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Declaration

I, **Joel Chinyama (student number 692429)**, enrolled in **MECN8006A** as part of the 2024 **MSc in Mechanical Engineering** program, hereby submit my work titled "Fatigue Crack Propagation in AlSi10Mg Additive Manufactured Aeronautical Parts Processed by Laser Shock Peening" in partial fulfilment of the course requirements.

I hereby declare the following:

- a) I confirm that, except where explicitly stated otherwise, the work submitted herewith for assessment in the aforementioned course is entirely my own original work, completed without assistance from others.
- b) This work has not previously been submitted for any course requirement, examination, or degree at any university or other tertiary educational institution, either by me or in collaboration with others.
- c) I acknowledge the University of the Witwatersrand's right to take disciplinary action if it is found that this work is not my own unaided effort or if I fail to properly credit the sources of any ideas or language used in this task.

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Abstract

Additive manufacturing (AM) offers advantages for complex aeronautical parts, but inherent defects can reduce fatigue life. Post-processing techniques such as laser shock peening (LSP) can be used to introduce beneficial compressive residual stress that hinders crack propagation. This study investigates LSP as a method to improve fatigue performance in additively manufactured AlSi10Mg aeronautical parts. It examined how varying LSP treatment laser power intensity ($1.5 - 4.5 \text{ GW/cm}^2$) affects LSP's effectiveness and identified optimal LSP residual stress profiles for peak fatigue performance. The residual stress profiles that were used in this research were adopted from previous experimental work done on AM-manufactured AlSi10Mg alloys within the Wits AM/LSP group.

Previous experimental work results on wrought AA2024-T351 (untreated and LSP-treated cases) indicated that LSP-treated samples have a fatigue life of at least four times longer as compared to as-built samples. AFGROW models with similar geometry, material properties and load conditions were used to predict the fatigue life of as-built and LSP-treated cases. An improvement in fatigue life of at least 3.8 times was observed, which was within an acceptable deviation from the experimental results. These results were used to validate AFGROW models for exploring different specimens.

Fracture mechanics models (AFGROW) were used to compare the fatigue life of as-built and LSP-treated AlSi10Mg samples with different LSP power intensity parameters. The results showed that LSP treatment can significantly extend fatigue life, with the optimal laser power intensity found to be 3.0 GW/cm^2 . This improvement is attributed to the introduction of compressive residual stresses by LSP, which suppress crack initiation and propagation.

The effectiveness of LSP was further explored in the context of the Cessna 172/175 horizontal stabilizer, a part that could benefit from AM for weight reduction and structural integrity. AFGROW models were developed to predict the fatigue life of the centre lightening hole in the forward spar, a critical location for crack initiation. The models incorporated a beta correction factor to account for the specific crack geometry and stress distribution. The beta correction factor was determined by comparing the stress intensity factors from the Finite Element Analysis (FEA) and AFGROW models. The results again demonstrated a significant increase in fatigue life (of at least six times) for LSP-treated parts compared to as-built parts. AFGROW models with a beta correction factor proved valuable for predicting fatigue life in components with complex geometries. This study confirms that LSP is an effective post-processing technique for mitigating fatigue crack propagation in AlSi10Mg AM aeronautical parts.

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Introduction

Companies have adopted advanced manufacturing technologies such as Additive Manufacturing (AM) to improve manufacturing costs, accuracy and turnaround times. AM offers a broader range of benefits compared to other manufacturing processes. Those advantages include the fabrication of complex parts as functional pieces eliminating the need for rigorous assemblies; reduction in raw materials wastage since the unused powder can be collected and re-used again in the building of other parts; AM allows for rapid prototyping of concepts with a high level of repeatability enabling the designers to make necessary adjustments to the designs at an early stage. Due to these benefits, AM technology attracts the attention of many industries, e.g. automotive, medical and aeronautical. In the aeronautical sector, AM can facilitate the production of lighter parts since the material will only be introduced where needed, making a provision for easier topological optimisation. This can significantly reduce the aircraft's total weight, leading to reduced fuel consumption and better performance.

Fatigue life is the number of loading cycles for a crack to initiate, propagate and finally cause part failure. The most life-limiting failure mechanism in AM parts is fatigue caused by cracks nucleated from defects and surface roughness. Defects are unavoidable in AM parts, as they are in any other manufacturing process, and they vary depending on the process, the feedstock and the building direction [1]. Part quality is difficult to ensure in AM parts due to the complexity of the pore characteristics and distributions, which affect the overall repeatability of the manufacturing process pore characteristics and distributions complexity, which influence the manufacturing process's overall repeatability. Due to thermal stresses caused by the rapid heating and cooling of the part during the manufacturing process, AM parts typically have adverse tensile residual stress profiles [1]. Because of the localised nature of fatigue failure, the fatigue life of parts is more influenced by the presence of defects, tensile residual stress and surface discontinuities, all of which are inherently present in today's AM metal parts. As a result, AM parts have significantly lower fatigue resistance compared to conventionally produced parts. The ability of manufacturers to predict discrepancies in the mechanical properties of AM parts based on their microstructure is critical to the full adoption of the AM process as the primary choice for producing actual application parts [1].

However, post-processing techniques such as laser shock peening (LSP) can be used to treat AM parts to change the as-built material properties to match the desired properties. According to research, LSP can introduce compressive residual stresses that can counteract the tensile residual stress caused by the AM process, potentially improving the fatigue strength of the part. During the treatment process, LSP also modifies the part surface, changing the surface roughness and the overall fatigue life of a part [2]. As a result, the ability to predict fatigue life based on process-induced defects, surface roughness and the combined residual stress field is proving to be an important technique in evaluating the performance of

innovative aeronautical components under cyclic loads. Air Force Grow (AFGROW) program can predict the fatigue life of metallic parts with different crack geometries and loading conditions, including tension, bending and bearing loads and residual stress states [3]. So AFGROW provides features that can be useful in modelling the fatigue properties of AM parts in an as-built condition and post-LSP treatment.

1. Literature Review

AM technology is gaining increased attention from various manufacturing industries due to its ability to produce complex parts or components as a single functional unit, thereby reducing assembly times and the need for joints [4]. In the aeronautical industry, AM can help with the production of lighter weight parts because the material is only added where it is needed, allowing for lightening holes. However, surface discontinuities and internal flaws of AM parts pose a danger to the fatigue life of parts in the aeronautical industry, where components are subjected to cyclic loads in service. The successful adoption of AM parts in the aeronautical industry greatly depends on the ability of the manufacturers to predict the component's fatigue life with the inherent flaws and surface finish [4].

1.1 Additive Manufacturing

AM uses a layer-by-layer building approach, a part is modelled with a 3D computer aided design software, and it will be divided into discrete layers by the AM machine [5]. Metallic powder is deposited on a uniform bed and the powder is melted using a laser or electron beam to form the base layer. The new powder is added and melted to fuse with the base layer, and it forms the second layer when it solidifies. The process is repeated layer by layer until the full part is formed. The part quality is dependent on the processing parameters presets, beam scanning pattern and the AM process used. The parts processed are ready for use in real applications with minimal to no post-processing, significantly reducing the manufacturing time. The most adopted AM technique is the selective laser melting (SLM), a laser power bed fusion (L-PBF) process. SLM utilises an adjustable laser beam wavelength, offering a high degree of material flexibility and accuracy. Other processes that can be used include electron beam melting (EBM), where an electron beam is used instead of a laser beam. This limits the materials that can be processed as the electrons require conductive materials. Both EBM and SLM use a layer-by-layer building approach. However, they differ in the operating atmosphere. EBM operates in a vacuum to avoid metal oxidation at high melting temperatures and the process uses hot powder. Whereas SLM uses cold powder in an inert environment and the size of a laser beam is smaller as compared to an electron beam, so offering a higher degree of precision. Hence EBM is faster since a wider beam can melt a larger area; however, this compromises the surface finish of the part [5].

In SLM, metal powder is added to a building platform and selectively melted by a laser beam following a layer geometry feed from the CAD design file. The molten metal quickly re-solidifies, forming the base layer, lowering the platform and adding new powder. The process is repeated with the layers fusing each other until the entire 3D part is formed on the building platform. Figure 1 shows an SLM process schematic diagram.

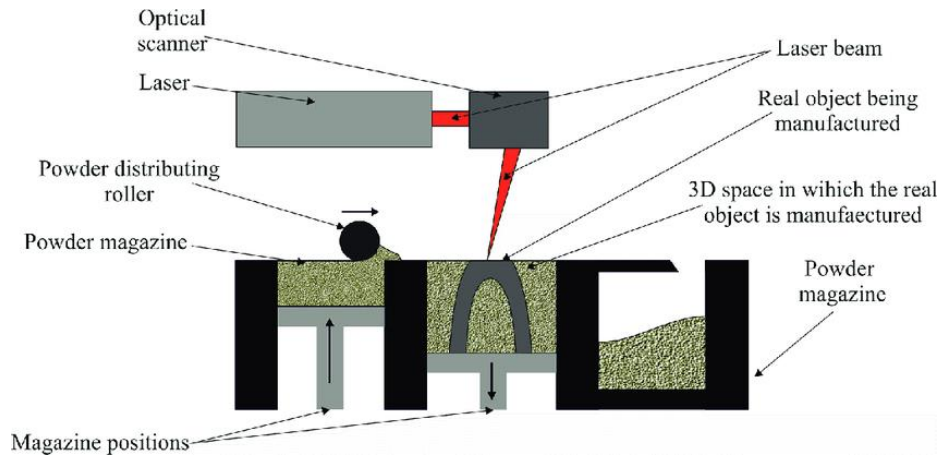


Figure 1: Selective Laser Melting schematic diagram [6].

The part quality is affected by the size of the metal powder particles, the scanning patterns and speed, hatch distance, laser intensity and layer thickness. AM parts tend to have an undesirable surface finish, porosity and inconsistent microstructure. Hence, it is important to develop a manufacturing strategy that optimises the sensitive parameters and produces a part with minimal defects [6].

During the AM process, the part is exposed to rapid heating and cooling thermal cycles, which leads to the development of residual stresses which are tensile in nature. When a new layer is molten on top of the previous layers, a thermal gradient is formed, and the new layer will be at a higher temperature than the previous layers. As the new layer expands, the expansion is limited by the lower temperature layers resulting in compressive stresses being developed in the new layer and tensile stresses in the previously deposited layers. The new layer experiences thermal contraction when the laser beam is removed causing it to shrink due to the difference in cooling rates for the new and previous layers. This results in residual stresses forming in the part, tensile in the top surface and compressive in the previous layers [7]. Figure 2 shows a residual stress model for the AM process.

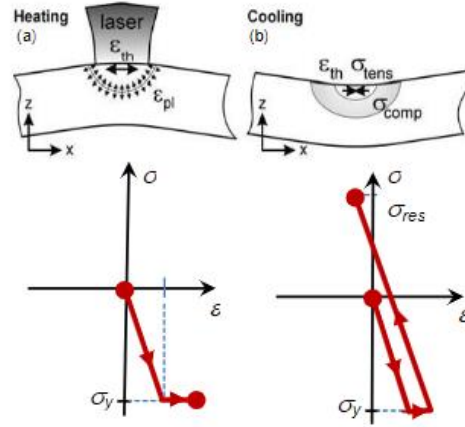


Figure 2: Residual stress formation model for the heating and cooling phase [7].

The challenge with the SLM process is minimising the tensile residual stresses and the surface roughness of the as-built part [7]. High levels of unintentional residual stresses can result in crack formation and accelerated crack growth which affects the fatigue life of AM parts leading to premature fatigue failure. The residual stress variation is also influenced by the part building direction. Building direction influences the residual stress variation due to the difference in heat dissipation paths [8]. Due to the complex nature of the SLM technique, it is common for AM parts to have an anisotropic nature. Thus, the building direction, heat dissipation and laser energy density can influence the mechanical properties of the part.

Incremental hole drilling (IHD) can be used to measure the residual stresses in AM parts. It involves carefully drilling a hole in the part while monitoring strain gauges attached to its surface. As the hole deepens, the relaxation of residual stress causes the material to deform, which is captured by the strain gauges [27]. This data allows the calculation of the stress profile throughout the part's depth. IHD offers high accuracy and a wide measurement range, making it valuable for analysing stress distribution in complex AM components. The aluminium-specific strain gauge rosette that accounts for thermal expansion during drilling to measure residual stresses is shown in Figure 3 [28].

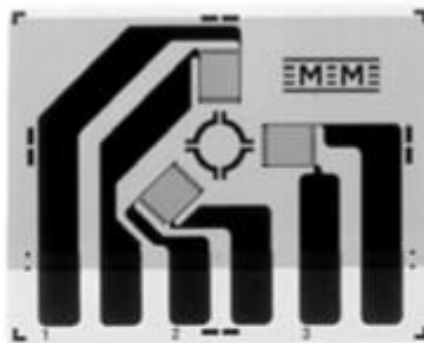


Figure 3: Strain gauge CEA-13-062UL-120 - Type A rosette [28].

However, IHD is a destructive technique, meaning the part is altered during measurement. This can be a drawback for high-value or limited-quantity components. In such cases, non-destructive methods become preferable. X-ray diffraction (XRD) is one such option. It utilises X-rays to probe the atomic structure of the material. By analysing the slight shifts in the atomic lattice caused by residual stress, XRD can estimate the stress state at the surface. Neutron diffraction (ND) offers a deeper look, providing information on stress distribution within the bulk material. However, both XRD and ND require specialised equipment and expertise, limiting their wider application [7]. The selection of the most suitable method depends on several factors, including the component's size, value, and the desired depth of stress information. IHD remains a powerful tool for in-depth analysis, while XRD and ND offer valuable alternatives for non-destructive assessment.

L-PBF technology is the most efficient process for producing parts with the best surface finish quality and relative density depending on the powder size. This technology unlocks the potential for complex part geometries, lightweight designs, and material property optimisation. However, the successful utilisation of AM hinges on the selection of appropriate materials. Metallic materials dominate the landscape of AM-suitable options for aerospace applications. Traditionally employed materials like aluminium alloys, stainless steel and titanium alloys continue to be relevant due to their established properties. Aluminium alloys, for instance, offer a compelling combination of low cost, light weight and a favourable strength-to-weight ratio. However, their limitations at elevated temperatures and, in some high-strength variants, compromised corrosion resistance restrict their applicability in certain aerospace environments. Titanium alloys represent another attractive option, boasting high specific strength, excellent corrosion resistance and exceptional high-temperature stability. These characteristics make them particularly suitable for demanding aerospace applications [4].

The evolution of AM necessitates a shift beyond simply adapting existing alloys. Early AM practices often relied on materials with established track records in traditional manufacturing processes. However, these materials may not be ideally suited for AM due to challenges like cracking, porosity formation, oxidation, or the emergence of other undesirable properties during the AM process. Fortunately, AM presents a unique opportunity to introduce novel and custom-designed alloys. These new materials can be specifically tailored for optimised AM processing, mitigating issues like cracking while simultaneously being further optimised for their intended aerospace application. Examples include the development of custom aluminium alloys like 6061-RAM2, AlSi10Mg and Scalmalloy, which offer superior strength and enable successful AM builds [4].

The construction of intricate, lightweight aeroplane parts has been transformed by additive manufacturing. In this process, powders are essential, and AlSi10Mg is a key component. This powdered aluminium alloy, which is composed of silicon (Si) and magnesium (Mg), is intended especially for additive manufacturing methods such as laser powder bed fusion. AlSi10Mg presents an attractive set of characteristics for use in aircraft. Because of its high strength-to-weight ratio, lighter parts are produced without sacrificing functionality. It is perfect for harsh aircraft conditions because of its excellent mechanical qualities and resistance to corrosion. Moreover, additive manufacturing enables complex designs that are not achievable with conventional processes, allowing for weight optimisation using strategies like lattice structures [4].

However, using AlSi10Mg powder in AM requires strict control. Consistent particle size and composition are essential for achieving defect-free parts with the desired properties. Leading suppliers offer high-quality AlSi10Mg powder specifically tailored for AM processes, ensuring reliable and successful production of critical aeronautical components. Lightweight, strong brackets for antennas are made using AlSi10Mg alloy. This material is perfect for parts that experience high stress loads due to its relative high strength. AlSi10Mg was also used to create a microturbine generator housing in a single piece, cutting down on waste and simplifying the design [4].

Ongoing research on LPB-F powders is evaluating the viability of even more advanced aluminium powder performance. Scalmetalloy is a high-performance aluminium alloy with magnesium and scandium. With its maximum strength among AM aluminium alloys, this novel material can effectively replace the high-strength 7000 series aluminium alloys that are currently in use [4][39]. Because of its remarkable strength-to-weight ratio, which is close to titanium's while maintaining aluminium's lower density, as well as its excellent weldability and resistance to corrosion, this superalloy is perfect for designing and manufacturing high-performance, lightweight parts for aerospace applications [4][40].

However, a major hurdle in using AM for critical aeronautical parts is porosity. These tiny air pockets trapped within the 3D-printed aluminium alloy can significantly weaken the material. Porosity acts as a concentration point for stress, making the part more susceptible to cracks and fatigue failure under the demanding conditions experienced during flight. Strict regulations govern the allowable level of porosity in aeronautical parts, and this ensures the safety and reliability of the aircraft. The challenge lies in minimising porosity during the AM process itself. Factors like laser power, scan speed and even the characteristics of the aluminium powder used can influence the formation and size of these air gaps. Researchers are constantly innovating to improve AM techniques. This includes optimising printing parameters for better fusion between layers and controlling the atmosphere during printing to minimise oxygen and moisture, both of which can contribute to pore formation [8]. AM process optimisation has

successively managed to produce parts with a relative density of up to 99% and a surface roughness of 20 microns on the top surface [8][41].

The different types of pores in AM parts include lack of fusion pores, keyhole pores and metallurgical pores, and these come in different shapes, sizes, and location distribution. Figure 4 shows keyhole pores and unmelted particle defects in AlSi10Mg AM parts.

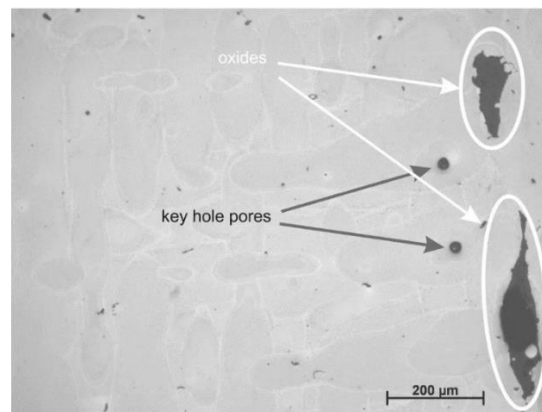


Figure 4: Pores in AlSi10Mg AM parts [9].

Lack of fusion pores are usually formed between the layers when the energy density is insufficient to melt and fuse the layers together. These pores are aligned perpendicularly to the sample building direction, and they reduce the load bearing area when a load is applied along the building direction. Studies have shown that a lack of fusion pores can function as stress concentrators hence they can influence the fatigue failure of the part. On the other hand, the presence of large subsurface pores can result in higher fatigue crack growth rates as compared to identical internal pores in the same sample [10]. The size and distribution of pores in AM parts can vary depending on the AM process used, the material being printed, and the process parameters. In general, AM processes that involve melting the material (such as laser melting and electron beam melting) tend to produce parts with fewer and smaller pores than processes that involve sintering powder [9].

Due to the complexity of the pore characteristics and distributions in AM parts, it is important to understand at what point pores become critical, posing a threat to the use of AM parts in aeronautical applications. Studies have shown that small pores (<0.5 mm) and even moderate total porosity (up to 1%) often have minimal impact on static strength and ductility. In such cases, surface roughness and part geometry play a more significant role in failure mechanisms. However, with increasing porosity, strength and ductility decrease, and failures tend to initiate at the largest pores [10].

Studies have been conducted to assess if surface finish could be a useful parameter in estimating the life of AM parts. Yadollahi et al. [1] investigated the effects of voids and surface roughness on the fatigue performance of Inconel 718 produced using L-PBF technology. The fatigue behaviour was modelled using crack closure-based fatigue models under cyclic loadings. The cracks were initiated from different shapes and sizes of elliptical surface flaws, and surface roughness with different maximum depths. Yadollahi et al. [1] observed that cracks originating from surface discontinuities and voids have life-limiting effects on the fatigue failure mechanism of AM parts.

Fatigue properties present a different scenario. Total porosity and proximity of defects to the surface become crucial, with pores within 1 mm initiating cracks. The largest near-surface pores pose the most significant threat [1][38]. This emphasises the importance of near-surface quality control in L-PBF for fatigue applications. The identification of such pores as critical defects underscores advancements in understanding L-PBF material behaviour [10]. Furthermore, void size measured perpendicular to the applied load's direction significantly affected the part's fatigue life. Therefore, knowing the maximum depth of surface roughness and size of voids present in a part is crucial in predicting the fatigue life of AM parts [1].

LSP is a post-processing technique increasingly used in AM to address porosity, a common challenge in AM processes. LSP utilises high-powered laser pulses to create shockwaves that impact the surface of the AM part. This impact creates compressive stresses that densify the material, effectively closing or reducing pores [11][42]. This pore closure leads to a denser, stronger, and more fatigue-resistant final product. The effectiveness of LSP in closing pores depends on several factors, including the laser pulse characteristics, the material properties of the AM part, and the number of LSP passes applied. By carefully controlling these parameters, manufacturers can achieve significant improvements in the porosity of AM parts, making them suitable for demanding applications [11]. Huang et al. [29] observed the average grain size of the unpeened sample as 200 μm , whereas the LSP-peened sample had an average grain size of 150 μm . This indicates that the LSP process resulted in a significant refinement of the grain size in the material as shown in Figure 5 [18].

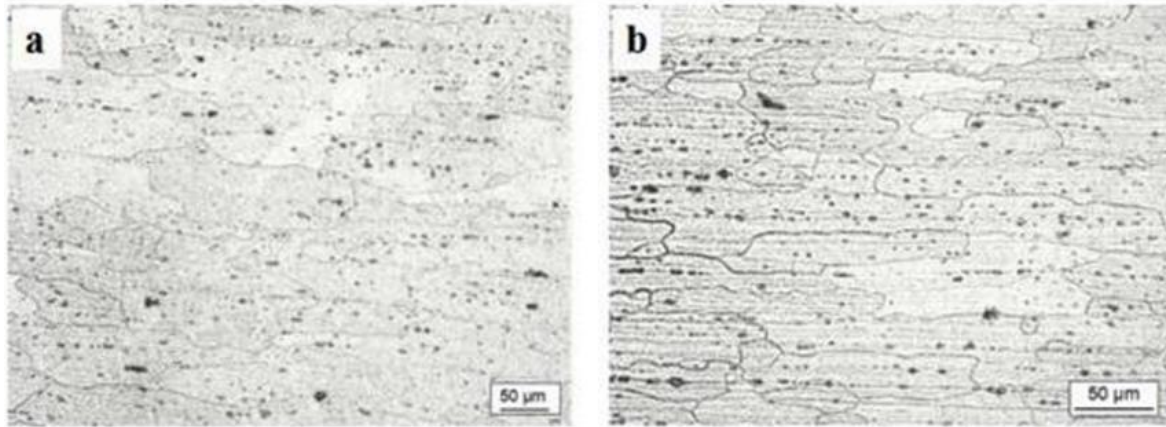


Figure 5: AA6065 grain size a) untreated sample b) LSP treated sample [29].

Other post-processing methods target porosity reduction in different ways. Hot Isostatic Pressing (HIP) exposes the component to high pressure and temperature in an inert gas environment. This forces any trapped gas out of the pores and closes them up. Machining techniques like milling or grinding can physically remove layers of material containing porosity, revealing denser metal underneath [2].

1.2 Laser Shock Peening

Laser Shock Peening (LSP), a surface treatment procedure, can be used to introduce compressive residual stresses in metal parts up to a depth of 1 mm [11]. Figure 6 shows an LSP schematic diagram.

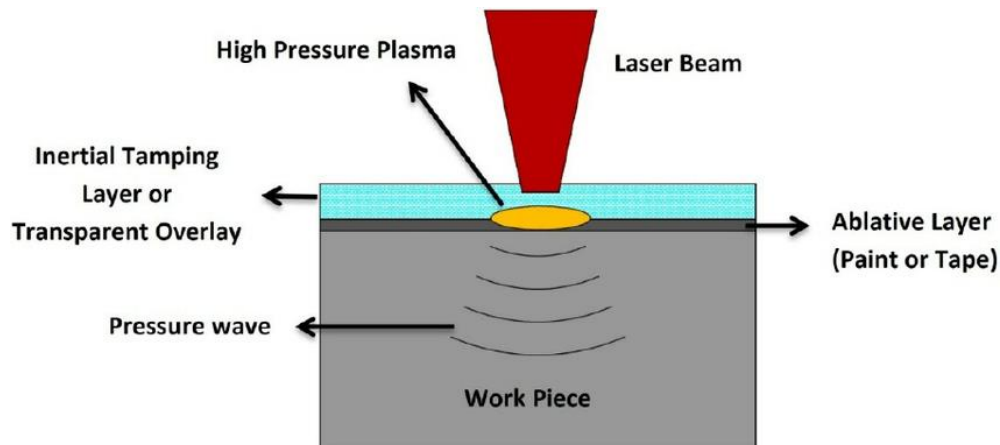


Figure 6: Laser Shocking Peening schematic diagram [11].

When a laser beam hits the target metal surface, a plasma shock wave is generated which in turn applies pressure onto the metal, changing the surface microstructure. The propagation of the shock waves within the material induces compressive residual stresses because of plastic deformation. An ablative layer made of paint or tape can be used to protect the part surface from further surface roughness developing during

the treatment process. Studies have shown that LSP induced surface roughness can greatly impact the corrosion resistance of LSP post-processed parts. The ablative layer can also influence the depth of the induced residual stresses, the induced stress tends to be deeper when a protective coating is used compared to direct exposure of the part surface to the laser beam [12].

The extent of post-processing depends on the nature of the LSP parameters used, this includes laser spot size, coverage, intensity, power, etc. These parameters can be varied to achieve the desired residual stress profiles and surface fatigue properties. The benefits of LSP include improved damage tolerance, high fatigue failure resistance and improved corrosion resistance. These properties shape some of the major requirements in the design of modern intercontinental aircraft, as airlines aim to reduce maintenance costs and increase profit.

Most of the literature available on LSP focuses on residual stress patterns and the surface fatigue properties of conventionally produced aluminium alloys. M. Sticchi investigated the effects of laser spot size and coverage on LSP-induced residual stress in thin aluminium samples treated under water LSP [13]. They observed that increasing the surface stress and optimising the applied pressure can result in deeper compression fields. The zero-depth (an indication of the extent of compressive residual stress through sample thickness) increased with an increase in spot size but there was no significant increase in the maximum compression stress. The maximum value of compression stress (residual stress after LSP) significantly increased when the coverage was increased [13].

The residual stress will be maximum closer to the processed surface and will gradually decrease with increasing depth (turning into tensile). LSP pre-stresses the part thereby decreasing the resultant stress experienced by the part during loading. The strain hardening of the part surface usually slows down the growth of cracks initiating within a region of 1 mm from the surface. This helps reduce the tensile residual stresses induced into the part during the AM process improving the damage resistance of the part. The alteration in the metal microstructure can significantly improve the fatigue life of AM parts since cracks are more likely to initiate from surface discontinuities or subsurface pores [14].

Clauer et al. [15] investigated the use of LSP to enhance the fatigue resistance of metal parts, where cracks initiating from the surface are the major cause of fatigue failure. A specimen with a fastener hole at the centre was subjected to an axial tensile stress load. The fatigue crack growth experiment was conducted on untreated (as-built) specimens and LSP treated specimens. For the LSP treated case, the area around the fastener hole was LSP treated using a spot size greater than the fastener hole diameter. The fatigue life was considered to be coinciding with the point where the crack length vs the number of cycles curve becomes almost vertical. Clauer et al. [15] observed that LSP treated specimens had a fatigue life 40 times longer

than as-built specimens when a single crack sample was evaluated and at least 7 times longer when two identical cracks were evaluated.

A. Jinoop [16] investigated laser AM Inconel 718 post-processing using LSP by varying peak laser power and number of shots at three different levels. They discovered that LSP altered the surface microstructure and mechanical properties of the AM structure. LSP treatment significantly improved the stress resistance of the AM samples by introducing compressive stress on the surface, measuring between 214.9 and 307.9 MPa. This is nearly double (1.7 times) the stress resistance compared to the untreated samples. The surface analysis utilising an optical profilometer and Vickers microhardness revealed a maximum profile depth of 10 μm and a hardness of 360 HV when the ideal power and number of shots were 170 mW and 7, respectively [16]. These results show that LSP can be used as a post-processing technique for enhancing the properties of AM parts.

N. Kalentics [17] investigated the use of LSP as a post-processing method on martensitic 15-5 hardenable PH1 and austenitic 316L printed using SLM. Treatments with and without an ablative medium, shot overlap, laser energy and laser spot size were all changed. The as-built residual stress condition of both materials was converted to a compressive state that was more beneficial. It was discovered that the LSP processing parameters had a considerable influence on the value and depth of the compressive stress [17]. This behaviour is similar to the one observed with AM aluminium alloys, demonstrating the usefulness of LSP as a post-processing surface treatment technique for AM metal parts regardless of the type of metal used [17].

L. Nayager [18] investigated using LSP as a post-processing technique for AM AlSi10Mg parts. The residual stress profiles of the parts were tensile prior to LSP treatment and compressive after treatment, up to a depth of approximately 0.8 mm. The induced compressive stress increased as the intensity increased, with the greatest change from tensile to compressive stress occurring at 4.5 GW/m². However, the LSP treatment process increased the surface roughness of the specimens when compared to as-built specimens, and the surface roughness increased as laser intensity increased. These trends demonstrate LSP's effectiveness in introducing compressive residual stresses in AM parts that are like conventional parts [18].

1.3 Aeronautical Fatigue and Fatigue Life Extension Methods

Aircraft are designed using a fail-safe approach, the material is considered to have initial defects that are capable of growing when the part is in service. Thus, the aircraft will be designed to endure structural damage without compromising operational safety up to a critical damage size, which can be observed by visual inspection during pre-flight inspections. Fatigue crack propagation analysis must be done on all

observed cracks to ensure that the crack will not reach the critical length before the subsequent inspection. Aircraft structures are designed to have multiple load paths and some redundancies to ensure that the aircraft will have residual strength even after the primary support structure has been compromised [19].

Due to the excessive cost of upgrading and replacing aircraft fleets, the fatigue life extension of existing aircraft has become a critical consideration. Non-destructive evaluation techniques, such as magneto-optic imaging (MOI) and the D-Sight Aircraft Inspection System (DAIS), are used to detect subsurface cracks without disassembling the aircraft [20]. LSP has become a vital post-processing technique for structurally critical parts. It has been used to improve the fatigue life of compressor blades, engine fans and airframe structures. LSP is capable of introducing compressive residual stresses that can aid in crack retardation, resulting in a longer component life span. However, due to the complexity of the procedure, LSP is not yet compatible with civil maintenance and repair operations. Hence, there is ongoing research on developing portable low-energy LSP machines and optimising the LSP process in order to get the best results possible [14].

1.4 Fracture Mechanics

Fracture can be described as a process whereby local bonds in a material split up on an atomic level leading to the creation of new surfaces. This bond splitting can be a result of severe thermal or mechanical loading weakening the material resulting in structural failure. Or the presence of cracks or surface discontinuities which can function as regions of stress concentration. Fracture failure can be understood based on crack propagation behaviours in different materials using crack propagation theory. Fracture mechanics use elasticity and plasticity theories in order to predict the threshold force necessary to promote crack propagation that eventually leads to failure. The major assumption of crack propagation is propagation will only occur after the stress intensity factor reaches a particular critical value (K_{IC}) which is dependent on the metallurgical properties of the material. As a result, fracture toughness can be assumed to be the stress intensity factor at which crack instability begins. Figure 7 shows three different fracture modes.

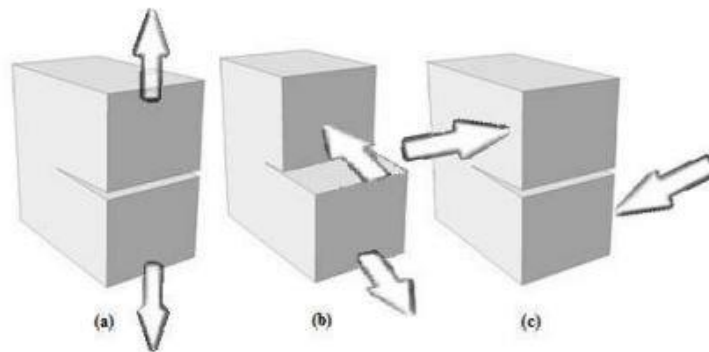


Figure 7: Fracture modes: (a)- First, (b)-Second, (c)- Third.

Due to the difference in lattice structures, materials exhibit unique mechanical responses to applied loads hence the variations in fracture mechanics theory behaviour and crack initiation. Crack propagation as a result of force applied in the x-direction is referred to as the in-plane shear mode, where y-direction is the out-plane shear mode and z-direction, is an opening mode. Crack propagation can be categorized into three stages: short cracks (stage 1), long cracks (stage 2), and final fracture (stage 3). Figure 8 shows the crack propagation stages.

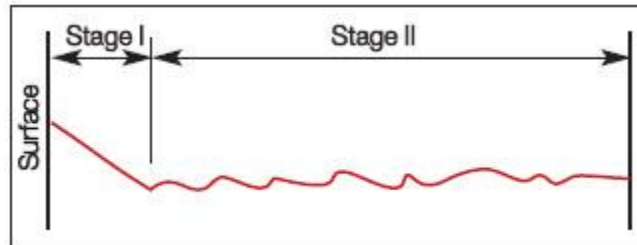


Figure 8: Crack propagation stages [21]

During the short crack growth stage, the crack extends at an inclination of about 45 degrees to the applied load following the high shear stress plane. The deceleration in crack growth will only occur if the crack encounters microstructural barriers, that will not permit further crack growth in the initial growth direction. Thus, surface treatment techniques such as LSP can be used to increase the number of barriers, resulting in an increase in the fatigue strength of a component [30]. The onset of the long crack stage is marked by surface slips occurring in different planes near the crack tip. This can be a consequence of an increasing stress intensity factor due to crack growth or increasing applied loads. Due to the successive blunting and re-sharpening of the crack tip, striations (ripples) develop on the fracture surface [31]. During these two stages, the crack growth is stable, and the fatigue fracture surfaces tend to be smooth because of the friction between the crack surfaces. The crack growth is unstable in the final fracture stage as the maximum stress intensity factor approaches the component's fracture toughness. The load ratio, stress/strain loading, and microstructure all become more important to the crack growth. Lower loads make cracks grow more slowly. This allows the crack to spread over a larger area before it breaks completely. In contrast, high loads cause cracks to grow rapidly, resulting in a smaller area of gradual growth before a sudden break [21].

The most common fracture mechanics theories are Dynamic (used on viscoelastic materials), Linear Elastic (used on linear elastic materials), and Elastic-Plastic (used on materials with elastic and plastic properties). The Linear Elastic Fracture Mechanics theory (LEFM) assumes that the material behaves in a linear elastic manner and is isotropic. As a result, the theory of elasticity can be used to calculate the stress fields near the crack tip, and crack growth occurs only when the stress around the crack tip exceeds the material's fracture toughness. The three critical parameters of linear fracture mechanics are applied stress, critical flaw

size and material fracture toughness. The third can be calculated using LEFM equations if either two are known. Figure 9 shows three critical fracture mechanics parameters.

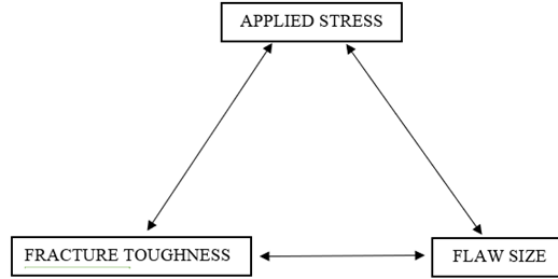


Figure 9: Fracture mechanics critical parameters.

However, a safety factor may be required because the exact magnitude and distribution of stresses are unknown. Because of manufacturing or post-treatment processes, residual stresses can be high in some cases, affecting the magnitude of the working stress. As a result, it is critical to understand the magnitude and distribution of inherent residual stresses in a component.

In most cases, crack propagation is a result of fatigue rather than the magnitude of the static load applied. Most applications of metal parts in the aeronautical industry result in a part experiencing cyclic loads during service. This results in the part having repetitive onset and offset of stress loads, promoting fatigue crack propagation and eventually fracture failure. The crack growth rate is related to the stress intensity using the Paris Law in Equation 1. Where a is the crack length, N is the number of cycles, ΔK is the stress intensity (the difference between the maximum (K_{max}) and minimum (K_{min}) stress intensity of a load cycle), m and C are material dependent constants [22].

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

$$\Delta K = K_{max} - K_{min} \quad (2)$$

$$R = \frac{K_{min}}{K_{max}} \quad (3)$$

At low crack growth rates ($\frac{da}{dN}$), the load ratio, the local environment around the crack and the material microstructure has a greater effect on the crack propagation rate. At high crack growth rates, crack propagation is sensitive to the stress ratio, material microstructure and specimen thickness. However, material microstructure has little contribution to the growth rate. Equation 1 gives the crack growth rate per

cycle for constant amplitude loading. However, when the load applied does not have a constant amplitude, the variation in maximum loading can cause fluctuations in the growth rate [22]. To deal with these fluctuations, the Wheeler and the Willenborg models were developed to account for the delays in crack growth due to plastic zones forming as a result of overloading. Loading cycles with a higher stress ratio (R) tend to have a high crack growth rate, which is attributed to the concept of crack closure. Studies on high strength AA7050-T7451 have shown that crack opening only occurs when the loading is at least 55% of the maximum load and below this threshold, the crack remains closed slowing down the rate of crack growth [23]. Crack faces tend to remain in contact at lower stress ratios, which reduces the stress intensity factor at the crack tip and slows down the rate of fatigue crack growth. However, for stress ratios above the critical value ($R > 0.7$), the crack faces hardly remain in contact (the crack opens) which in turn increases the effective stress intensity factor resulting in a high crack growth rate.

The far field stress is related to the stress intensity at the crack tip by a geometry factor as shown in Equation 4, where σ , is the tensile stress applied to the specimen perpendicular to the crack plane, and β is a geometry factor:

$$K = \beta \sigma \sqrt{\pi a} \quad (4)$$

The critical crack length before the specimen experiences failure can be found by substituting K_{max} and the maximum stress applied (σ_{max}) into Equation 4 and solve for the crack length. However, material fracture toughness varies depending on the crack growth direction, whether perpendicular or parallel to the grain boundary. Studies have shown that fatigue crack growth slows when the angle between the grain boundary and the crack exceeds 90 degrees. The grain boundary, on the other hand, is most likely to fracture during the loading cycles, so a connection between the crack tip and the ruptured grain boundary is unavoidable. Because of the rapid crack growth rate caused by this connection, variations in material fracture toughness will have insignificant effects on the fatigue life of the part near the end of its life [23].

1.5 Air Force Grow (AFGROW)

AFGROW is a damage tolerance analysis program capable of predicting crack initiation, propagation, and fatigue life of metal parts. It has a vast library of stress intensity factors data that was modelled to account for over 30 crack geometries under different loading cases, tension, bearing and bending. AFGROW with the help of Finite Element Analysis (FEA) solutions, can independently analyse the behaviour of multiple cracks in a plate, making it possible to assess the crack propagation properties of cracks initiating from various locations or cracks growing towards holes [3].

To determine the crack length growth per load cycle, AFGROW uses five different crack growth models: Walker Equation, Forman Equation, Nasgro Equation, Tabular Lookup and Harter-T Method. For the load interaction, five different models can be used, this includes Crack Closure, Fastran, Hsu, Wheeler and Generalized Willenborg. AFGROW also offers the capability to apply beta (geometry) factors which account for the geometrical difference between the actual specimen and model solutions provided in the library. The Harter-T Method and the generalised Willenborg model are useful tools for simulating fatigue crack growth in AFGROW. The Harter-T Method, which employs a point-by-point adaptation of the Walker equation, tackles the issue of limited data. This enables accurate crack growth rate estimation even with only 25 rate of crack growth (da/dN) values available. Furthermore, for enhanced accuracy, the technique accounts for the stress ratio change independently for each da/dN value. This is especially useful for materials with limited experimental data. The generalised Willenborg model is concerned with forecasting the influence of overload events on crack growth retardation. The Shutoff Overload Ratio (SOLR), quantifies retardation in the Willenborg model, comparing peak overload stress to the stress needed to stop crack propagation. Higher SOLR signifies stronger retardation, requiring a significantly higher overload to resume crack growth [3]. This parameter is crucial in the commonly used Generalised Willenborg model, particularly in Air Force inspections, providing a more realistic understanding of crack behaviour and contributing to safer structures.

Combining these two methods allows AFGROW to estimate growth rates for various stress ratios even with minimal data and to highlight the effects of cutoff overload on model fatigue life. Another significant advantage is the ability to capture the genuine behaviour of fracture development under varying fatigue loads. This enables AFGROW to provide more accurate projections of fatigue life, which can minimise the time required for product development [3]. Another important feature of AFGROW is the capability of applying external residual stress profiles to the model: these profiles can be a result of the manufacturing process or post-processing treatment procedures. This allows the model to better resemble the material properties of a real-life part, increasing the prediction's accuracy. AFGROW is also capable of calculating stress intensity factors based on the geometry input and loading cases specified by the user, allowing for the development of new stress intensity model solutions [3].

The full effects of pores, surface roughness and residual stress on the fatigue properties of AM parts are not fully understood. Therefore, there is a need to explore the effectiveness of LSP in mitigating fatigue crack propagation in metal AM aeronautical parts. AFGROW can be used to model AM parts with known pores geometry and predict their fatigue life based on the crack propagation properties in as-built state and post-LSP surface treatment. The fatigue life for the two cases will be compared to assess the effectiveness of LSP in enhancing the fatigue performance of AM parts.

2. Problem statement

Aeronautical parts are subjected to cyclic loads during service, and they are prone to experience fatigue failure after load cycles, thus, the ability to predict the fatigue life of AM parts is vital. Due to the local nature of fatigue failure, the fatigue performance of parts is more influenced by the presence of defects and surface discontinuities, which are inevitably inherent in the current AM metal parts. However, LSP can be used to introduce beneficial compressive residual stresses in AM metal parts to improve fatigue performance. Current studies have assessed the effects of LSP on the fatigue performance of metals that were produced by conventional processes (e.g. extrusion, rolling). There is inadequate data on the application of LSP on AM parts. Therefore, the objective of this research will be to investigate the effectiveness of LSP in enhancing the fatigue properties of AM parts for aeronautical applications by assessing residual stress profiles and surface roughness using different LSP parameters. This research will focus on the fatigue crack propagation in AM AlSi10Mg parts in an as-built state and with LSP surface treatment.

2.1 Research Question

Is Laser Shock Peening an effective post-processing technique for mitigating fatigue crack propagation in AlSi10Mg additively manufactured aeronautical parts?

2.2 Research Objectives

1. To compare the fatigue life of as-built and LSP treated AlSi10Mg AM samples using different LSP parameters using Finite Element and Fracture Mechanics models.
2. To characterise the effectiveness of LSP parameters in enhancing the fatigue life of AlSi10Mg AM samples by varying laser power intensity.
3. To identify the best suited LSP residual stress profiles for optimal fatigue performance of a selected AlSi10Mg AM aeronautical part.

3. Research Methods

3.1 Apparatus

A 64-bit (8-core) simulation computer with access to AFGROW and ANSYS Mechanical 2023 R2 software licenses is required. ANSYS will be used to determine the geometry correction factors for models that deviate from the geometry of standard models in AFGROW. Crack propagation models of as-built and LSP treated samples will be created and analysed using AFGROW.

3.2 Experimental data source

The residual stress profiles that will be used in this research were adopted from previous experimental work done on AM manufactured AlSi10Mg alloys within the Wits AM/LSP group. The AM specimens were produced with the parameters listed in Table 1 below, utilising the SLM 280 2.0 machine and the SLM process [18].

Table 1: AM build parameters.

Laser power	Incremental up to 400 W
Laser scan speed	10 m/s
Beam focus diameter	80 μm
Scanning pattern	Stripes
Temperature	150°C
Deposit layer thickness	0.03 mm

The material properties of the AM specimens are listed in Table 2 [18]

Table 2: AM material properties.

Young's modulus	75 GPa
Yield strength	275 MPa
Ultimate tensile strength	450 MPa
Poisson's ratio	0.33

The AlSiMg10 alloy maintains good mechanical properties similar to the high-strength AA7075-T6. Additionally, the Poisson's ratio falling within the range for isotropic materials (between -1.0 and 0.5) suggests the AlSiMg10 samples behaved uniformly in all directions under stress. The material's pores do not start to show up until about 100 μm from the sample's surface [18].

A near infrared switch pulsed Nd: YAG (neodymium-doped yttrium aluminium garnet) laser was used to treat specimens with dimensions of 13 x 13 x 9.6 mm. The specifications for this laser are listed in Table 3. Access to the laser was made possible by the NLC's Rental Pool Programme [18].

Table 3: LSP Parameters [18].

Power Intensity	1.5 – 4.5 GW/cm ²
Spot diameter	1 mm
Coverage	80%
Pulse frequency	20 Hz
Wavelength	1064 nm

The residual stress profiles were obtained using Incremental Hole Drilling (IHD) measurements for a 9.6mm thick sample at different laser intensities. The residual stress profiles observed are represented in Figure 10. The residual stress profile was tensile before LSP treatment with a maximum stress of 237.78 MPa. After LSP treatment the stress profiles were converted from tensile into compressive up to a depth of approximately 0.8 mm, with a maximum conversion of 183 percent occurring when a laser intensity of 4.5 GW/cm² is used.

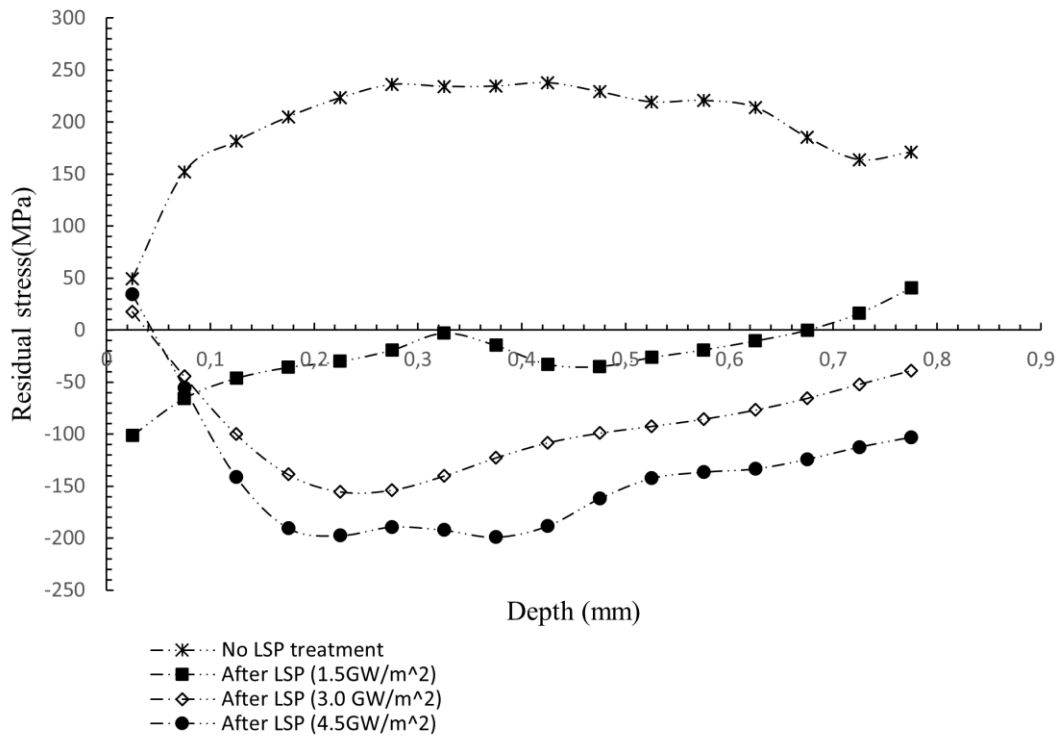


Figure 10: Residual stress profiles for a 9.6 mm AlSi10Mg specimen.

3.3 Validation model specifications

AFGROW models will be developed to predict the crack growth for conventional produced AA2024-T351 (untreated and LSP treated case), and the results will be compared with observations and experimental results recorded by Clauer et al. [15]. In Clauer's research, a specimen 254 mm long, 102 mm wide gauge section and 6.3 mm thick, with a 4.83 mm diameter fastener hole in the centre, was used to assess the growth of 0.5mm cracks originating from adjacent sides of a fastener hole. The geometry setup excluding the grip zones is shown in Figure 11 below.

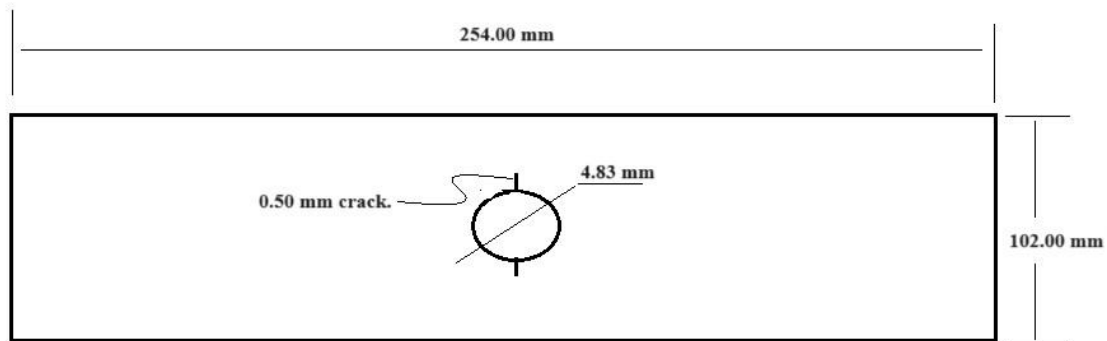


Figure 11: Clauer geometry setup.

The plate was subjected to a tensile maximum stress amplitude of 103 MPa with a stress-to-strain ratio of 0.1. For the LSP treated case, the area around the fastener hole was treated using a solid spot with a diameter of 11.43 mm and a laser intensity of 12 GW/cm². The fastener hole was in the centre of a LSP treated region [15]. The residual stress profiles observed after IHD measurements are represented in Figure 12 [15]. After LSP treatment the stress profiles turned to be more compressive up to a depth of approximately 0.6 mm. The unpeened residual stress profile will be applied to the untreated AFGROW model (in order to match the structure of the metal used in the experiment) using residual stress correction and the crack propagation will be simulated. To imitate the post-processing treatment, LSP compressive stress profile will be applied to the treated AFGROW model and the crack propagation under tensile load will be observed.

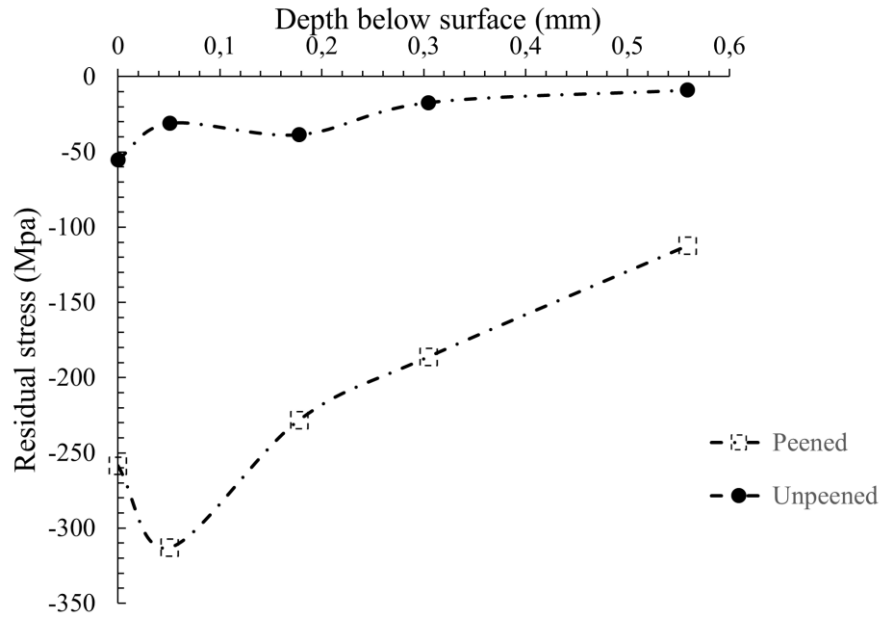


Figure 12: Residual stress variation with depth below the surface.

In Clauer's experiment [15], the crack length growth vs the number of cycles was observed for both the untreated and LSP-treated case at an intensity of 12 GW/cm^2 . The LSP treated plate proved to have a fatigue life of at least 4 times more than the as-built plate [15]. Further proving that LSP is a successful post-processing procedure for reducing fatigue fracture development and enhancing the fatigue life of aluminium specimens. The similarity of results and trends of the AFGROW models with observations made by Clauer et al. [15] will be used as the criterion to judge if these models are valid to explore different sets of parameters.

4. Methodology

4.1 Model validation - AA2024-T351 specimen modelling

Untreated AA2024-T351 specimens:

- a. Develop an AFGROW model for untreated AA2024-T351 specimens using the material properties, geometry, and loading conditions from Clauer's experiment.
- b. Apply unpeened residual stress profile observed after IHD measurements to the untreated AFGROW model and simulate crack propagation.
- c. Compare the simulated crack length growth vs. number of cycles with Clauer's experimental results.

LSP-Treated AA2024-T351 specimens:

- a. Develop an AFGROW model for LSP-treated AA2024-T351 specimens using the material properties, geometry, and loading conditions from Clauer's experiment [15].
- b. Apply LSP compressive stress profiles to the treated AFGROW model and simulate crack propagation.
- c. Compare the simulated crack length growth vs. number of cycles with Clauer's experimental results.
- d. The number of cycles to failure for the untreated and treated cases will be compared to assess the extent of fatigue life improvement. The AFGROW results trends will be compared with the findings from Clauer's experiment to ascertain the validity of the models.

4.2 AlSi10Mg AM Specimen Modelling

Untreated AlSi10Mg AM specimen:

- a. Create a simple geometry model of an AlSi10Mg AM specimen in AFGROW similar to the validation model.
- b. Apply AM residual stress profiles obtained from previous experimental work within the Wits AM/LSP group to the AFGROW model [18].
- c. Simulate crack propagation and record crack length growth vs. number of cycles.

LSP-Treated AlSi10Mg AM specimen:

- a. Modify the residual stress profiles of the untreated AFGROW model by adding LSP residual stress profiles from previous experimental work within the Wits AM/LSP group [18].
- b. Simulate crack propagation for different laser intensities between 1.5 GW/cm² and 4.5 GW/cm².
- c. Compare crack length growth trends between as-built and LSP-treated models.

4.3 Aeronautical Application Part

Real-Life AlSi10Mg AM Aeronautical Part:

1. Part Selection and Modelling

- a. Select a real-life AlSi10Mg AM aeronautical part.
- b. Model the part geometry in ANSYS.
- c. Implement an initial crack with size and shape based on literature.

2. Crack Growth Model

- a. Utilise ANSYS Mechanical's SMART crack growth tool to evaluate the stress intensity factor range.
- b. Determine the maximum stress intensity factor for the particular crack geometry.

3. Stress Intensity Factor Comparison

- a. Compare the stress intensity factor from the ANSYS model with the AFGROW standard model's stress intensity factor from the AFGROW library.
- b. Calculate the geometry correction factor (Beta).

4. AFGROW Modelling

- a. Model the part geometry and crack initiation position in AFGROW using a standard library model.
- b. Apply the Beta correction factor to modify the stress intensity factor solutions.
- c. Apply AM residual stress profiles obtained from previous experimental work within the Wits AM/LSP group to the AFGROW model for as-built case [18].
- d. Implement the best-suited LSP residual stress profiles observed from previous models for the LSP treated case.
- e. Simulate crack propagation for both as-built and LSP treated case.

5. Analysis and Evaluation

- a. Compare crack growth trends between the as-built and LSP treated models.
- b. Evaluate the effectiveness of LSP in enhancing the fatigue life of AlSi10Mg AM part.

5. Results

5.1. Model Validation

The fatigue performance of small cracks was investigated using classic AFGROW Double Corner Crack at Hole models in conventionally produced AA2024-T351 plates subjected to axial stress loading. The model was 102 mm wide (W) and 6.3 mm thick (t), with a 4.83 mm diameter fastener hole in the centre. The cracks were 0.5 mm long and originated from adjacent sides of the fastener hole. The model is represented in Figure 13. Material data for AA2024-T351 was retrieved from the integrated NASGRO database.

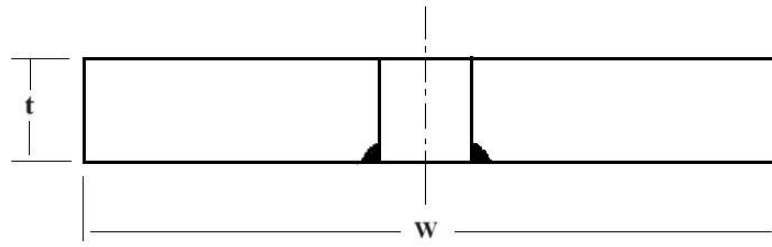


Figure 13: AFGROW model.

A constant-amplitude spectrum with a stress ratio (R) of 0.1 and a maximum of 103 MPa was applied to the model. The Harter-T Method was used to determine the crack length growth, and a generalised Willenborg model with a shutoff overload ratio of 2.8 was used to account for the crack growth retardation due to the crack-closure concept. In this model, cracks are assumed to grow in a straight line through the component without turning, and all load initially applied to the component remains within it even as the crack propagates. This model ignores the possibility of redundant load paths that could potentially divert stress away from the cracked area [3].

To accurately represent the material properties of the tested specimens, both untreated and LSP-treated AFGROW models were adjusted with the corresponding 2-dimensional residual stress profiles derived from unpeened and peened samples, respectively. This correction ensured the models reflected the actual stress state of the materials used in the experiment. Crack propagation under tensile loading was observed in both model configurations. The crack length variation with the number of cycles to failure for wrought AA2024-T351 specimens is represented in Figure 14.

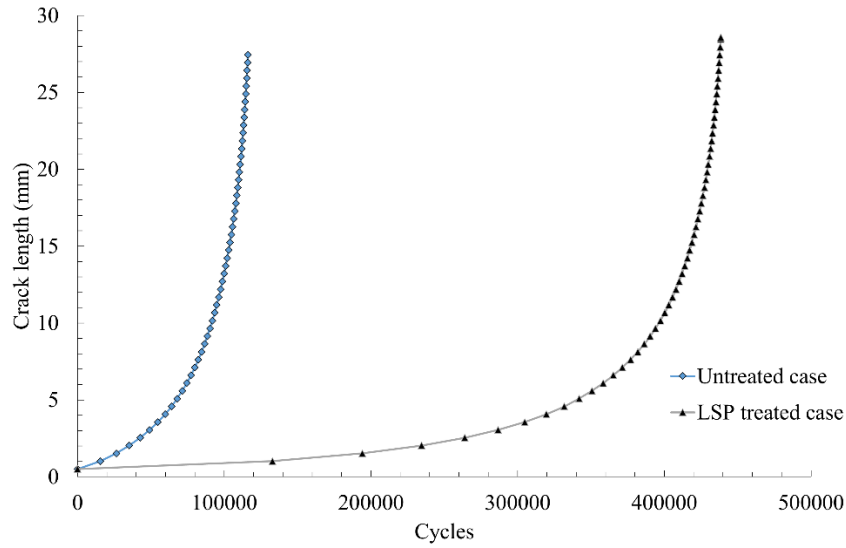


Figure 14: Crack length variation with the number of cycles to failure for wrought AA2024-T351.

The fatigue life of LSP-treated wrought AA2024-T351 specimens (116116 cycles) is at least 3.8 times greater than that of untreated specimens (438438 cycles). This improvement is similar to at least four times observed by Clauer et al. [15], with a deviation of 5 percent. The deviation might be attributed to large slope changes in the input stress distribution, which can result in the generation of erroneous Gaussian integration points. AFGROW approximates how much a crack will grow by employing Gaussian integration on a series of points around the crack origin. The residual stress intensity is calculated by interpolating between these positions [3]. This could underestimate or overestimate the crack growth rate, leading to an inaccurate fatigue life prediction by the model.

Fatigue crack growth feeds on tensile stresses at the crack tip. These stresses function as minuscule wedges, pushing the fracture sides apart during each loading cycle and promoting further propagation. LSP creates compressive stresses ahead of the crack tip. These compressive stresses push the crack surfaces shut during each loading cycle, preventing them from opening and expanding properly. This effectively reduces the stress intensity at the crack's tip, hindering crack propagation under cyclic loading [22]. The residual stress profile for untreated specimens is compressive, however with smaller magnitudes as compared to the LSP treated case. The greater compressive stresses in the treated specimen result in a lower fatigue crack growth which in turn translates into more cycles to fatigue failure.

The observed similarities in trends lead to the conclusion that these AFGROW models are valid for exploring different specimens with greater confidence. Surface treatment techniques such as LSP can be used to increase the microstructural barriers, resulting in an increase in the fatigue strength of a component [32].

5.2 AlSi10Mg AM specimen modelling.

The influence of pore size on a material's properties is dependent on the material itself. However, pores below a certain threshold size are generally considered negligible. Studies have shown the minimal impact of pores smaller than 0.5 mm on static strength and ductility [10]. Therefore, a surface elliptical defect with a major and minor radius of 0.5 mm, with an aspect ratio of 1 was chosen for this investigation. The flaws, located on adjacent sides of the hole, were modelled using a classic AFGROW Double Corner Crack at Hole with a crack length of 0.5 mm ($a/c = 1$) subjected to axial tensile stress load. Additively manufactured AlSi10Mg alloy properties (Table 2) were applied to the model and the crack growth was predicted under the same load spectrum as before. Harter and Willenborg models were used, incorporating residual stress profiles from previous experiments (as-built and LSP-treated between 1.5 GW/cm² and 4.5 GW/cm²) [18]. Crack length growth was simulated, and fatigue life was defined as the number of cycles to fracture. The crack length variation with the number of cycles to failure for AlSi10Mg specimens is represented in Figure 15.

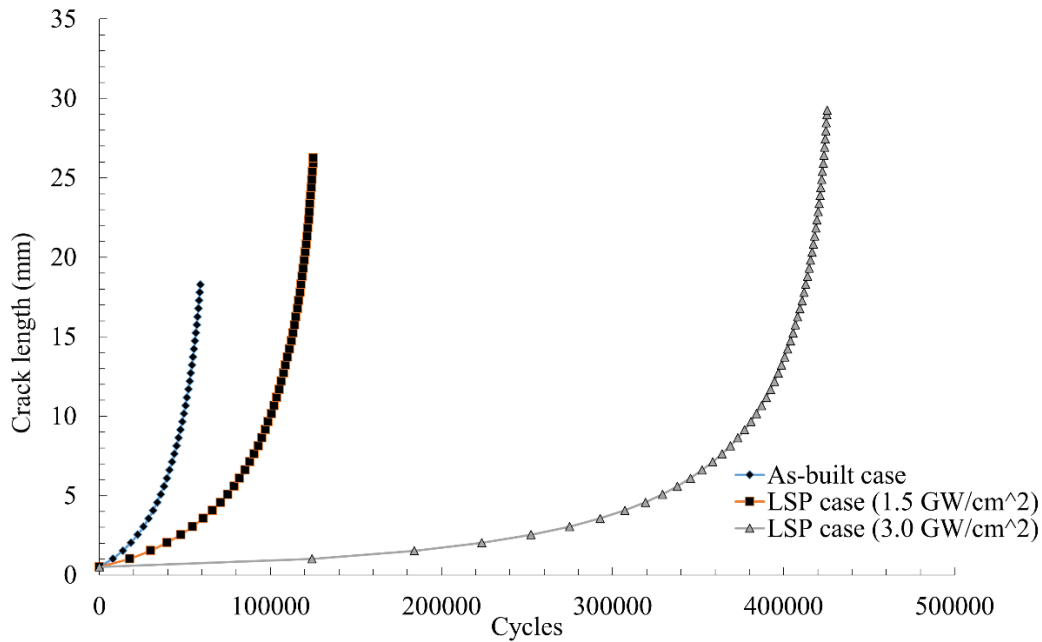


Figure 15: Crack length variation with the number of cycles to failure for AM AlSi10Mg specimens.

The number of fatigue cycles is at least 2 times higher for the AM AlSi10Mg treated case at 1.5 GW/cm² (125125 cycles) compared to the as-built case (59059 cycles), and the cycles are at least 7 times higher for the LSP treated case at 3.0 GW/cm² (438438 cycles). LSP-treated specimens exhibited a longer fatigue life than as-built ones, and the number of fatigue cycles to failure is higher when a higher laser power intensity is used.

The introduction of compressive stresses via LSP post-processing demonstrably reduces the fatigue crack growth rate in the treated specimen. This can be attributed to a decrease in the effective stress intensity factor at the crack tip during cyclic loading. The compressive stresses hinder crack propagation by counteracting the tensile stresses driving crack growth [33]. At a laser intensity of 4.5 GW/cm^2 , the suppressive effect of the compressive layer becomes excessive, leading to vanishingly slow crack growth rates beyond the capabilities of the current model [34]. This makes the crack growth prediction model unreliable at high laser intensities. Based on the observed fatigue crack growth behaviour, the ideal LSP treatment intensity for producing the best-suited LSP residual stress profiles is 3.0 GW/cm^2 .

These findings are consistent with previous research, which has shown that LSP can improve the fatigue life of metals by introducing compressive residual stresses to the surface [33]. Yaxin et al. [35] observed that LSP significantly extends the lifespan of wrought AA2024-T62 specimens, making them last 4.5 to 9.8 times longer on average. The observed trends confirm the validity of these AFGROW models for exploring AM AlSi10Mg alloy specimens.

5.3 Real life application model

The Cessna 172/175 horizontal stabilizer spars can greatly benefit from AM. The relatively simple geometry of the horizontal stabilizer spar sections makes it a perfect candidate for this technology. By utilising AM, the spar can be manufactured in fewer sections, eliminating the need for numerous joints. This approach could reduce the weight and improve the structural integrity of the stabilizer. The internal structure of a Cessna 172/175 horizontal stabilizer is represented in Figure 16.

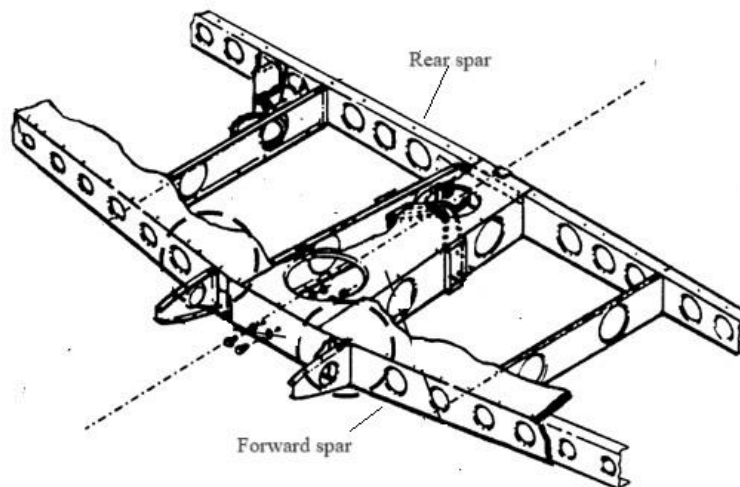


Figure 16: Cessna 172/175 horizontal stabilizer [24].

Traditionally, aircraft components like stabilizer spars were constructed using multiple parts fastened together. This conventional method can introduce weak points in the connection areas. AM can reduce the

overall weight of the stabilizer and enhance its durability and performance. The lightening holes used to reduce weight can become stress concentration points in the spar. Cracks can initiate and grow from these holes due to fatigue as shown in Figure 17, potentially leading to catastrophic failure if left unchecked.

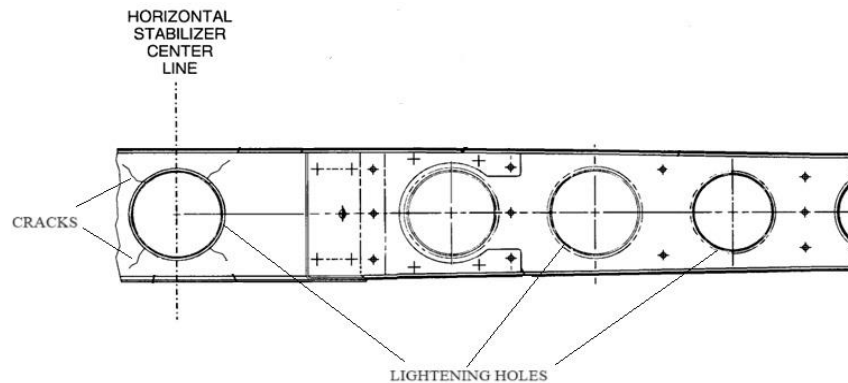


Figure 17: Cessna 172/175 horizontal stabilizer spar [24].

In recent cases, cracks in the forward horizontal stabilizer spar of Cessna 172/175 series aircraft were discovered by maintenance technicians. According to the FAA Service Difficulty Reporting System database, these situations were reported at least 76 times over the last few decades. The studies suggested that cracks may occur in the area aft of the centre lightening hole in the horizontal stabilizer forward spar. Pushing or pulling on the tail section during ground handling stresses the forward spar, which can result in fracture and distortion [24]. It is crucial to note that the horizontal stabilizer front spar in Figure 18 was made using traditional processes rather than AM. A similar problem is likely to be amplified if the spar is produced using AM techniques due to the presence of subsurface pores.



Figure 18: Cessna 172/175 forward horizontal stabilizer spar [24].

To minimise the recurrence of this issue, the FAA and Cessna made some recommendations. When moving the aeroplane on the ground, always use a tow bar or a steering tiller. This uniformly distributes weight and prevents excessive stress on the tail. Avoid pressing or pulling on any control surfaces or the horizontal stabilizer outside edges. The FAA recommended that the horizontal stabilizer forward spar be inspected on a regular basis for cracks and buckling. If a crack is discovered, a competent mechanic will determine the degree of the damage and make the necessary repairs or replacements [24].

The repetitive stresses placed on the Cessna 172/175 horizontal stabilizer during ground handling, such as towing and manoeuvring, can contribute to fatigue crack growth, particularly in the forward spar. This area is susceptible due to the combination of stress concentration and the cyclic nature of ground handling loads. LSP treatment of the area surrounding the central lightening hole may help reduce crack propagation [37]. AFGROW models can be used to predict the fatigue life based on the crack propagation properties. The crack initiation position is similar to that of a classic AFGROW double corner crack at the hole. However, the beta correction factor should be applied to the model to modify the stress intensity factor solutions [3].

5.4 Beta corrections

AFGROW approximates how much a crack will grow by employing Gaussian integration on a series of points around the crack origin. The residual stress intensity is calculated by interpolating between these positions. AFGROW uses pre-programmed solutions for various crack geometry. Real-world cracks may not exactly match these ideal shapes, resulting in erroneous predictions of the stress intensity. This could underestimate or overestimate the crack growth rate, leading to an inaccurate fatigue life prediction by the model. It is critical to choose a reference model that is as similar to the intended model as possible [3]. Beta correction in AFGROW can help enhance the accuracy of fatigue crack growth predictions, particularly for complicated geometries. It modifies a previously known stress intensity solution (K-solution) for a similar geometry to fit the exact geometry of the desired model [35]. For each crack length increment, AFGROW calculates a beta factor using a user-defined table or internal algorithms. This beta factor is then multiplied by the base K-solution from the specified geometry to provide a more precise K-value for the desired geometry ($\beta_{unknown} = \beta_{known} \times \beta_{correction}$).

Beta correction has flaws since it is unable to fully account for changes in stress distribution as the crack grows in size. It performs best on shorter crack lengths, where the majority of the fatigue life is used. For this research, only short cracks are being assessed and the possibility of redundant load paths that could potentially divert stress away from the cracked area will be ignored. Therefore, Beta correction can be used with confidence to modify a previously known K-solution for a similar model to fit a real application part model [3][35].

5.5 Stress intensity factor prediction

Finite element analysis (FEA) is an effective approach for determining the stress intensity factor of fractures originating from holes [25]. For the model geometry, the front spar's centre section was examined, with a 66 mm diameter central lightening hole. Two diagonally opposite cracks originating from the middle lightening hole were used as the pre-defined crack. The material properties in Table 2 were applied to the FEA model, with the crack shape assumed to be semi-elliptical, with a minor and major radius of 0.5 mm. The forward horizontal stabilizer spar centre section geometry as seen in Figure 22 was created in CAD and imported into ANSYS.

The geometry and mesh in FEA are depicted in the illustration in Figure 19, tetrahedron elements with a mesh size of 1 mm were used. For simplicity of modelling, only the area around the central lightening hole was considered as the crack initiation is localised around the central hole. A tensile pressure of 103 MPa was applied to the model on the top and bottom surfaces. The crack growth model was based on static crack growth, and the stress intensity factor range was evaluated using ANSYS Mechanical's SMART crack growth tool. ANSYS' SMART crack growth tool simulates crack behaviour by auto-meshing the advancing crack tip, enabling stress intensity factor calculation [26].

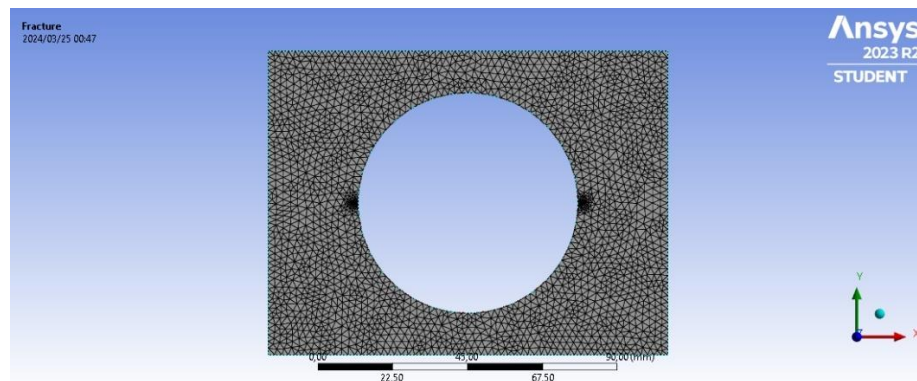


Figure 19: FEA mesh geometry.

FEA simulations were performed on the model, and the maximum stress intensity factor was determined to be $280.62 \text{ MPa}\sqrt{\text{mm}}$. The simulation results are presented in Figure 20. The stress intensity factor for the AFGROW model was determined to be $92 \text{ MPa}\sqrt{\text{mm}}$ using a geometry factor for corner cracks ($\beta = 2.24/\pi$). Using the Beta correction formula, the correction value is derived as the ratio of the FEA stress intensity factor to the AFGROW stress intensity factor. The beta correction factor was calculated to be 3.05.

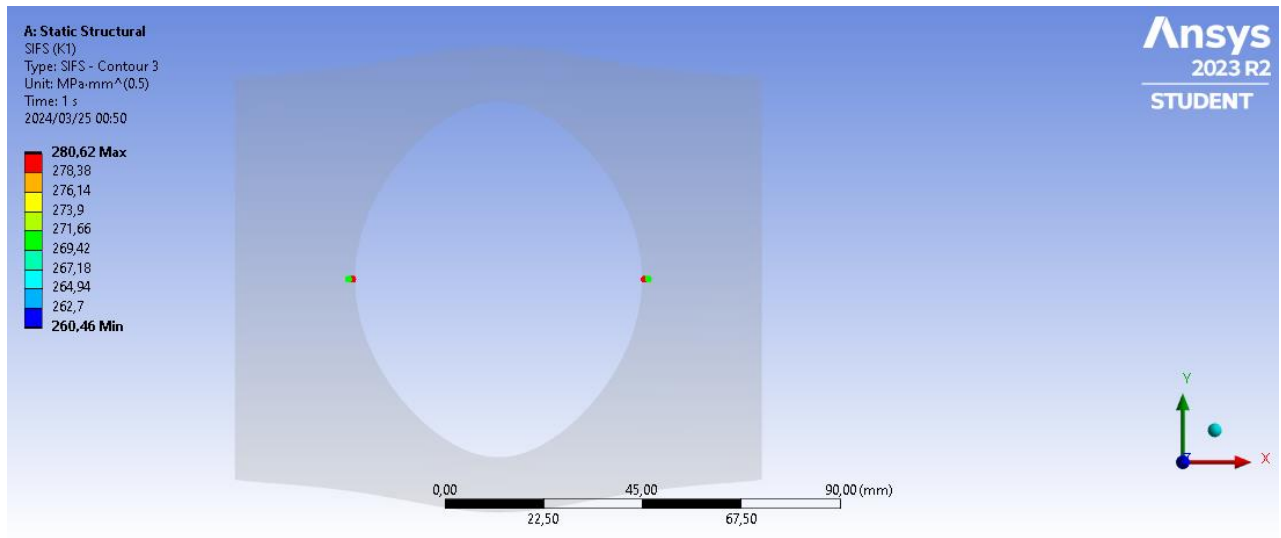


Figure 20: FEA stress intensity factor results.

The horizontal stabilizer front spar was modelled as a classic Double Corner Crack at Hole from the AFGROW library. A maximum beta correction factor of 3.05 was applied to the model to modify the stress intensity factor solutions. The additively manufactured AlSi10Mg properties (Table 2) were applied, and the crack growth was predicted under the same load spectrum used before. Harter and Willenborg models were used, incorporating residual stress profiles from previous experiments (as-built and LSP-treated). The best suited LSP residual stress profile observed when the laser intensity was 3.0 GW/cm² was applied to this model for the LSP treated case. The crack length variation with the number of cycles to failure for the model is represented in Figure 21.

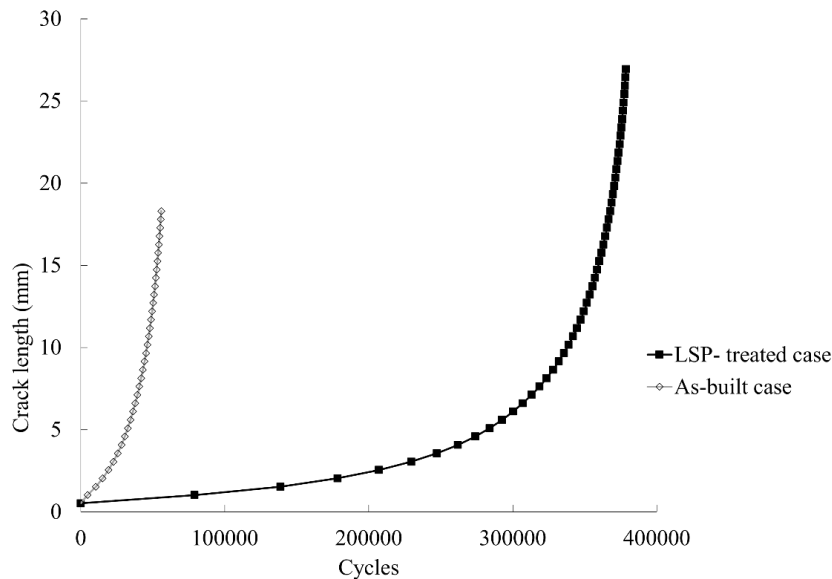


Figure 21: Crack length vs cycles to failure for AM front spar centre section.

Compared to the as-built parts (55933 cycles), LSP-treated parts (378668 cycles) exhibited an increase in fatigue life of at least six times longer at a power intensity of 3.0 GW/cm^2 . LSP treatment demonstrates a significant improvement in the fatigue life of AlSi10Mg alloy AM aeronautical parts. This finding aligns with previous research on LSP's ability to enhance fatigue resistance in metals [35]. The mechanism behind this improvement lies in the introduction of compressive residual stresses on the surface by LSP, hindering crack initiation and propagation. LSP is an effective post-processing technique for mitigating fatigue crack propagation in AlSi10Mg AM aeronautical parts.

AFGROW models incorporating the beta correction factor exhibited a reduction in predicted fatigue life compared to non-corrected models. This finding aligns with the understanding that the beta factor essentially amplifies the stress intensity near the crack tip, which is the most vulnerable area. This increase in stress intensity essentially accelerates the growth of the crack, leading to a material failing sooner than predicted by non-corrected models [36]. Thus, beta-corrected models give a more accurate prediction of the fatigue life of the real aeronautical part compared to non-corrected models, which tend to overestimate the fatigue life.

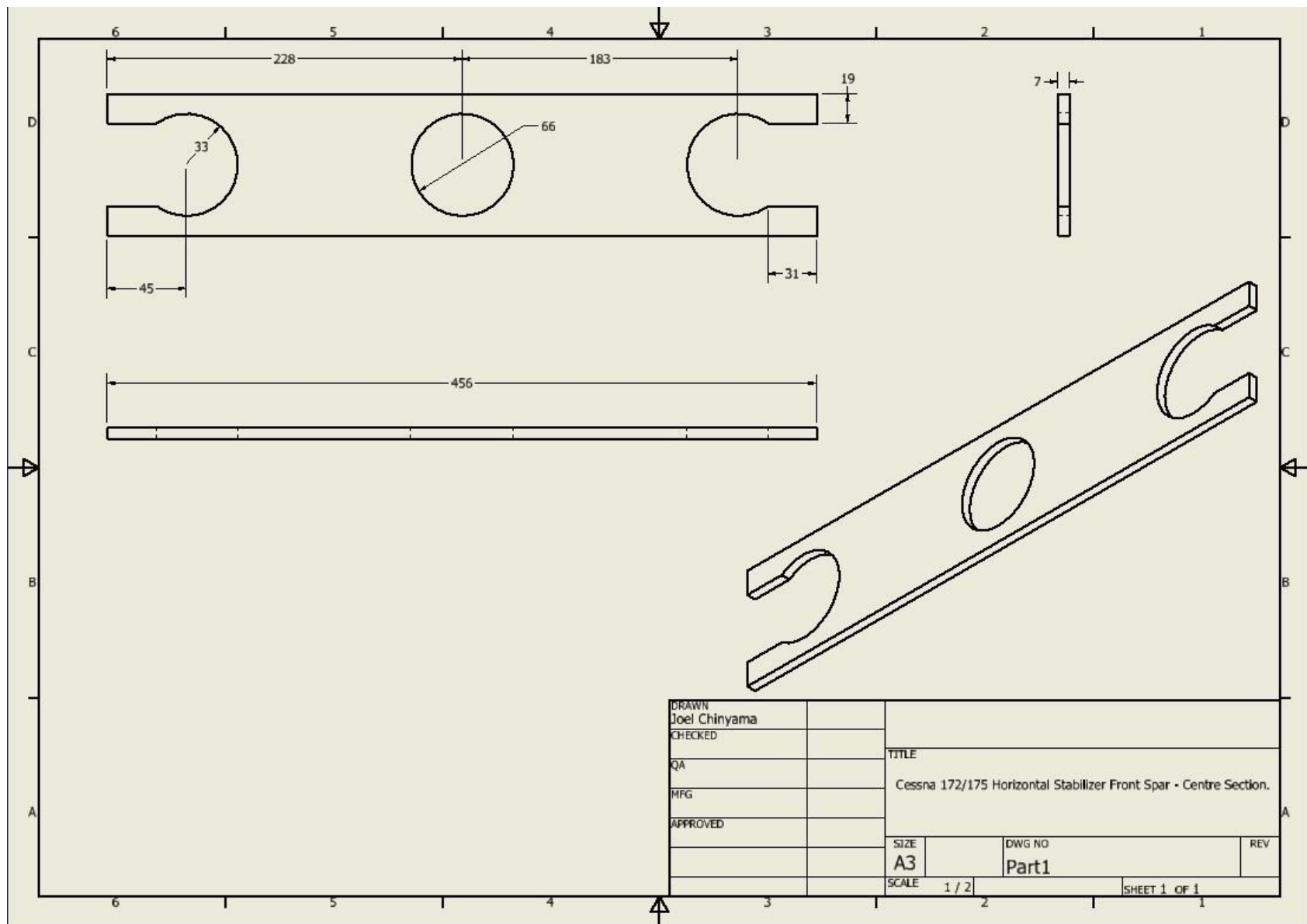


Figure 22: Forward horizontal stabilizer spar mid-section.

6. Conclusions

This research investigated the effectiveness of Laser Shocking Peening (LSP) as a post-processing technique for mitigating fatigue crack propagation in AlSi10Mg Additive Manufactured (AM) aeronautical parts. Using AFGROW and ANSYS, simulations of fatigue crack growth under varying LSP power (1.5-4.5 GW/cm²) in an effort to identify the optimal LSP parameters for maximising fatigue life and ensuring structural integrity. Based on our investigation, we can conclude that:

1. AFGROW models are valid for assessing the fatigue life of AM parts post-processed by LSP.
2. The fatigue life of LSP-treated parts is greater than that of as-built AM parts.
3. The number of fatigue cycles to failure is higher when a higher laser power intensity is used. For this research, the optimal fatigue performance was found to occur when the laser intensity was 3.0 GW/cm².
4. AFGROW models incorporating the beta correction factor exhibited a reduction in predicted fatigue life compared to non-corrected models.
5. LSP is an effective post-processing technique for mitigating fatigue crack propagation in AlSi10Mg AM aeronautical parts.

7. Recommendations

- Simulating the AM and LSP treatment process in ANSYS AM for a test specimen and determining the residual stress profile. Comparing the residual stresses measured in the experiment to the ANSYS prediction will reveal how closely the simulation resembles reality. Mapping these discrepancies, if any, will help optimise the AM and LSP processes for longer-lasting parts.
- Additively manufacture a test component and post-process it with LSP using the parameters that resulted in optimal fatigue performance in this research. The component can undergo fatigue life cycle testing with the same loads as those used in the AFGROW simulations. Comparing the experimental fatigue results with those predicted by AFGROW simulations can help determine the accuracy of simulations in predicting real-world performance.
- A study to quantify the impact of embedded pores on the real-world performance of additively manufactured parts. By analysing test specimens with controlled porosity levels, the threshold embedded pore size at which residual strength or fatigue life is significantly compromised can be determined. This information will be crucial for optimising manufacturing processes and predicting the service life of AM components.

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Appendix A: AFGROW model setup

This section provides the important parts to note when setting an AFGROW model for a Double Corner Crack at Hole.

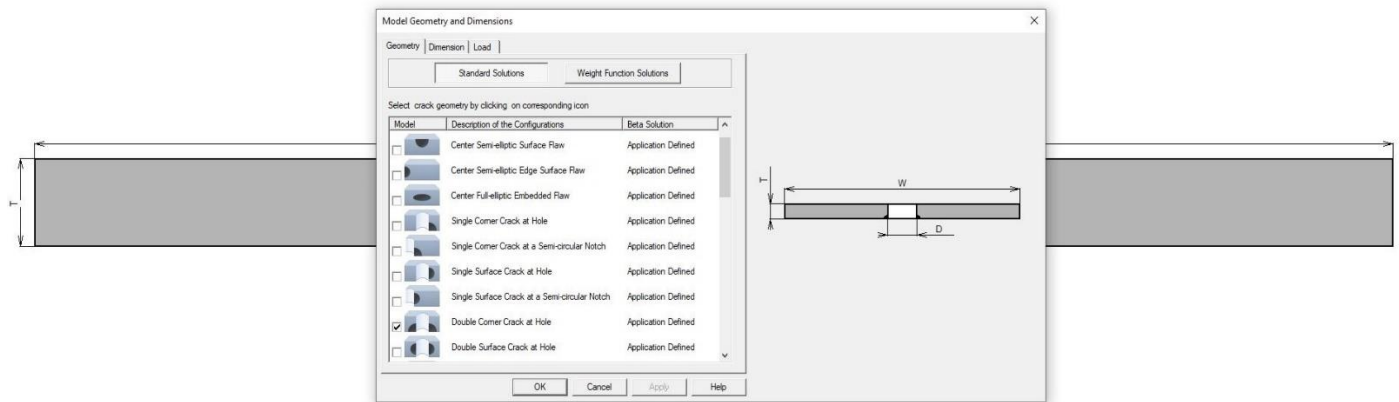


Figure 23: AFGROW classic model geometry.

Please note that the dimensions given in Figure 24 are in inches, not millimetres.

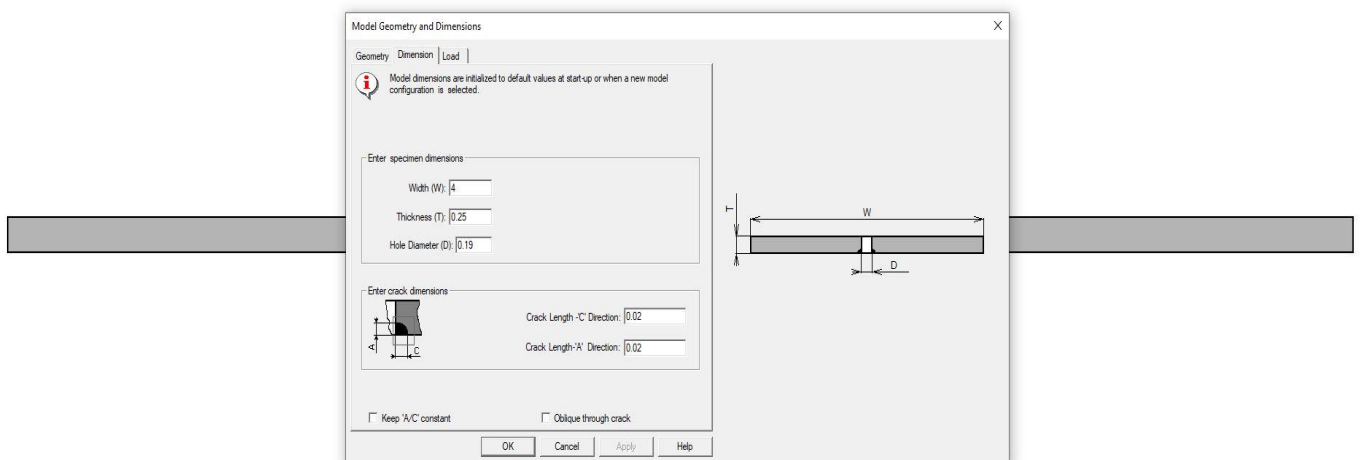


Figure 24: AFGROW model dimensions.

The normalized load spectrum with a stress ratio (R) of 0.1 and the stress multiplication factor was set to 103.

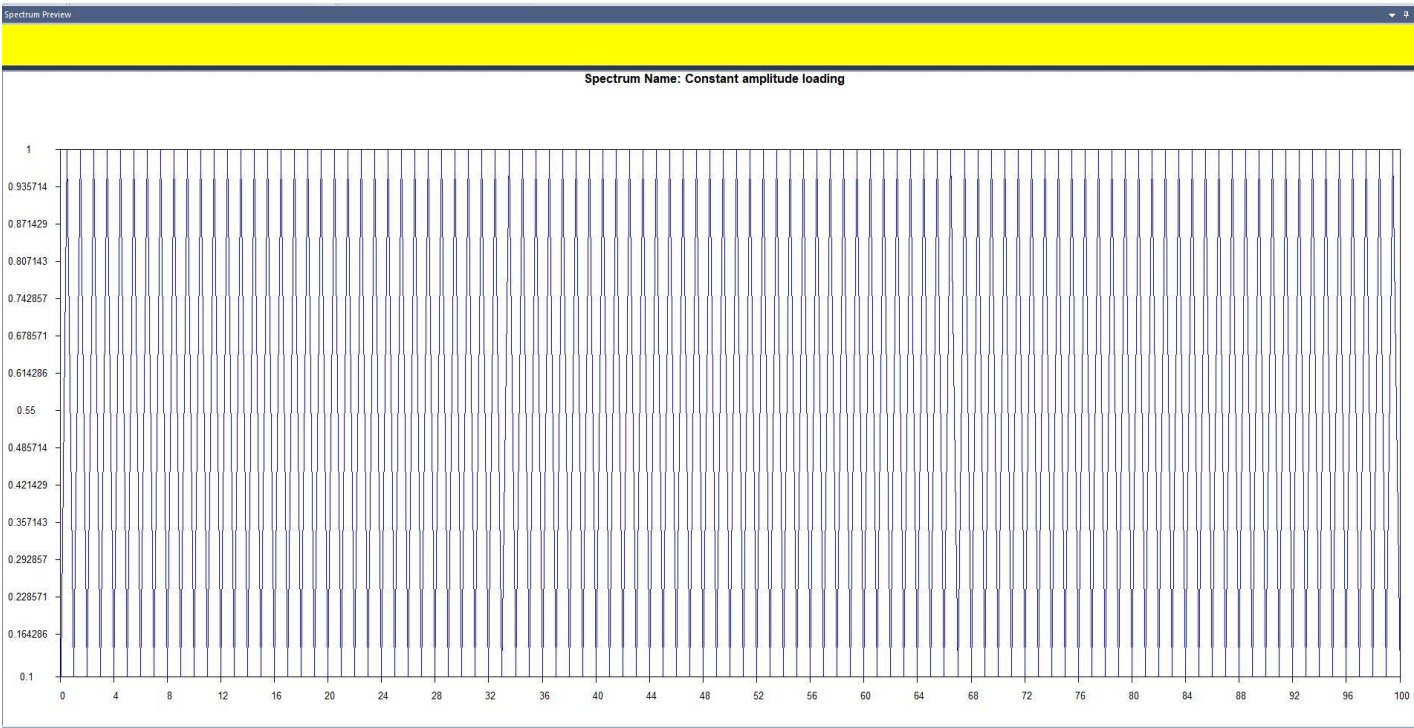


Figure 25: Load Spectrum

Beta correction for the aeronautical part model.

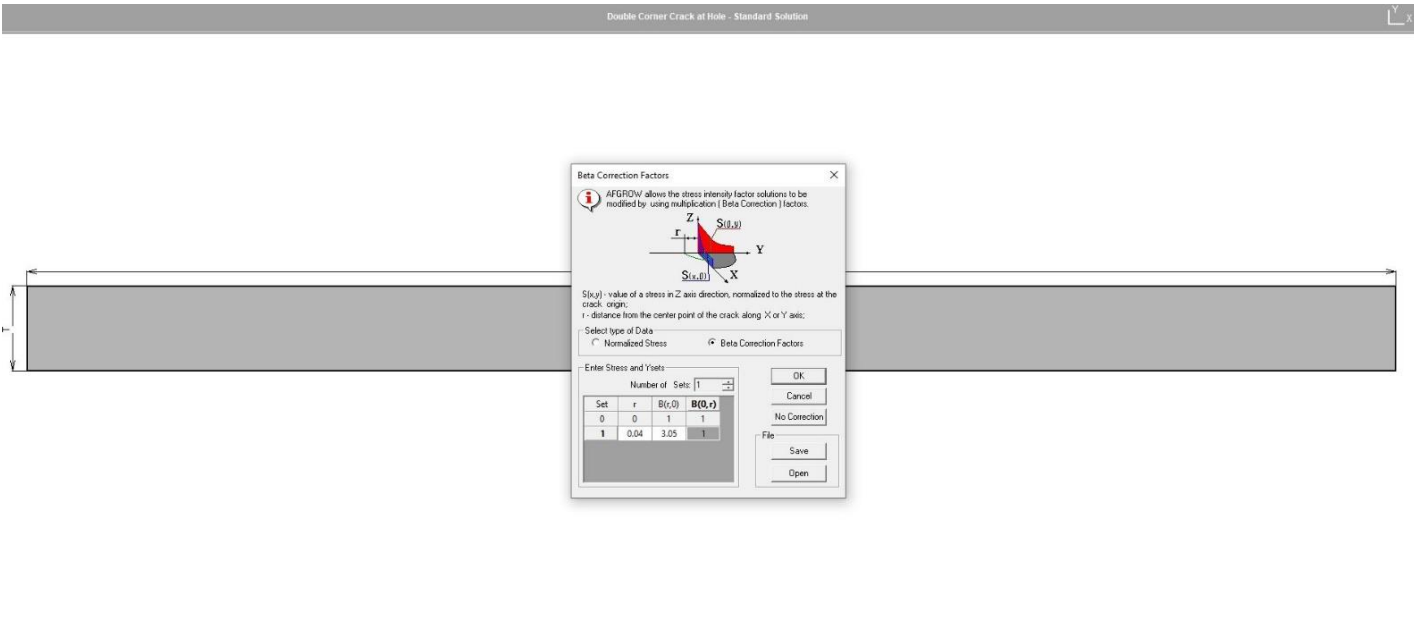


Figure 26: Beta correction for the aeronautical part.

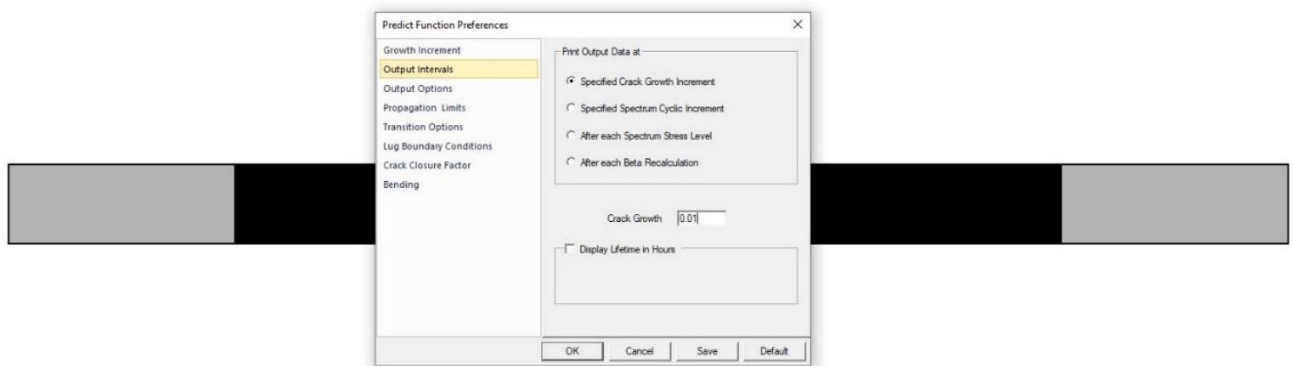


Figure 27: Crack growth rate specification.

Appendix B: FEA setup

In this section, the FEA model geometry, boundary conditions and stress intensity factor plot are presented.

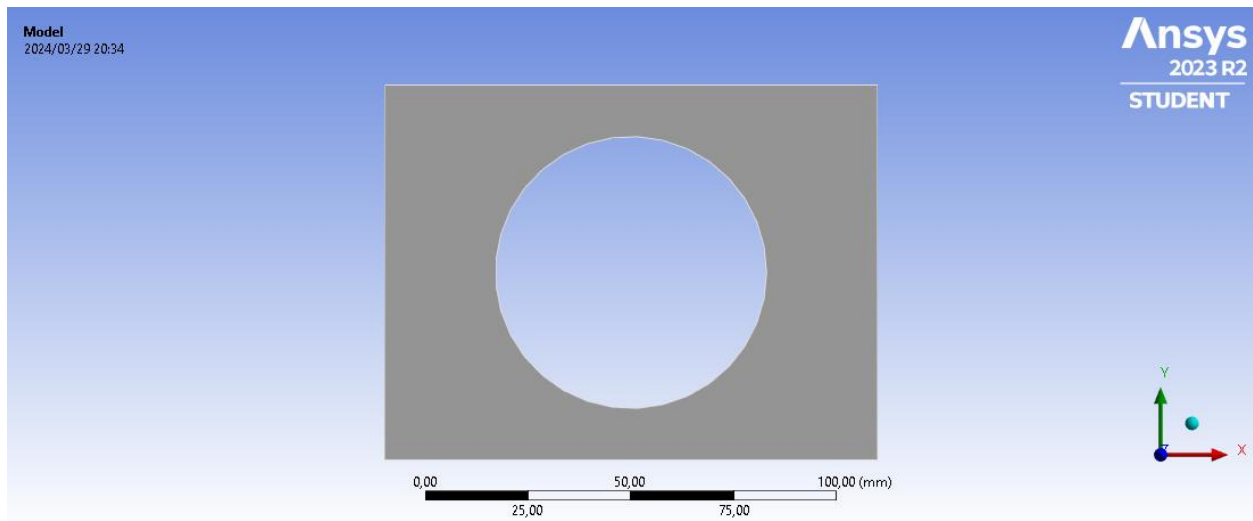


Figure 28: FEA model geometry.

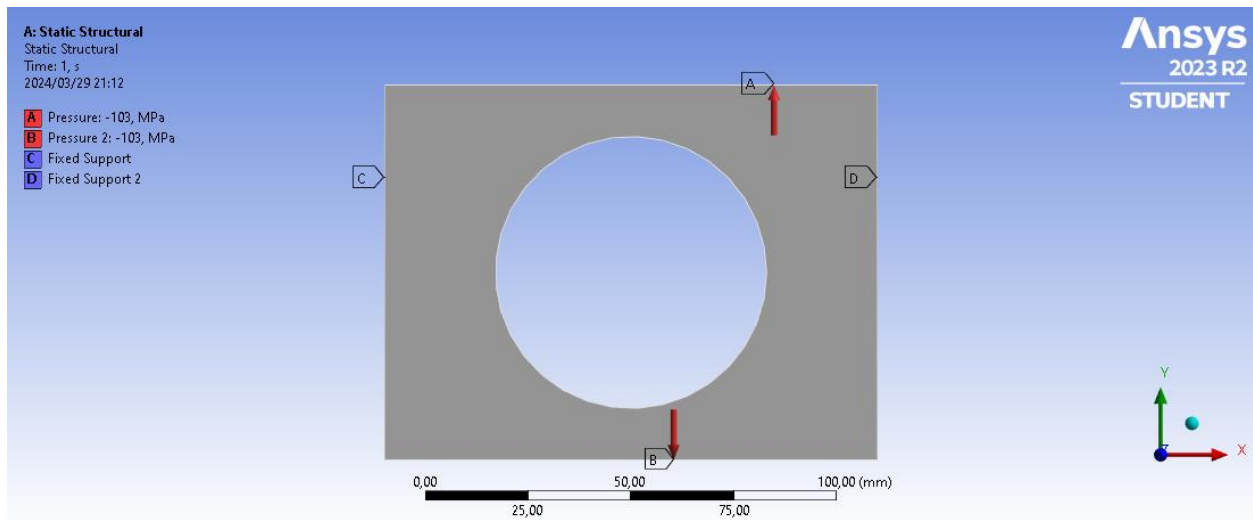


Figure 29: FEA load and boundary conditions.

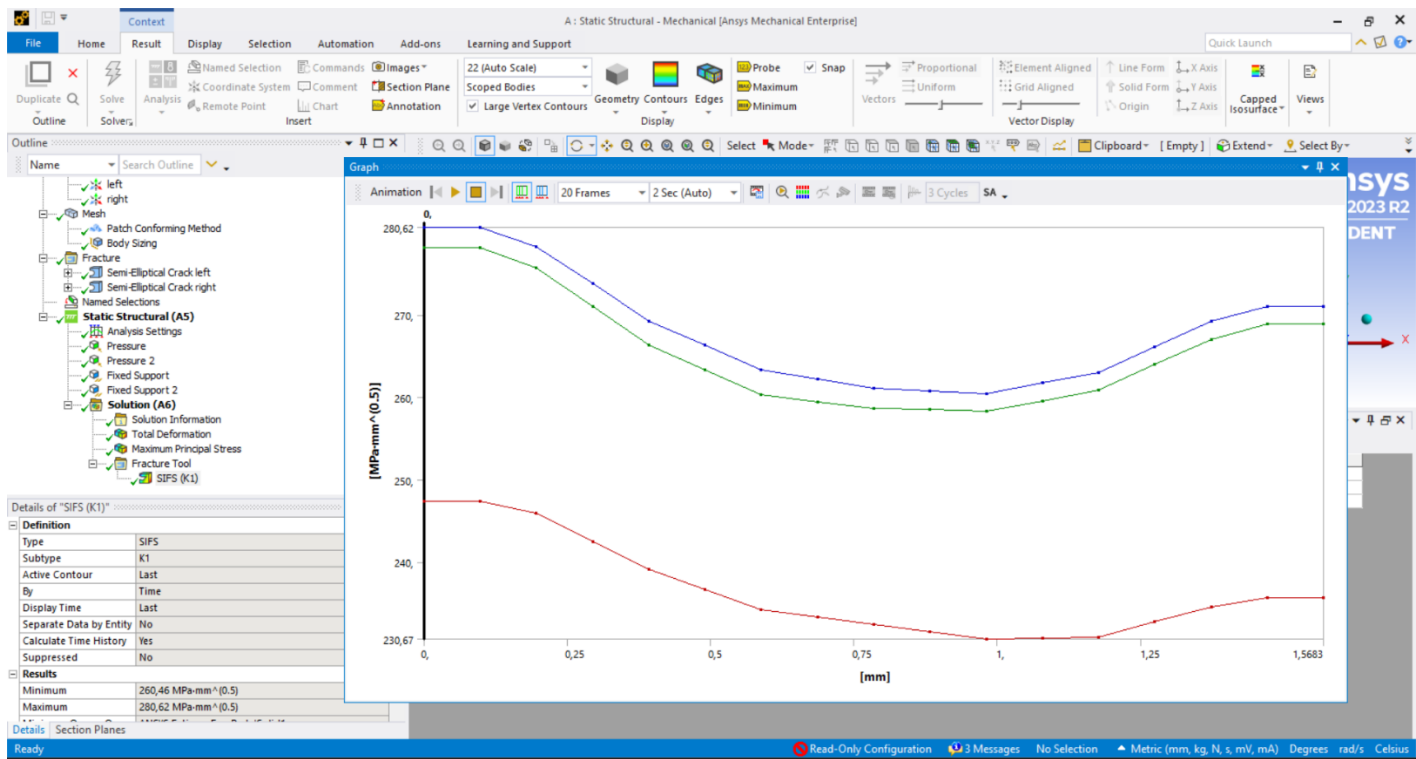


Figure 30: Stress intensity factor plot for both cracks.