS and EBM specimens were produced with two surface conditions; rough as-built AM surface and machined-and-polished. In this thesis, the rough AM produced surface is referred to as rough as-built surface even though blasting and heat treatment were performed as post processes.

Table 5. Overview of the investigated fatigue test series for Ti6Al4V. HIP=Hot Isostatic Pressing, SR=Stress relieving.

Material	Heat treatment	Surface	Constant amplitude testing	Variable amplitude testing
			Specimen type	Specimen type
EBM	HIP	Machined-and-polished	1 & 2	-
EBM	HIP	Rough as-built	1 & 2	1 & 2
EBM	none	Rough as-built	1 & 2	1 & 2
LS	SR+HIP	Machined-and-polished	1 & 2	-
LS	SR+HIP	Rough as-built	1 & 2	1 & 2
LS	SR	Rough as-built	1	-
Wrought bar	Mill annealed	Machined-and-polished	1 & 2	1 & 2

Figure 12. Fatigue specimens with rough as-built surfaces and machined surfaces. Images from paper II.

Figure 13. Type 2 specimen notch with stress concentration $K_t=2.5$. Machined notch (left), LS-built notch (middle) and EBM-built notch (right). Images from paper I.

4.2. Testing

4.2.1. Hardness Testing

Vickers hardness (HV5) was tested with a Struers Durascan hardness test equipment. The minimum distance between both individual indents and to the outer edge fulfils the requirements in ASTM E384.

4.2.2. Surface Roughness

The surface roughness of cut-out samples was studied using a Nikon Optishot optical microscope and further evaluated with image analysing technique. The surface roughness over an evaluation length of 15 mm was image analysed with an in-house Matlab script [32] that acquires the combined surface roughness profile for multiple micrographs. The surface roughness parameters, R_a (arithmetical mean deviation within a sampling length) and R_v (maximum profile valley depth within a sampling length) are thereafter calculated from the roughness profile.

4.2.3. Internal Defect Investigation

A Nikon Optishot optical microscope was used to investigate the presence of internal defects of polished cut-out AM samples.

4.2.4. Tensile Testing

Tensile testing was performed at room temperature in a servo hydraulic test rig with an Instron 8800 control system. A loading rate corresponding to 0.006 mm/mm/min was applied up to the yield strength and thereafter 0.043 mm/mm/min until fracture.

4.2.5. Constant Load Amplitude Testing

Fatigue testing with constant amplitude loading was performed in a servo hydraulic fatigue test rig with an Instron 8800 controller and an Instron $\pm 50\text{kN}$ load cell. All constant amplitude tests, in this study, were performed at room temperature with a load frequency of 20Hz and a stress ratio of $R=0.1$. The fracture surfaces were investigated by stereomicroscopy and representative fracture surfaces from each test series were further analysed by a HITACHI SU-70 field emission Scanning Electron Microscope (SEM) operating at 15kV.

4.2.6. Aircraft Spectrum for Fatigue Loading

The fighter aircraft wing bending spectrum FALSTAFF (Fighter Aircraft Loading STandard For Fatigue) [33] was used for both cumulative damage calculations and variable amplitude fatigue testing. Short-FALSTAFF, developed by CEAT in Toulouse [34], which is a modified version of the standard FALSTAFF was used to decrease the test times. Compared to the standard FALSTAFF, the Short-FALSTAFF, illustrated in Figure 14, has about 50% less cycles but the remaining cycles still contribute to almost all of the cumulative damage achieved with the standard FALSTAFF sequence [35]. One Short-FALSTAFF sequence correspond to 200 simulated flights and consists of 9 006 rain-flow counted cycles.

Figure 14. One Short-FALSTAFF load sequence in which the maximum tensile peak (100) correspond to the maximum net section peak stress used in the experimental tests. Graph from paper II.

4.2.7. Constant Amplitude Fatigue Design Data

In general, the fatigue life of variable amplitude loaded structures are calculated using constant amplitude fatigue data and a cumulative damage approach with, for example, Palmgren-Miner's rule [36], presented in Eq. 1 [37,38]. The constant amplitude fatigue results, presented in this thesis, were manually curve-fitted to produce Wöhler curves. Moreover, Wöhler curves for Ti6Al4V castings, from the Saab Aeronautics company material database, were scaled to fit these new curve-fitted Wöhler curves with a stress amplitude (σ_a) linear adjustment function which is schematically presented in Figure 15.

Figure 15. A schematic illustration of the linear adjustment procedure. A and B are constants. Graph from paper II.

The same adjustment function was then further applied to the complete Haigh diagram for Ti6Al4V casting, from the Saab Aeronautics company material database, in order to derive a Haigh diagram for each of the constant amplitude test series presented in this thesis.

4.2.8. Cumulative Damage Approach for Fatigue Life Prediction

The rain-flow counted cycles in the Short-FALSTAFF load sequence and the derived Haigh diagram, for each fatigue test series, were used for cumulative damage calculations according to Palmgren-Miner rule [37,38], see Eq. 1, in which D is the cumulative damage, n_i is the numbers of applied load cycles of type i and N_i is the number of type i cycles that equals fatigue failure.

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

A schematic distribution of the rain-flow counted cycles in one Short-FALSTAFF load sequence is illustrated in a Haigh diagram format in Figure 16.

The amount of cycles to fatigue failure for each data point in Figure 16 is calculated for constant mean stress (σ_m) for $R < -1$, for constant minimum stress ($\sigma_{\min}$) for $R > 0$ and by interpolation of amplitude stress (σ_a) between different R -values when $-1 \leq R \leq 0$ using extracted Wöhler curves in the derived Haigh diagram.

Figure 16. A schematic Haigh diagram for one Short-FALSTAFF load sequence. Larger data points represent a greater number of that rain-flow counted cycle in the load sequence. Graph from paper II.

4.2.9. Variable Load Amplitude Testing

Variable amplitude fatigue testing was performed at the maximum net section peak stress that was calculated by cumulative damage approach to give 15 000 simulated flights. The testing was performed at 10 Hz at room temperature using a servo hydraulic fatigue test rig, an Instron 8800 control system and an Instron ± 50 kN load cell. For each test series, the Short-FALSTAFF load sequence was scaled to correspond to the maximum net section peak stress that was predicted to give 15 000 simulated flights. The load sequence was applied over and over again until the test specimen failed by fracture or runout. The fracture surfaces were investigated by stereomicroscopy and further analysed by a HITACHI SU-70 field emission scanning electron microscope (SEM) operating at 15 kV.

5. STATIC STRENGTH

Static tensile strength for AM Ti6Al4V has previously been widely studied and average values of tensile properties are presented in Table 6. The tensile strength for AM material with machined surfaces is in the same range as the strength of wrought material even though there are variations between material from different AM equipment, batch-to-batch variations and variations between different material orientations in the build chamber [2]. AM Ti6Al4V has, however, generally lower ductility compared to wrought material [2]. The tensile fracture mode is mainly intergranular along α -grain boundaries or columnar prior β -grain boundaries which are aligned in the vertical build direction [28]. This results in a rougher fracture surface for specimens loaded in the vertical direction since the cracks cannot follow the columnar grain boundaries in contrast to horizontal loaded specimens [28].

The microstructure of AM Ti6Al4V is coarsened during post heat treatments and it has previously been reported that HIP treatment reduces the static strength and increase the ductility of the material [22]. This behaviour was confirmed in the present study, both by Vickers hardness and tensile testing which is illustrated in Figure 17. The reduction of strength and hardness for material subjected to HIP is considerably larger for LS material compared to EBM material. This can, at least partly, be attributed to the EBM material already having a coarsened microstructure inherent from the hot manufacturing process.

Thin walled AM material with rough as-built surface has reduced static strength compared to bulk material [24]. This is behaviour can most likely be attributed to the surface morphology in which the rough as-built surface is a large part of the thin wall cross section and the load bearing area is thereby considerably reduced. This reducing effect can be neglected for thicker wall thicknesses, above 4 mm, and for AM material with machined surfaces [24].

Hardness testing performed in multiple positions, at a given interval between the edge and the centre of the samples, showed no hardness variation across the thickness profile which is illustrated by Figure 17.

Table 6. Tensile strength of AM Ti6Al4V with machined surfaces (average values). HIP = Hot Isostatic Pressing at 915-920°C for 2h at 1000 bar, SR= stress relieving at 650-700°C for 1-3h, Z= vertical direction, X= horizontal direction, L=longitudinal

Material	Load direction	Ultimate tensile strength, MPa	Ultimate tensile strength, MPa	Elongation to fracture, %	Elongation to fracture, %
no HIP / HIP		no HIP	HIP	no HIP	HIP
EBM This study	Z	1065	1005	12	16
EBM [26,39] [26]	Z	935	905	14	14
	X	970	960	12	14
LS This study	Z	N/A	970	N/A	14
LS [40,41] [21,27]	Z	1200 1135 (SR)	1020	3 9 (SR)	15
	X	1185 (SR)	N/A	7 (SR)	N/A
Wrought, annealed. This study	L	1000	N/A	17	N/A
Wrought, annealed [21,39]	N/A	930	N/A	19	N/A

Figure 17. Mean hardness for different material conditions of Ti6Al4V, ranging from specimen edge to centre. The error bar indicates the maximum and minimum hardness measurement for each position. Three tests per position. Graph from paper I.

6. SURFACE ROUGHNESS

The raw as-built surface of AM material can be very rough and depends both on process parameters and part geometry. Materials manufactured with EBM have about twice the surface roughness compared to LS materials, as illustrated in Figure 18 and Table 7, which can be attributed to the thicker build layers, larger powder sizes and higher scan speeds of the EBM process [13]. The surface roughness R_a (arithmetical mean deviation) has been found to be in the same range as the individual layer thickness of each build [12], see Table 7. Furthermore, the part geometry and the orientation of part in the build chamber have a large impact on the roughness [2]. The surface roughness of a surface parallel to the vertical build direction, Z, can be 2-3 times rougher than a flat horizontal surface [2] and the surface roughness can be attributed to several mechanisms including stair stepping and partially melted powder grains on the surface [42].

Figure 18. As-built AM surfaces compared to machined-and-polished surface. The AM surfaces were post processed with light blasting to remove loosely bound powder grains. Images from paper I.

Table 7. Average surface roughness for EBM and LS Ti6Al4V. R_a = arithmetical mean deviation within a sampling length, AB= as built surface, m&p=machined-and-polished surface

Surface	Surface orientation	Layer thickness (μm)	Surface roughness R_a (μm)
m&p, this study			2
EBM AB, this study	Z	50	34
EBM, [12,43]	Z	100	114
EBM, [44]	Z	50	26
LS, this study	Z	30	14
LS, [12,15,28]	Z	40-50	36

The topography of rough as-built AM surfaces consists of partially melted powder grains which form sharp radii of curvature as illustrated in Figure 19. These radii act as micro notches which give rise to local stress concentrations which can be detrimental for fatigue life [12,42].

Figure 19. Micro notch formed at the surface of an EBM sample. A fatigue crack initiation is visible at the root of the notch. Image from paper I.

In a previous study, Chan et al. [12] compared the rough as-built surfaces of both EBM and LS Ti6Al4V and found that EBM surfaces consist of peaks and valleys, in which the valleys are incompletely filled layers while LS surfaces have completely filled layers. Moreover, Chan et al. calculated the local stress concentrations factor, K_t , for the rough as-built AM surfaces at typical crack initiation locations using the surface roughness, R_v , as notch depth and the radii of curvature at the crack initiation position. The EBM surface corresponded to $K_t=9.1$ and the LS surface to $K_t=5.4$ which both are major stress concentrations factors.

Surface roughness can be measured with different equipment in which one of the most common is the stylus profilometer. However, the rough as-built surface of AM materials contains narrow valleys and overhangs which can be difficult to reach with the stylus profilometer tip. Therefore, the surface roughness measured with a profilometer could be underestimated if the stylus cannot follow the AM peaks and valleys correctly [44]. The surface roughness investigated in this study were therefore measured with image analysing of micrographs.

7. FATIGUE

The fatigue properties of AM material are dependent on both AM method and post process procedures and the fatigue life can be reduced due to, for example, the rough AM as-built surface, geometrical notches or material defects inside the material. All these features lead to an increased local stress concentration which promotes fatigue crack initiation. Moreover, the fatigue behaviour of AM materials with rough as-built surfaces is dominated by the surface roughness rather than by internal defects [18].

The constant amplitude fatigue behaviour of AM Ti6Al4V has been investigated in the present study both for samples with machined surface and samples with rough as-built surface. The fatigue limit is compared, in Table 8, to several previous studies for different material conditions showing a large spread in strength which further enlighten the fact that there can be a large variation in material quality for AM materials even though the same type of AM equipment is used.

Table 8. Fatigue limit at 5×10^6 cycles for AM Ti6Al4V. Un-notched (type 1) specimens tested with constant amplitude loading at stress ratio $R=0.1$.

Material/condition	This study	Previous studies
EBM, HIP, m&p surface	800 MPa (Z)	550-600 MPa (Z) [26,46] 570-650 MPa (X) [22,26]
LS, SR, HIP, m&p surface	500-600 MPa (Z)	650 MPa (X) [22]
EBM, HIP, AB surface	200 MPa (Z)	140 MPa (X) [22]
LS, SR, HIP, AB surface	300 MPa (Z)	185 MPa (X) [22]
EBM, AB surface	180 MPa (Z)	200-250 (Z) [46] 150 (X) [22]
LS, SR, AB surface	300 MPa (Z)	200-450 MPa (Z) [47-48] 200 MPa (X) [22]

HIP= Hot isostatic pressing, m&p=machined-and-polished, SR= stress relieved, AB=as-built surface, Z=loading in vertical direction (building direction), X=loading in horizontal direction.

7.1. Effect of Surface Roughness

The as-built AM surface is generally very rough and the roughness depends both on the AM process and the surface orientation in the built chamber. Fatigue specimens with rough as-built surfaces generally have fatigue failure starting from the rough surface [11,23,47,48], see Figure 19, and results from the present study show that there is a distinct trend that a rougher surface contribute to a reduced fatigue limit as illustrated by Figure 20. For machined AM surfaces, however, fatigue cracks can either start from internal features or from the surface, at internal features that is located at the after machining [11,21], see Figure 21.

Figure 20. Fatigue limit (at 5×10^6 cycles) in comparison to surfaces roughness. R_v = maximum profile valley depth, AB= as-built surface., HIP= Hot Isostatic Pressing. Graph from paper I.

Figure 21. Fracture surfaces with crack initiations location marked with a red circle. a.) EBM+HIP sample with machined-and-polished surface with crack initiation at the surface, b.) LS+HIP sample with machined-and-polished surface with crack initiation at an internal feature. HIP= Hot Isostatic Pressing. Images from paper I.

7.2. Effect of Hot Isostatic Pressing

In literature, it is often stated that Hot Isostatic Pressing (HIP) improves the fatigue properties of AM materials by eliminating internal pores and voids, see Figure 11. This statement is based on fatigue tests with machined-and-polished specimens in which several previous investigations show similar fatigue life for HIP:ed LS [21,40] and EBM [26] Ti6Al4V material compared to conventional wrought material. However, results from the present study show that HIP has negligible enhancing effect on fatigue strength for EBM and LS materials with rough as-built surfaces, see Figure 22 and Figure 23. These findings apply both for un-notched (type 1 samples with $K_t=1$) geometries but also for geometrical notches with as-built surface (type 2 sample with $K_t=2.5$) built directly by AM. These findings are confirmed by a recent study by Greitemeier et al. [22] in which un-notched samples with rough as-built surfaces were studied. Consequently, the same fatigue design data, for fatigue analysis, can be used for either HIP:ed or non-HIP:ed AM materials.

Even though negligible for fatigue design data, the fatigue results for the un-notches EBM specimens (type 1), presented in Figure 22, show a minor tendency of lower fatigue limit for specimens without HIP. This could be explained by the presence of multiple Lack-of-Fusion (LOF) defects in the EBM samples, see Figure 24, and even though the cracks start from the rough surface these LOF will reduce the load bearing area of the fatigue specimen and thereby reduce the apparent fatigue strength. Rough measurements show that approximate 5% of the fatigue fracture area for EBM specimens without HIP was covered by LOF defects. If the maximum stress, for the un-notches EBM specimens (type 1) without HIP, is re-calculated with 5% smaller cross section area, the test results for the un-HIP:ed material will be in line with the HIP:ed material. This shows that, even though the fatigue properties of AM material with rough as-built surfaces is dominated by the surface roughness, a large amount of internal defects can still have a minor influence on the fatigue strength.

Figure 22. Fatigue life for AM samples with and without HIP treatment and $K_t=1$ (type 1) geometry with rough as-built (AB) surface. Graph from paper I.

Figure 23. Fatigue life for AM samples with and without HIP treatment and $K_t=2.5$ (type 2) geometrical notch with a rough as-built (AB) surface. Graph from paper I.

Figure 24. Fracture surface of EBM sample without HIP showing multiple lack of fusions. Images from paper II.

7.3. Fatigue Notch Factor

The fatigue behaviour of un-notched (type 1) Ti6Al4V specimens with rough as-built AM surface has been investigated in previous studies, [13,21,22,45–48]. Few aerospace parts have, however, simple flat geometries without any radii or corners that would introduce local stress concentrations. A combined effect of a rough as-built AM surface and a geometrical notch built directly by AM is therefore needed in order to predict the fatigue life for AM parts. The present study is the first study, to our knowledge, that has investigated this combined effect.

A console for the JAS 39 Gripen fighter has been re-designed, for demonstration purpose only, to an AM design to reduce the weight of the part, see Figure 25. The re-designed part has rough as-built AM surface and geometrical notches built directly by AM which both leads to increased local stress concentrations.

Figure 25. A console for the JAS 39 Gripen fighter, re-designed for AM for demonstration purpose.

The fatigue notch factor, K_f , describes the reduction of the fatigue limit due to the presence of a notch in the material, according to Eq. 1 [49].

$$K_f = \frac{\text{un - notched fatigue limit}}{\text{notched fatigue limit}} \quad (\text{Eq. 1})$$

The fatigue notch factor depends on the notch-sensitivity, q , of the material and can therefore deviate from the stress concentration factor, K_t . In this study, both the fatigue reduction due to macro notches (geometrical notches) and due to micro notches (rough as-built AM surfaces and internal defects) have been evaluated using the fatigue notch factor. The fatigue limit for wrought bar with an unnotched ($K_t=1$, type 1) machined-and-polished surface was used as base line and the fatigue notch factor, K_f , was calculated in relation to this base line for all other fatigue test series using Eq. 2. The fatigue limit was defined as the maximum stress at 5×10^6 cycles to failure for each test series. The resulting fatigue notch factors are presented in Table 9, Figure 26 and Figure 27 indicating the severity of different material defects in respect to the fatigue limit.

$$K_f = \frac{\text{fatigue limit for wrought bar } K_t = 1(\text{type 1})}{\text{fatigue limit for each test series}} \quad (\text{Eq. 2})$$

Table 9. Fatigue notch factor K_f for both specimens with (type 2) and without (type 1) a geometrical notch. HIP= hot isostatic pressing, AB= as-built.

Fatigue notch factor K_f	Wrought bar, machined/polished surface	EBM+HIP, machined/polished surface	LS+HIP, machined/polished surface	LS + HIP/no HIP, rough AB surface	EBM + HIP/no HIP, rough AB surface
Un-notched (type 1)	1	1.0	1.5	2.8	4.3
Notched (type 2)	1.61	1.8	1.8	6.2	6.6

The fatigue notch factor for the notched fatigue test series (type 2 specimens) were similar when comparing EBM to LS material, for both machined and AM build notches respectively, while the un-notched test series had significant differences in fatigue notch factors.

In previous investigations by Chan [42] and Chan *et al.* [12] of rough as-built surfaces, both the average local stress concentration for surface micro notches, $K_t=3.3$ for EBM and $K_t=2.3$ for LS, and the actual local stress concentration at typical crack initiation sites for un-notched specimens, $K_t=9.1$ for EBM and $K_t=5.4$ for LS, were determined. Consequently, there is a considerable larger difference between the maximum stress concentrations at the crack initiation compared to the average stress concentrations.

The similar fatigue notch factor, in the present study, for EBM and LS material, with machined and AM build notches respectively, can therefore most likely be attributed to a volume effect in which the crack will be guided to start at the cross section of the notch for notched samples. The probability is then low that the most severe surface or internal defect of the sample will be located at the notch and an average local stress concentration would be more likely. This will result in a similar fatigue behaviour for the notched EBM and LS samples while the un-notched samples will have failure from the most severe surface or internal defect located anywhere in gauge section of the specimen keeping the inherent differences of the EBM and LS materials.

Figure 26. Fatigue notch factor, K_f , for LS material compared to wrought material. K_t = Stress concentration factor. AB= as-built surface. Graph from paper I.

Figure 27. Fatigue notch factor, K_f , for EBM material compared to wrought material. K_t = Stress concentration factor. AB= as-built surface. Graph from paper I.

7.4. Notch Sensitivity

Chan *et al.* [12] has determined the local stress concentration, K_t , at typical as-built surface crack initiation locations, as discussed in the previous section. If the stress concentrations from Chan *et al.* is combined with the fatigue notch factor determined in the present study, the notch sensitivity, q , which is given in Eq. 3 [49] can be determined for both LS and EBM material with rough as-built surfaces, see Table 10.

$$q = \frac{K_f - 1}{K_t - 1} \quad (\text{Eq. 3})$$

Table 10. Notch sensitivity, q , determined from the stress concentration factor, K_t , and the fatigue notch factor, K_f , for AM material with rough as-built (AB) surfaces. Machined wrought bar is given as a reference.

Material	K_t	K_f	q
LS AB surface	5.4 [12]	2.8*	0.4
EBM, AB surface	9.1 [12]	4.3*	0.4
Wrought bar with machined notch (reference)	2.5	1.6**	0.4

* $K_t=1$ (type 1) specimen, ** $K_t=2.5$ (type 2) specimen

The notch sensitivity, q , in Table 10 appears to be equal for EBM and LS material with rough as-built surfaces and wrought bar with machined surface even though the fatigue behaviour differs greatly.

7.5. Variable Amplitude Fatigue

Prior to this study, there have been no previously published studies, to our knowledge, on variable amplitude fatigue behaviour for any AM metal material, Ti6Al4V included. This is not unexpected since a lot of variable amplitude fatigue testing is company specific and performed in-house at companies, hence the low number of publications. Moreover, the focus in academia for AM research has so far been primarily on fundamental material behaviour at the expense of applied research like variable amplitude fatigue testing.

7.5.1. Predicted Fatigue Life

The fatigue life for specimens, both with (type 2) and without (type 1) geometrical notches, has been predicted with a critical cumulative damage sum $D=1$ for fatigue loading with the variable amplitude load sequence Short-FALSTAFF. The predictions are presented in Figure 29 and Figure 30 and the predicted

maximum net section peak stress that correspond to 15 000 simulated flights for each test series was then further used for fatigue testing.

7.5.2. Experimental Results Compared to Predictions

The fatigue test results with the Short-FALSTAFF variable amplitude load sequence are in good agreement with the predicted fatigue life for all test series as illustrated by Table 11 and Figure 28, in which an experimental fatigue life exceeding 15 000 simulated flights generates a $D > 1.0$. However, even though in good agreement to the predictions, the experimental fatigue life was generally slightly underestimated resulting in an average experimental cumulative damage of $D \geq 1.0$ for all test series which is presented in Table 11.

Figure 28. Predicted fatigue life compared to experimental results. Graph from paper II.

Table 11. Average fatigue life and corresponding cumulative damage. $K_t=1$ (type 1) and $K_t=2.5$ (type 2) specimens are combined in the evaluation. 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
Predicted fatigue life, all series	15 000	N/A	N/A
Wrought bar	17 950	1.2	0.8-1.6
LS (HIP) *	22 320	1.5	1.5
EBM (HIP)	17 125	1.1	1.0-1.3
EBM (no HIP)	14 470	1.0	0.8-1.2
EBM (both HIP and no HIP)	15 800	1.1	0.8-1.3

* All specimens had similar fatigue life, i.e. no scatter

7.5.3. Effect of Hot Isostatic Pressing (HIP)

The EBM material was tested both with and without HIP treatment and no distinct difference can be seen between the two conditions, see Figure 29 and Figure 30, even though there are tendencies that the non-HIP samples without geometrical notches (type 1, $K_t=1$) had slightly shorter fatigue life. This behaviour can be related to the discussion in section 7.2, in which non-HIP samples had an apparent lower fatigue strength due to a 5 % smaller load bearing area due to a considerable amount of internal defects in the fracture surface. The same theory applies for the variable amplitude test results, in which a re-calculation of the maximum net section peak stress with a 5% smaller cross-section area, would result in non-HIP fatigue life in line with the HIP:ed samples.

Moreover, since this tendency only can be seen for un-notched samples without HIP, this correspond well with the discussion in section 7.3. The notched specimens (type 2, $K_t=2.5$) will have failure starting from a location, in the notch, with an average severity in the local stress concentration while the un-notched (type 1, $K_t=1$) specimens will have cracks starting from the most severe surface or internal defect in the gauge section of the specimen. Hence, the notched samples, with rough as-built surface, will have more similar behaviour regardless of HIP or not compared to the un-notched samples.

Figure 29. Fatigue life for variable amplitude test with un-notched samples (type 1, $K_t=1$). AB= as-built, HIP=Hot Isostatic Pressing. Graph from paper II.

Figure 30. Fatigue life for variable amplitude test with notched samples (type 2, $K_t=2.5$). AB= as-built, HIP=Hot Isostatic Pressing. Graph from paper II.

8. SUMMARY OF INCLUDED PAPERS

Paper I: Fatigue behaviour of notched additive manufactured Ti6Al4V with as-built surfaces

In this study, titanium alloy Ti6Al4V produced by the Additive Manufacturing (AM) processes Electron Beam Melting (EBM) and Laser Sintering (LS) were investigated. The main purpose of this paper was to determine the effect on constant amplitude fatigue properties for combinations of rough as-built AM surface and geometrical notches built directly by AM. Furthermore, the effect of Hot Isostatic Pressing (HIP) treatment on specimens with rough as-built surface was investigated.

The rough surface was found to be the single most severe factor for materials with rough as-built surfaces. Consequently, the fatigue strength for materials with a rough as-built surface were approximate 65-75 % lower than for conventional produced material and a geometrical notch in combination with a rough as-built surface reduced the fatigue strength even more. HIP treatment did not give any improvement in fatigue life for samples with rough as-built surfaces since the fatigue behaviour will be dominated by the local stress concentrations at the rough surface rather than by internal defects.

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

The purpose of this study was to investigate the variable amplitude fatigue behaviour for Ti6Al4V, with rough as-built surfaces, manufactured with Additive Manufacturing (AM). Material produced with the AM processes Electron Beam Melting (EBM) and Laser Sintering (LS) was investigated using both notched and un-notched specimens. The fatigue life was predicted for variable amplitude load sequence Short-FALSTAFF (Fighter Aircraft Loading STandard For Fatigue) using constant amplitude fatigue data and a cumulative damage approach. Variable amplitude testing was performed and the predicted and experimental fatigue life showed good agreement, even though a majority of the experimental results slightly exceeded the predicted life. Furthermore, Hot Isostatic Pressing (HIP) treatment had negligible enhancing effect on the fatigue properties for material with rough as-built surfaces.

9. CONCLUSIONS

The research presented in this licentiate thesis deals with the fatigue behaviour of the titanium alloy Ti6Al4V produced with the Additive Manufacturing (AM) processes Laser Sintering (LS) and Electron Beam Melting (EBM). The studies in this thesis has been focused on determining the fatigue properties of material with rough as-built AM surfaces and the combined fatigue behaviour of geometrical notches with rough as-built surfaces. It was found that the rough as-built surface was the single most severe factor for fatigue. The rough as-built surface alone resulted in a fatigue notch factor, K_f , of 2.8 for LS material and 4.3 for EBM material, which correspond to 65-75% reduction in fatigue strength.

Few aircraft parts have, however, simple flat geometries and the effect of stress concentrations like corners or radii of curvature need to be considered. AM specimens with geometrical notches with rough as-built surfaces were investigated and resulted in fatigue notch factors of $K_f=6.2$ for LS and $K_f=6.6$ for EBM in relation to smooth specimens of wrought bar material. The notch sensitivity, q , was found to be equal for LS and EBM material with rough as-built surface and machined wrought material.

Furthermore, the constant amplitude fatigue data and cumulative damage calculations were used to predict the fatigue life for the variable amplitude load sequence Short-FALSTAFF (Fighter Aircraft Loading STandard For Fatigue) which is a tensile dominated load spectrum. Cumulative damage calculations were used to predict a load level corresponding to 15 000 simulated flights which were further used for variable fatigue testing. The predicted fatigue life was overall consistent to the experimental results, even though most experiments slightly exceeded the predicted life. Consequently, a cumulative damage approach can therefore be used, at least for tensile dominated load sequences, to predict the fatigue life for variable amplitude loaded Ti6Al4V structures manufactured by AM.

Neither constant nor variable amplitude loading showed any significant improvement in fatigue life for material subjected to Hot Isostatic Pressing (HIP) treatment for specimens with rough as-built surfaces. The conclusion is that the fatigue behaviour will be dominated by the rough as-built surface rather than by defects inside the material.

Finally, to fully be able to use the potential of AM in aerospace applications, the fatigue properties need to be improved by further work to reduce the surface roughness, either by process parameter optimization or by post processing.

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