

Fatigue and Fracture Behaviour of Steel Wire-Arc Additively Manufactured Structural Materials

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

There is an increasing demand for automation that has influenced many industries to find ways to integrate it into their markets. Within the civil sector, the integration of automation into the various stages of a project unlocks new opportunities that were previously difficult to achieve. If the desires of the architects appeared unachievable due to high planning and manufacturing costs, this can now be resolved with the addition of automation and robotics embedded in the early stages of project development.

The wire arc additive manufacturing (WAAM) process is an additive manufacturing (AM) process that allows efficient fabrication of structural elements. This process, also referred to as gas-metal arc additive manufacturing (GMAAM), uses directed energy deposition (DED) to create components. Specific to the WAAM process, a metal wire is fed into an electric arc, and then welded into a designed shape. For structural steel fabricators, this automated technology could allow for the reduction of supply chains, part inventories, and scrap waste, and will help improve the digitalization of the fabrication process. Moreover, the WAAM process allows the fabrication of customized connection nodes and unique structural shapes that are difficult to achieve with conventional subtractive manufacturing.

Despite the many potential advantages of the WAAM process, research is needed for WAAM structural steel to be used in the civil engineering sector. Mechanical properties such as the elastic modulus, yield strength (YS), and the ultimate tensile strength (UTS) of WAAM material should be tested and validated. In addition, WAAM steel can have a very rough and wavy surface due to the additive manufacturing process. The rough surface can cause stress concentration zones within the material that may affect its fatigue performance. Although this can be mitigated by post-processing steps such as surface milling, it is important to study its properties in its as-built state

as milling is an additional fabrication step, which takes time and cost and may not be necessary for some projects and applications.

This thesis aims to explore the material properties, fracture toughness, and fatigue behaviour of WAAM steel components. Through experimental testing, mechanical properties such as the elastic modulus, yield strength, and ultimate tensile strength are determined. Further test results include Charpy v-notch impact tests to determine fracture toughness, as well as tests to determine crack propagation properties. Lastly, the experimental program included testing the fatigue behaviour of WAAM steel for both the smooth and rough (as-fabricated) specimens. The experimental program also examined the effects of weld direction by including tests on specimens oriented both perpendicular and parallel to the weld.

The fatigue data collected from the experimental program was used to plot a stress-life (S-N) curve for WAAM steel. The data was then statistically analyzed and compared to current codes such as CSA S6 and S16. It was found that the fatigue behaviour of the WAAM steel was dependent on the weld direction. The specimens oriented parallel to the weld showed behaviour similar to CSA Detail Category B. Specimens oriented perpendicular to the weld showed behaviour similar to CSA Detail Category E.

A metallurgical study of the WAAM steel showed that its microstructure showed resemblance to welded steel components. Looking at the microstructure, the grain sizes and boundaries indicated differences in the as-deposited zones and the reheated zones. The reheated zones, where the addition of new layers disturbed the microstructure, consisted of finer grains expected to exhibit greater toughness.

Lastly, a linear elastic fracture mechanics (LEFM) model was used to predict the fatigue lives of the WAAM steel fatigue specimens in the perpendicular- and parallel-to-weld orientations. The model was able to predict the fatigue behaviour of the WAAM steel specimens, but the results were greatly dependent on the assumed surface stress concentration factors, K_t . More research is needed to obtain K_t values that will enable greater accuracy in determining the fatigue behaviour of WAAM steel.

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1 Introduction

1.1 General

The increasing demand for automation has led many industries to investigate ways to incorporate its potential into their markets. Accordingly, it does not come as a surprise that recent developments in civil engineering are also increasingly relying on automation. The embedding of automation into different stages of a project opens up new opportunities that were previously out of reach for architects and designers. If the desires of the architect once appeared unachievable without risking high planning and manufacturing costs, this can now be resolved with the use of automation and robotics as a part of the early stages of project development [1].

The Wire Arc Additive Manufacturing (WAAM) process is an innovative manufacturing process that allows the fabrication of structural elements using directed energy deposition. This process is also sometimes referred to as Gas-Metal Arc Additive Manufacturing (GMAAM). For structural steel fabricators, the use of this automated technology promises to reduce supply chains, part inventories, scrap waste, and improve constructability through the digitalization of the fabrication process. The WAAM process allows the exploration of new ideas that expand the scope of possibilities for structural steel production. These may include customized connection nodes printed on standard wrought sections, unique structural shape transitions, rapid prototyping, and the creation of components with integral weld backing to simplify field erection and welding. The WAAM process is not limited to the production of unique steel components but is also a promising fabrication process for various other metallic engineering materials such as titanium, aluminum, and nickel alloy [2]. Furthermore, when compared to the conventional subtractive manufacturing processes, it has been said that the WAAM process can reduce the fabrication time by 40-60% and post-machining time by 15-20% depending on the size of the component [2].

Despite the many advantages of the WAAM process, like all new materials, thorough research is needed to be able to effectively implement the WAAM structural steel into the civil engineering sector. Mechanical properties such as the elastic modulus, yield strength, and the ultimate tensile strength of the material must be tested and validated. More importantly, the rough characteristics induced on the product by the WAAM process raises many questions regarding its fatigue and fracture properties. Unlike conventional steel, WAAM steel in its unmilled state can have a very rough and wavy surface that results from the additive manufacturing process. The main concern is that the roughness will cause stress concentrations zones that will affect the fatigue performance of the steel. This can be mitigated by post-processing steps such as surface milling, but it is important to study its properties in its as-built state to achieve its utmost efficiency. Therefore, experimental fatigue and fracture toughness testing is crucial to investigate how the material acts similarly or differently to conventional or smooth steel. Analysis tools such as fracture mechanics, specifically linear elastic fracture mechanics (LEFM), can also be implemented to better understand and predict the fatigue behaviour of the WAAM steel.

The obtained fatigue life, whether obtained by experimental or analytical means, can be compared to the “detail categories” or “S-N curves” presented in many structural design codes and recommendations such as CSA S6 [3] or S16 [4]. From this comparison, the fatigue performance of the WAAM steel can be easily compared to the current standards for conventional structural steel welded components. The ability to classify this material in a language that is currently being used is advantageous for effectively introducing this material into the industry.

Another area of concern is the internal defects that could be embedded in components manufactured by this process. These defects can include inclusions, porosity, and/or lack of fusion defects. Since the process involves constant heating and cooling of the material, it is important that

the selection of manufacturing parameters is optimized. To study this, metallurgical analysis is helpful to observe how the grain boundaries are formed by the WAAM process. Relating the microstructural properties such as grain boundaries and sizes to the manufacturing parameters allows optimal parameters to be selected to suit the needs of the designer.

This thesis will provide insight into the material properties of WAAM steel in comparison to conventional structural steel. There will be a focus on the fatigue and fracture toughness of the material using both experimental and analytical approaches to classify this material according to current codes. Furthermore, the thesis will examine the material on a microstructural level to examine the defect profile and metallurgical characteristics of fabricated material samples.

1.2 Objectives

The objectives of the current thesis are as follows:

1. to employ various methods of material testing to establish material parameters including impact toughness and crack propagation parameters for WAAM materials,
2. to conduct small-scale fatigue tests and analysis methods to establish properties such as the constant amplitude fatigue limit (CAFL) for WAAM materials, and
3. to use results from Objectives 1) and 2) as inputs for a fracture mechanics analysis to establish relationships between surface roughness and performance needed to eventually develop performance-based quality control guidelines for WAAM materials.

1.3 Scope

The scope of the work presented in this thesis includes the review of literature regarding WAAM processes and WAAM structural steel. Following this, experimental testing of material and fatigue

parameters is presented, along with a metallurgical analysis of the material microstructure, and a fracture mechanics analysis of WAAM fatigue specimens under cyclic loading.

1.4 Thesis Organization

In this thesis, the literature review in Chapter 2 Literature Review will cover the production side of the WAAM process. This includes the utilization, the advantages, the applications, and the material compatibility. On the product side, the literature review will examine the testing and analysis methods conducted by previous studies. These studies will examine the mechanical properties, the microstructural properties, the fatigue and fracture toughness properties, and the defects of the WAAM structural steel. Chapter 3 Fatigue and Materials Testing goes through the steps taken for testing the mechanical, fatigue, and fracture toughness properties of the WAAM structural steel. This is followed by Chapter 4 Fatigue and Materials Testing Results, which presents the data compilation and results of the aforementioned tests. Then in Chapter 5 Metallurgical Analysis, the steps taken to conduct a metallurgical analysis and resulting observations are presented. From the gathered information, statistical analysis and linear elastic fracture mechanics (LEFM) analyses of the fatigue test results are performed and presented in Chapter 6 Analysis. Lastly, in Chapter 7 Conclusions and Recommendations for Future Work, conclusions and recommendations for future work in this general research area are discussed.

2 Literature Review

This chapter presents a review of the existing research on the WAAM process as well as WAAM structural steel. Firstly, literature stating the general procedures of the WAAM process as well as its input parameters is reviewed in Chapter 2.1. Specifically, in Chapters 2.1.1 - 2.1.3, the advantages, the applications, and material compatibility are discussed. In Chapter 2.2, focuses on WAAM structural steel including the testing and analysis of WAAM structural steel conducted by others in Chapter 2.2.1, mechanical properties in Chapter 2.2.2, microstructural properties in Chapter 2.2.3, and fatigue properties in Chapter 2.2.4.

2.1 The WAAM Processes

Wire Arc Additive Manufacturing (WAAM) is an innovative Additive Manufacturing (AM) technology that uses an electric arc as its source of heat generation. The ASTM standard classifies all metallic AM processes into three categories: direct energy deposition (DED), powder bed fusion (PDF), and sheet lamination [5]. Out of the three, the WAAM process falls under direct energy deposition which involves feeding a wire melted by the electric arc power source to produce a 3D structure or component. These products are created by a layer-by-layer deposition of material hence the name *additive manufacturing* [6]. The first patent in relation to WAAM was filed around 1925, but it has only begun to gain interest from different industries within the last two decades [6]. Since then, much more research has been done to study the process and the effects on the material microstructure and mechanical properties. Some notable research includes, one of the first studies of the mechanical properties of WAAM components by Brandl et al. [7], a parametric study to improve the WAAM process by Xiong et al. [8], a study on residual stress as a main concern with the WAAM process and its improvements by Colegrove et al. [9], finite element analysis to study and mitigate residual stress and distortion by Montevecchi et al. [10], and investigation of

the improvement of geometrical and microstructural properties using non-destructive testing by Lopez et al. [11], to mention some key examples.

According to Srivastava et al. [6], the overall WAAM process can be separated into three steps: (a) process plan, (b) depositing layer, and (c) post-processing. Other explanations of the WAAM process steps have minor differences but they generally follow the same three steps. More specifically, the WAAM process involves a Computer-Aided Design (CAD) model that is put through 3D slicing where the model is sliced into a Standard Triangle Language (STL) which is a required parameter to define the step-by-step metal deposition [12]. Once the 3D slicing is complete, the path of fabrication is planned and executed using a fabricating machine such as a robotic arm and other computer numerical control (CNC) arrangements [12]. Depending on the application, post-processing such as machining of the surface may be required. While details may vary, similar procedures are mentioned in a number of studies [2, 12, 13].

Within the depositing layer step, there are many parameters to consider. Dinovitzer et al. [5] points out that it is crucial to consider key input factors such as, travel speed, wire feed rate, working distance, arc voltage, and deposition strategy or path planning, to have the optimal material characteristics in the steel components produced by the WAAM process. With many steps and parameters required in the use of this technology, more research is necessary in developing WAAM procedures that are tailored to the requirements of the application. Through this research, the WAAM process holds countless opportunities and is advantageous in achieving different material characteristics simply by changing input parameters.

2.1.1 Advantages of WAAM Processes

Kumar et al. [14] explain that the WAAM process is found to be the most successful and efficient method of additive manufacturing that falls under direct energy deposition. Originally named Wire and Arc Additive Layer Manufacturing (WAALM) in 2011, the process boasts fast production with a lower cooling rate than that of laser and electron-based deposition counterparts [14]. The most attractive quality of the method is its ability to create thin additive layered structures with the least amount of processing time including deposition rate and post-machining [14].

In addition to the freedom in geometrical design and efficiency it offers, the method is also useful where problems arise from the load-bearing capacity limits of conventional solutions. Closed shapes, such as hollow sections, are difficult to access the inside to provide stiffening reinforcement. In addition, with conventional casting techniques, the improvements are limited to gradual wall thickening. However, with WAAM, internal reinforcements can be implemented from the original production of the component, as shown in Figure 1 [1].



Figure 1: Conventional detail (left) and WAAM process detail (right) of a T-joint rectangular hollow profile [1]

Compared to other forms of AM processes such as powder-bed systems, the WAAM process has a significantly higher deposition rate though the precision of the fabricated components may be lower [15]. Panchenko et al. [16] summarizes the advantages of the WAAM process over other AM processes in Figure 2. WAAM offers high performance with a deposition rate up to 3 kg/h and a power efficiency of up to 90% while the equipment costs are relatively low [16]. Certain methods of WAAM processes such as the Gas Metal Arc Welding (GMAW), can even achieve deposition rates up to 10 kg/h [1].

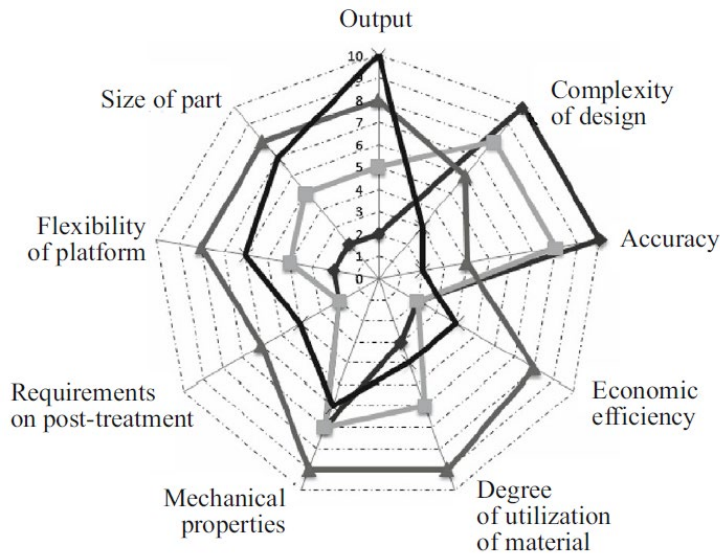


Figure 2: Advantages of WAAM over other AM processes: bed deposition (◆), direct deposition (■), electron beam freeform fabrication (×), WAAM (▲) [16]

2.1.2 Applications of WAAM Processes

Additive manufacturing processes have been implemented many times in the construction industry. These applications, however, have generally been more focused on concrete structures such as the Winsun houses and offices built in 2013 by the architectural firm, Winsun [17]. As the construction industry strives to tackle the demands for automation, other mediums such as metal are increasingly being considered. So far there have been applications of metal additive manufacturing

in the construction industry at a much smaller scale such as the Nematox façade node, shown in Figure 3, and the lighting node designed by Arup, shown in Figure 4 [17]. However, these examples used the powder bed fusion method rather than the WAAM method.

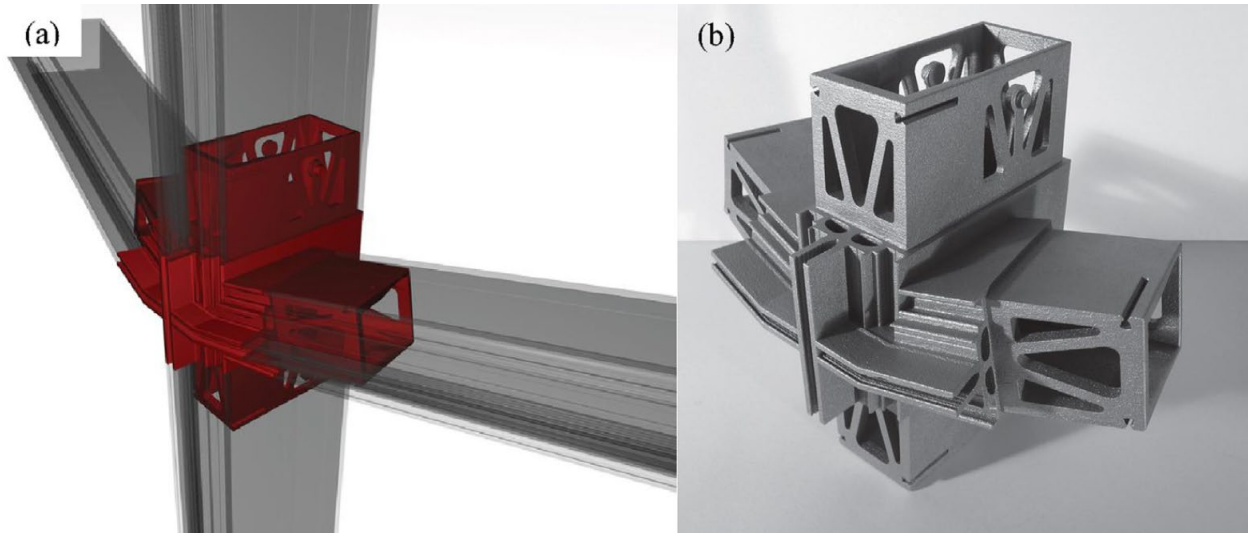


Figure 3: (a) Nematox Facade node rendering and (b) a full-size aluminum prototype of the node [17]

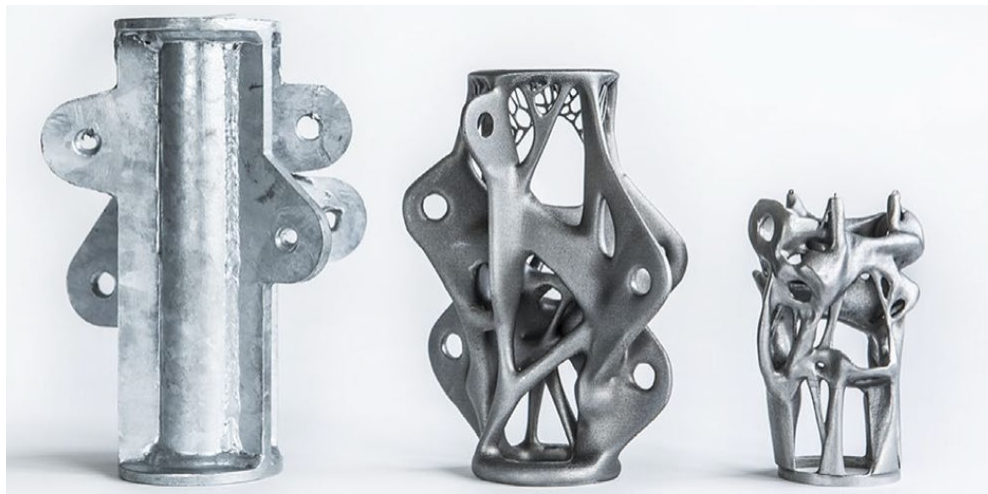


Figure 4: Conventional lighting node to two AM optimised lighting nodes [17]

On a larger scale, a 10 m span pedestrian bridge was developed by MX3D with engineers from Arup and researchers from Imperial College London [17]. This bridge, shown in Figure 5, has a width of 2.5 m and was built using WAAM with a 6-axis robotic welding arm. Gardner et al. [18]

goes through an in-depth report on the manufacturing, testing, and verification process of the MX3D bridge. The bridge was printed in four main pieces along with four corner swirls then manually welded together. These manual welds were located at approximately the midspan and quarter points of the bridge. Over 1100 km of Grade 308LSi austenitic stainless-steel wire was used with a general deposition rate of about 0.5-2.0 kg/h. For bridge elements that had a nominal thickness of 3.5 mm, a 1.0 mm diameter wire was deposited with a speed of 15-30 mm/s and a wire feed rate of 4-8 m/min. For bridge elements that had a nominal thickness of 8.0 mm, a wire of 1.2 mm diameter was used with a speed of 13 mm/s and a wire feed rate of 5.7 m/min. The printing took over approximately six months to complete in total, and structural testing was done both during and following the printing period [18].



Figure 5: MX3D bridge made by WAAM, Amsterdam [17]

2.1.3 Material Compatibility of WAAM Processes

The WAAM process is not only limited to steel but other metallic mediums such as Ti-6Al-4V, copper, titanium, chromium, aluminum, Inconel, and nickel bronze [19]. There are various design opportunities to be explored for every material. Kawalkar et al. [20] goes through the behaviour of material with respect to the selection of WAAM process parameters. These parameters can include the selection of the heat source, wire feed, rolling, processing conditions, and heating techniques for enhancing and optimizing the manufacturing process [20].

A common alloy used in the WAAM process is the Ti-6Al-4V alloy. The Ti-6Al-4V alloy is widely used in the aerospace industry and has been actively researched to enhance its performance over the years [20]. When laser is used as the heat source, the alloy typically exhibits grain sizes and widths in direct relation to the laser power and wire feed rate but inversely proportional to weld speed. Chaturvedi et al. [19] mentions that the mechanical properties of the WAAM Ti-6Al-4V alloy are anisotropic, and hence the material has a better fatigue strength and ultimate tensile strength (UTS) along the deposition direction. Furthermore, when plasma is used as the heat source, both sources [19, 20] agree that there is an increase in the tensile strength by approximately 12% and a wider wall width can be achieved. In addition, Wang et al. [21] investigate the mechanical properties and the microstructure of TiAl compounds by depositing varying atomic ratios such as Ti-35Al, Ti-45Al, and Ti-55Al using a dual wire. Figure 6 shows the microhardness results and the tensile test results from this study [21]. The microhardness, yield strength, the UTS decreased with the increase of Al content. However, the effects on the elongation were inconsistent. WAAM is useful in being able to combine and alter the atomic ratios of the component using a dual-wire system. This allows the flexibility to utilize the various characteristics of each material. However, parameters to be varied in such a process should be further researched.

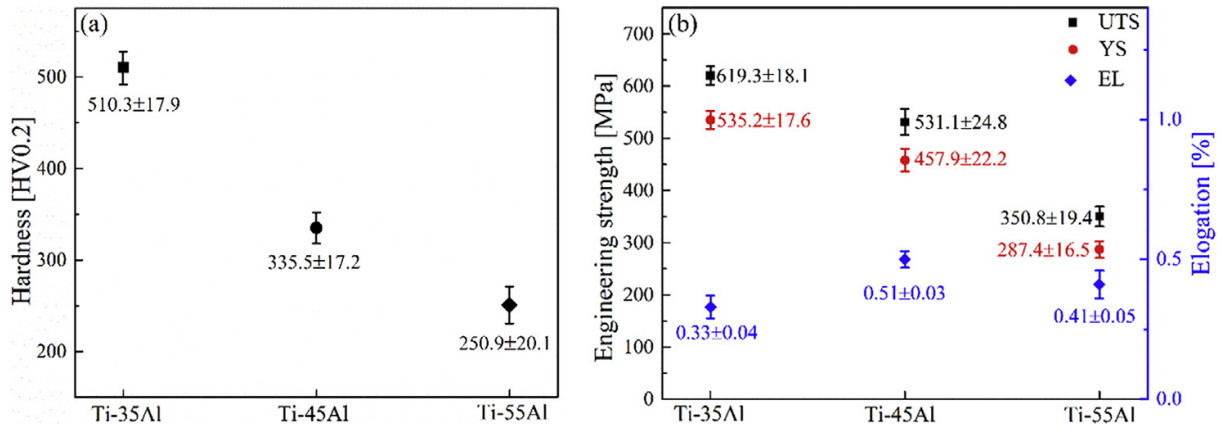


Figure 6: (a) Microhardness and (b) tensile properties of TiAl samples with different Al content [21]

Another commonly used alloy is the aluminum alloy. A study by Geng et al. [22] examines the geometric limitations and the tensile properties of the WAAM 5A06 aluminum alloy made with a 1.2 mm thick wire. Geng et al. explains that the tensile strength and elongation are isotropic in the parallel and perpendicular directions to the build with an average tensile strength, yield strength, and elongation of 273 MPa, 124 MPa, and 34%, respectively. In the directions parallel and perpendicular to the texture orientation, the material exhibits anisotropic behaviour. The tensile strength, yield strength, and elongation of the parallel specimen was 228 MPa, 87 MPa, and 31%, respectively. For the perpendicular specimen, the results were all higher with a tensile strength, yield strength, and elongation of 259 MPa, 104 MPa, and 37 %, respectively [22].

Chromium is another metal that has been studied for compatibility with the WAAM process. Ge et al. [23] use the WAAM process to deposit a thin-wall part made of 2Cr13, a martensitic stainless steel, using a robotic cold metal transfer (CMT) equipment. The study was done to investigate the process stability, phase identification, microstructural evolution, and tensile properties in different layers. Ge et al. explains that ferrous-based parts manufactured using AM processes go through repeated cycles of heating and cooling which normally results in significant inhomogeneity and

hence introduces anisotropy mechanical properties [23]. However, using WAAM, specifically robotic CMT-AM processes can limit anisotropic behaviour. Through the study of tensile properties of 2Cr13, it was found that the UTS remained consistent regardless of the specimen orientation. Moreover, the experiment results presented a high UTS with a maximum of 1416 MPa [23].

Nickel-based alloys are another material that is widely used in the aerospace and nuclear industry, such as in transition ducts and gas turbines [15]. These alloys offer high strength at high temperatures, low thermal expansion, and excellent corrosion resistance. The WAAM process can benefit the use of Ni-based alloys by eliminating material waste. Ni-based alloys tend to be costly and are difficult to machine making the WAAM process ideal for efficient and cost-effective production [15]. Ni-based alloys such as Inconel 625 and Inconel 718 have mechanical properties and morphology that are dependent on its thermal history [15]. The Ni-based alloy Inconel 625 had been studied with the use of WAAM by Wang et al. [24]. In this study, an WAAM wall of Inconel 625 was deposited by the GTAW-ALD technique. Tensile test coupons were extracted from the plate in two directions, the longitudinal direction (Y) and vertical build direction (Z) [24]. The result was that the material exhibits anisotropic behaviour with the UTS and elongation in the Y-direction being about 722 MPa and 42%, respectively. While in the Z-direction, the UTS and elongation were about 684 MPa and 40% [24]. In addition, the shielding gas has an influence on the mechanical and geometrical properties of final product where the UTS was increased by 50 MPa when 97.5 % Ar and 2.5% CO₂ shielding gas was used [25].

Finally, magnesium alloys are increasingly being sought out as an alternative to aluminum to reduce the weight of parts in the automotive and biomedical industries [15]. One downfall to the use of magnesium was its flammability risk. However, this was mitigated by adding aluminum,

rare-earth elements (zirconium, gadolinium, dysprosium, yttrium, neodymium, and cerium), and other additional trace elements (Ca, Sr, Sb) to the magnesium, therefore limiting the flammability risk [15]. In addition, due to its microstructure and poor ductility, magnesium incurs defects during forging or extrusion and thus is mostly processed using casting. In addition, recent trends have included the development of monolithic components to further expand the lightweight capabilities of the Mg-alloy. Although monolithic Mg-based components are difficult to achieve with conventional forging and casting methods, AM methods, specifically WAAM, can be utilized to meet these requirements [15]. In the study done by Guo et al. [26], a WAAM process is used to deposit a wall of using 1.2 mm diameter AZ31 magnesium alloy wire. To refine the grains and obtain effective mechanical properties of the AZ31 Mg-alloy, the effects of pulse frequency (1, 2, 5, 10, 100, and 500 Hz) on the macrostructure, microstructure, and tensile properties were examined [26]. In terms of macrostructure, the surface morphologies vary depending on the different pulse frequencies. With the increase of pulse frequency, the weld ripples become finer and increase in number. This creates the effect that they seem to be continuous resulting in a much smoother surface compared to those of lower frequencies [26]. As for the microstructure, the grains were the finest at pulse frequencies of 5 Hz and 10 Hz while other frequencies both, lower and higher, resulted in coarser grains [26]. Lastly, the tensile properties of the material showed significant variation with changes in the pulse frequency. The UTS ranged from 221 to 263 MPa, and the yield strength (YS) ranged from 79 to 104 MPa. It was found that at 5 Hz and 10 Hz, the material exhibited the greatest UTS and YS resulting in magnitudes of 263 MPa and 104 MPa, respectively, which is similar to the forged AZ31 alloy according to [26].

2.2 WAAM Structural Steel

On the product side of the WAAM process, WAAM structural steel products have been researched and reported in numerous studies. From mechanical properties to microstructural properties, research has been done to examine the final products of this technology, in order to improve our understanding of its advantages and limitations. In addition, defects specifically caused by the process reported on, porosity, inclusions, and lack of fusion defects, and methods for their mitigation. This chapter will go through these literatures, examining the methods employed to obtain mechanical and fatigue properties, as well as microstructural properties.

2.2.1 Testing and Analysis Methods

To test WAAM structural steel products, the material must first be fabricated and then cut into specimen dimensions. Generally, this involves fabricating a wall of welded material using a robotic WAAM platform. Rafieazad et al. [27] deposited a wall comprised of six beads with a length of 135 mm and a height of 150 mm. In total this wall contained 50 layers of material with 3 mm center-to-center overlap resulting a width of 22 mm. A schematic of the wall is shown in Figure 7. The employed robot was a Lincoln Electric GMAW machine with a torch mounted on a 6-axis Fanuc robot. An interlayer temperature of 165°C was adopted [27]. The specimens were tested for tensile strength. An Instron load frame was used with a displacement rate of 8 mm/min. Strain was recorded using an extensometer [27]. In terms of microstructure characterization, standard steel grinding and polishing procedures were performed using a Tegamin-30 Struers auto-grinder/polisher followed by etching using 5% Nital as the reagent [27].

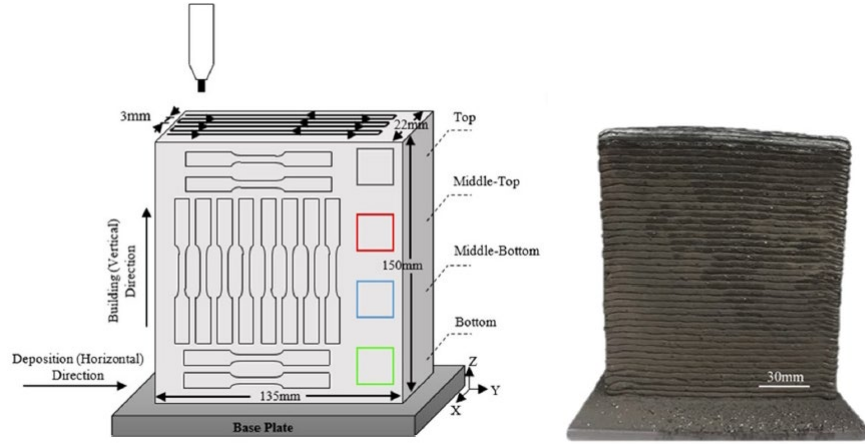


Figure 7: Schematic of WAAM-ER70S-6 steel wall (left) and the manufactured wall using WAAM method (right) [27]

Moore et al. [28] performed a similar analysis of mechanical properties involving the manufacturing of arc-AM deposited walls. Moore et al. [28] adopted two different techniques in depositing the walls. For one method, similar to what was presented by Rafieazad et al. [27], the bead was woven lengthwise within each layer and reversed for the consecutive layer, as shown in Figure 8 (left). The second method was an oscillating deposition technique where a single bead was woven widthwise within each layer and direction and the starting point was reversed for the consecutive layer, as shown in Figure 8 (right). In both methods, the overall dimensions of the wall were 500 mm long by 30 mm wide and 250 mm tall [28]. From each plate, six round tensile specimens with a gauge diameter of 10 mm, six single-edge notched bend (SENB) fracture toughness test specimens with dimensions 15 mm by 30 mm by 150 mm, and six Charpy specimens with dimensions 10 mm by 10 mm by 55 mm with a machined V-notch were extracted [28]. Furthermore, some additional small specimens were extracted for basic metallographic analysis and chemical composition analysis [28].

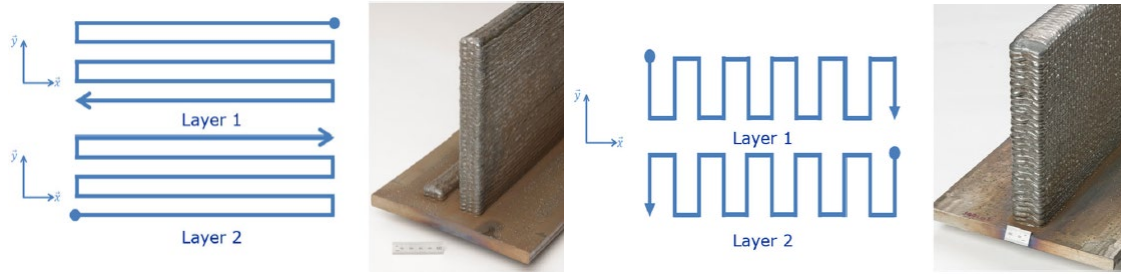


Figure 8: Bead deposition techniques: parallel bead deposition (left) and oscillating bead technique (right) [28]

The current research on WAAM structural steel products is not limited to static loading behaviour but has also examined behaviour under cyclic loading. Bartsch et al. [29] performed fatigue analysis on similar specimens fabricated by WAAM processes. Ten samples, four “long” and six “short”, were water jet cut out from WAAM welded plate of approximately 250 mm by 100 mm by 5 mm [29]. The main purpose of the test program was to investigate the influence of the surface roughness and waviness caused by the manufacturing process; hence the surfaces were left unmilled [29]. The tests were carried out in pure tensile forces with a stress ratio (minimum stress level divided by maximum stress level) of $R = 0.1$ [29].

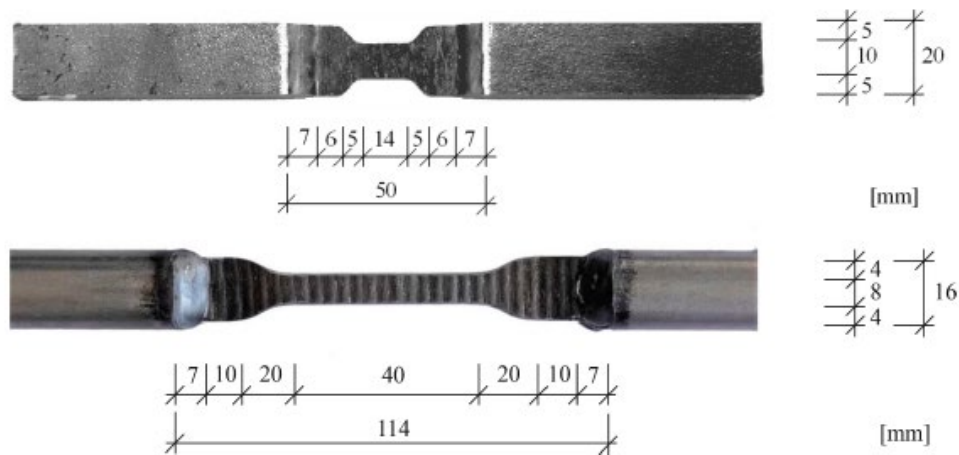


Figure 9: Sample of fatigue test specimens conducted by Bartsch et al.: short (top) and long (bottom) [29]

Finally, a study by Huang et al. [30] investigated the mechanical and fatigue properties as well as the microstructure of the WAAM steel. The difference between this study and the previously mentioned studies was that instead of the specimens being extracted from a welded plate, they were extracted from flat oval tubes as shown in Figure 10. Plates were cut from as-built and machined tube walls as shown in Figure 11a [30]. From these plates, specimens for tensile testing, fatigue testing, and metallurgical testing were extracted, shown in Figure 11b [30].

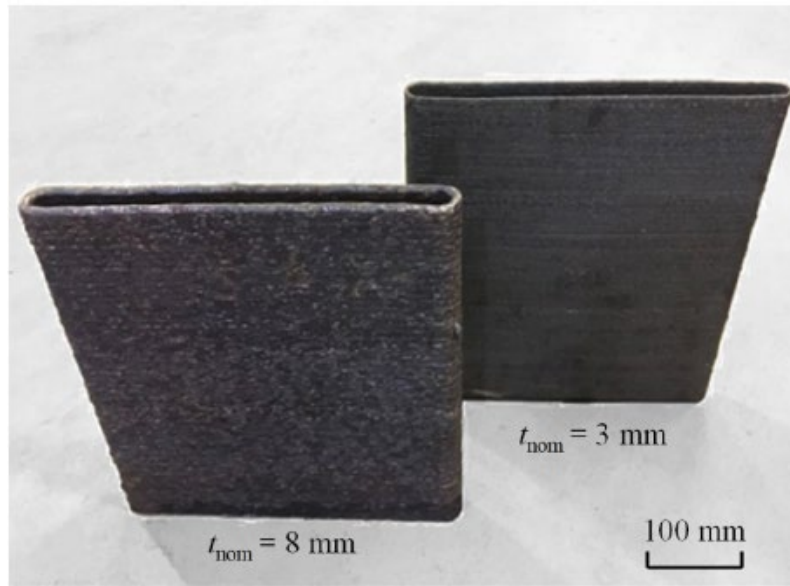


Figure 10: WAAM oval tubes produced by Huang et al [30]

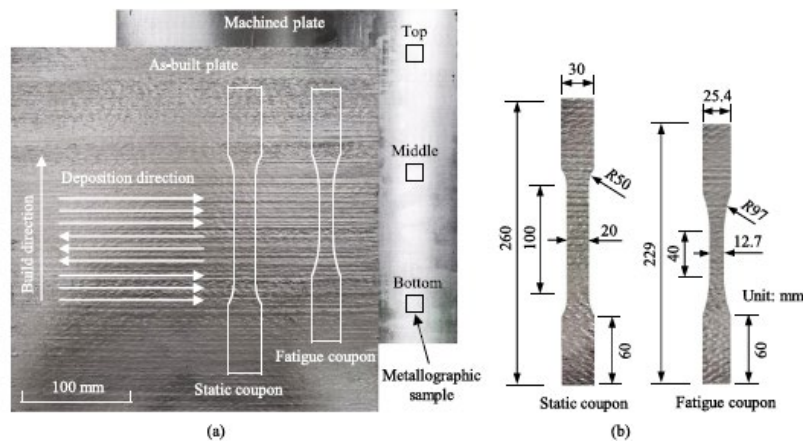


Figure 11: a) As-built and machined plates for extraction of test coupons and metallographic samples, b) static tensile and fatigue as-built specimens [30]

Mechanical property analysis was conducted by Huang et al. [30] in accordance with EN ISO 6892-1 [31]. Two machined and two as-built tensile coupons were tested using digital image correlation (DIC) to monitor the deformations and strains [30]. The material microstructure was examined through optical microscopy in accordance with ASTM E3-11 [32]. Lastly, the fatigue strength was investigated by means of constant amplitude uniaxial fatigue testing in accordance with ASTM E466-21 [33]. A total of 75 high-cycle fatigue tests were performed on the as-built and machined coupons with ranging stress ratios of $R = 0.1, 0.2, 0.3$, and 0.4 [30].

2.2.2 Mechanical Properties

A stress-strain curve was plotted from the WAAM-ER70S-6 tensile tests reported in [27] along both the horizontal (parallel-to-weld) and the vertical (perpendicular-to-weld) direction, shown in Figure 12. The embedded bar chart summarizes the tensile properties obtained from the stress-strain curves including, yield strength (YS), and ultimate tensile strength (UTS). The average values of the yield and ultimate tensile strength in both directions was 396 ± 26 MPa and 503 ± 21 MPa, respectively [27]. The results show that the WAAM material exhibits isotropic tensile behaviour under static loading. However, Figure 12 indicates that the vertical specimens show lower elongation, hence suggesting the material is rather anisotropic in ductility [27]. Overall, the observed stress-strain relationship resembles that of conventional structural steel.

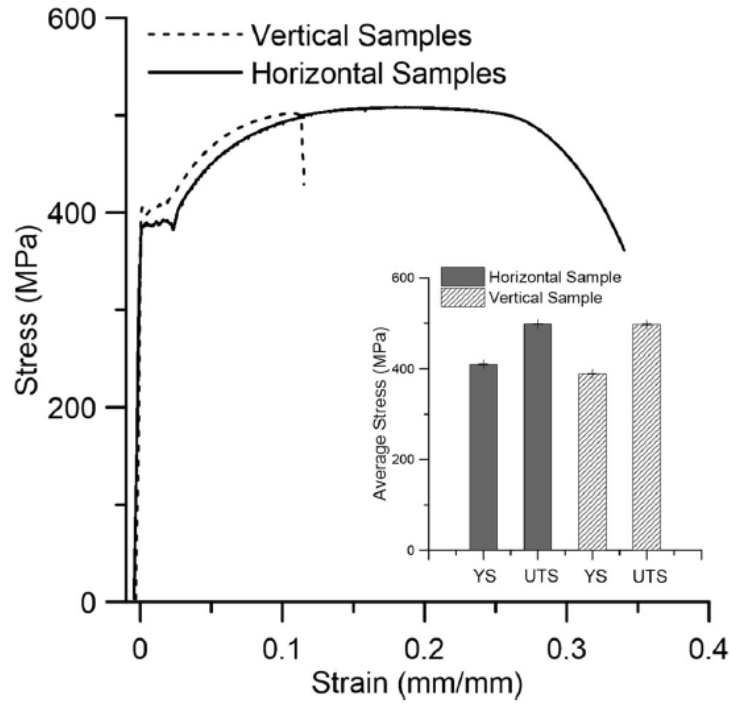


Figure 12: The stress-strain curves and their respective tensile properties for the vertical and horizontal specimens by Rafieazad et al. [27]

The static tensile test performed by Moore et al. [28] shows different results for the two types of weld patterns. For the parallel bead deposition, the yield strength of the parallel specimens were within the range of 381 – 401 MPa while the perpendicular specimens were within the range of 308 – 317 MPa. For the oscillating bead deposition, the yield strength of the parallel specimens was within the range of 346 – 360 MPa while the perpendicular specimens were within the range of 328 – 351 MPa [28]. The oscillating bead deposition showed a reduced influence of specimen orientation. The stress-strain curves for both cases are shown in Figure 13.

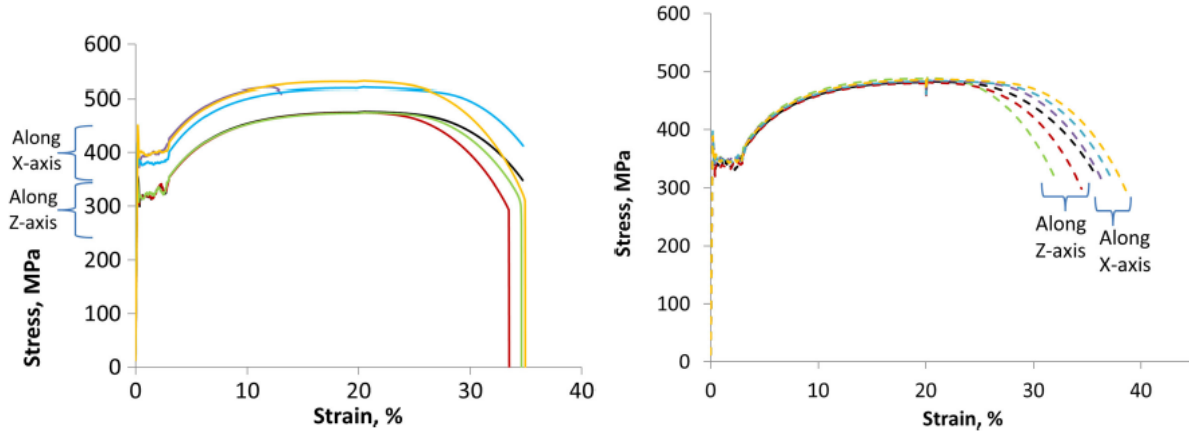


Figure 13: Stress-strain curves for carbon WAAM steel in the parallel- and perpendicular-to-weld direction by Moore et al.: parallel bead deposition (left), oscillating bead deposition (right) [28]

The Charpy impact toughness test results showed that the specimen orientation and the bead deposition technique has only a small effect on the toughness of the material [28]. The specimens that were notched parallel to the welds resulted in a higher room temperature upper shelf toughness than the specimens notched perpendicular to the weld. The parallel bead deposition and the oscillating bead deposition parallel specimens resulted in an average upper shelf energy of 234 J and 255 J, respectively. The perpendicular specimens resulted in an average upper shelf energy of 215 J for both bead deposition techniques. The tanh curve fitted to all of the test data gave a T_{27J} temperature of -88.5 °C, suggesting exceptional toughness behaviour [28]. The results of the Charpy impact test conducted by Moore et al. are shown in Figure 14.

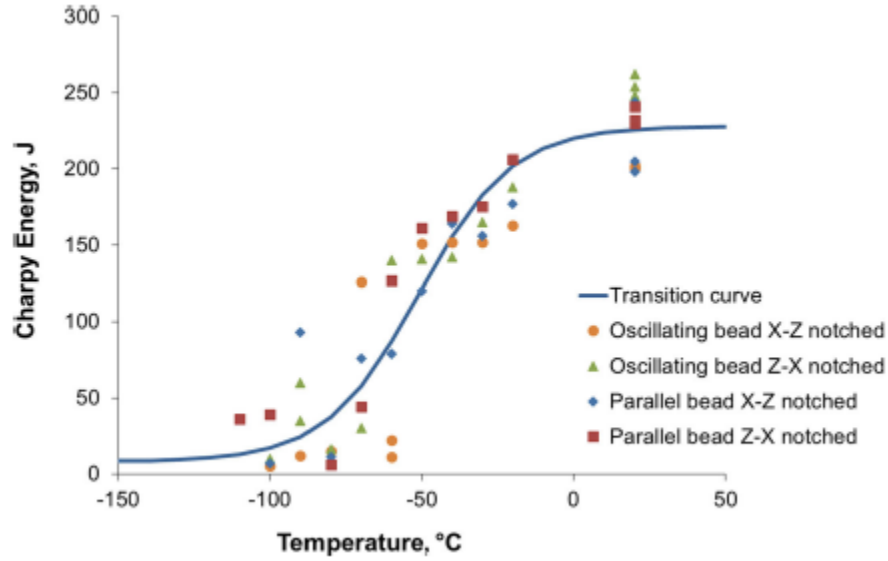


Figure 14: Charpy impact test results with a fitted transition curve for carbon WAAM steel by Moore et al. [28]

Lastly, the static tensile tests conducted by Huang et al. [30] show a comparison of the mechanical properties of machined and as-built WAAM structural steel. The two machined specimens produced yield strengths of 412 MPa and 415 MPa, while the two as-built specimens produced yield strengths of 311 MPa and 339 MPa. The ultimate tensile strengths were 504 MPa and 503 MPa for the machined specimens and 446 MPa and 459 MPa for the as-built specimens [30]. It is apparent there is an improvement in the mechanical properties when post-processing such as surface milling is done. The resulting stress-strain curve is shown in Figure 15.

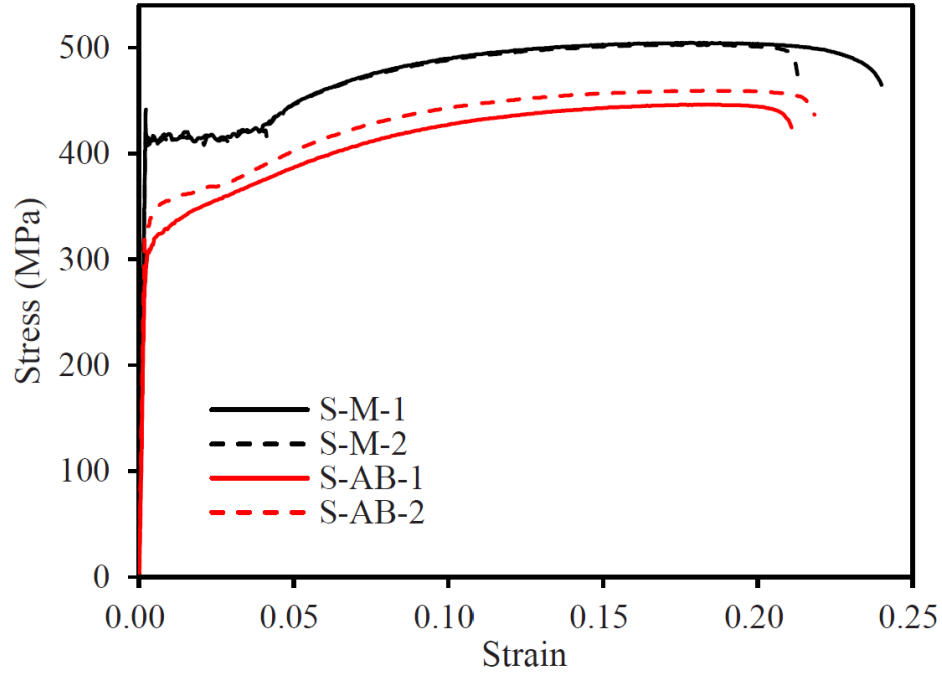


Figure 15: Stress-strain curves for the machined and as-built static tensile coupons performed by Huang et al. [30]

2.2.3 Microstructural Properties

Physical and mechanical properties of metallic components are related to the material microstructure. Especially when looking at welded components, the grain size and morphology has a significant influence on the overall mechanical properties and the anisotropy of metals. Typically, fine grained microstructures exhibit higher strength properties [6].

The microstructural properties of WAAM steel were investigated by Rafieazad et al. [27] on the welded wall by collecting four samples from different locations of the wall. This included bottom, middle bottom, middle top, and the top sections of both the deposition direction and the building direction, as illustrated in Figure 7. The microstructure was imaged using an optical microscope (Nikon Eclipse 50i) and a field emission scanning electron microscope (FEI MLA 650F). The results of the analysis are shown in Figure 16a. The variation of the microstructure is presented in the figure, where the enclosed area B, shown in Figure 16b and Figure 16d, shows the

microstructure of the melt-pool center, typically composed of fine polygonal ferrite as the primary phase and a low volume fraction of lamellar pearlite (P) phase, which is dominant in the ferrite grain boundaries [27]. On the other hand, the boundaries of the melt-pool, shown in Figure 16c and Figure 16e, present the forming of acicular ferrite along the bainite regions (AF+B) beside the melt-pool boundary [27]. It can be observed that the boundaries of the melt-pool have much smaller grain sizes.

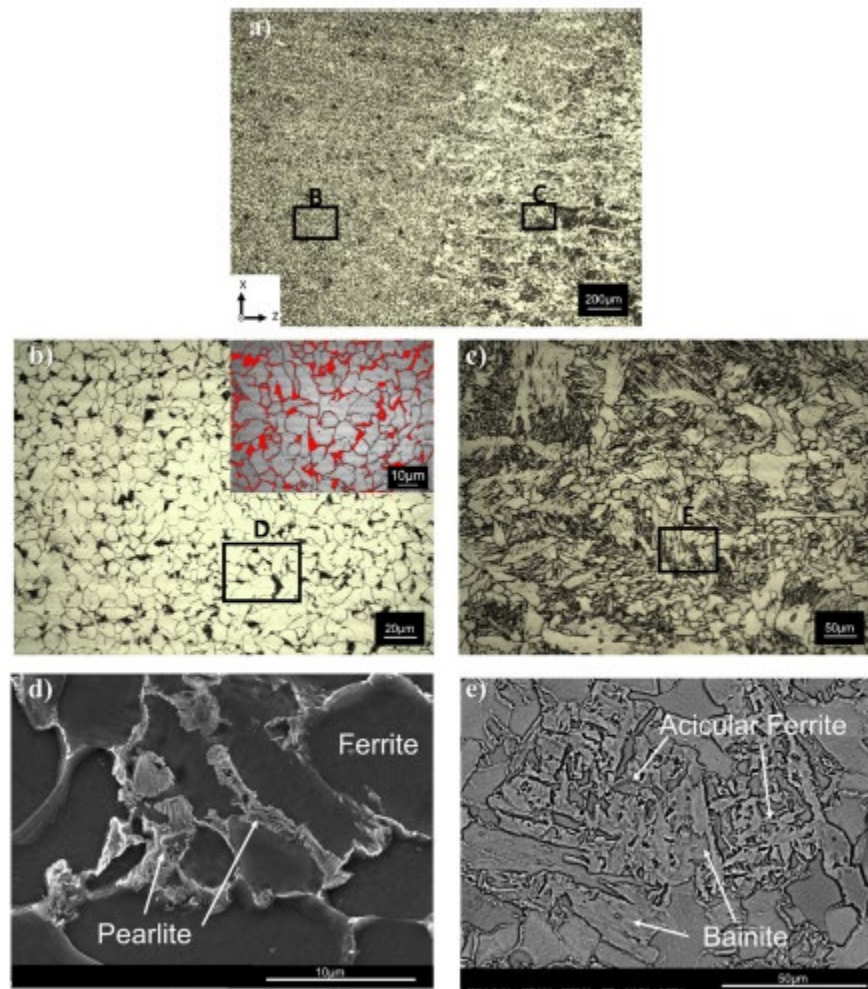


Figure 16: Optical micrographs from a) the WAAM-ER70S-6 steel wall at the fusion line and center of the melt pool, b) higher magnification of enclosed area B from a), also showing phase fraction analysis micrograph with the distribution of the pearlite phase (red) along the ferrite grain boundaries, c) enclosed area C from a), enclosed area D from b), enclosed area E from c) [27]

Although not the primary focus of the study, Moore et al. [28] performed a post-test metallography of the tensile specimen fracture initiation location. The microstructure of the WAAM steel consisted of an extremely fine grain size, which is consistent with the high fracture toughness properties of the material. In addition, a pore was present at the crack initiation location which Moore et al. reasoned was the cause of the outlier of their fracture toughness results [28]. It was also pointed out that this pore was present where the microstructure was most coarse [28].

In the optical microscopy done by Huang et al. [30], metallographic samples were extracted from the WAAM plates at different locations (top, middle, and bottom). The microstructure of the specimens shared similar grain morphologies, compositions and sizes. The constituents of the specimens were similar to those of conventional non-alloyed structural mild steels with a primarily ferritic-pearlitic microstructure [30].

Colegrove et al. [9] examine the effect of surface rolling on WAAM components not only to reduce distortion and surface roughness, but also to induce grain refinement. From the macrosections of the specimens, it was observed that the profiles of the specimens consisted of a series of bands beneath the fusion layer, which is the last deposited layer. These were classified as the refined regions and the non-refined regions. The refined regions displayed the area that was reheated due to the addition of a new layer. Whereas the non-refined region displayed the area that was undisturbed/as-deposited. The rolling had a direct impact on the grains for the refined region. It was found that the rolling reduced the size of the refined microstructure and by increasing the rolling load, the grain size would be further reduced. The non-refined region showed less impact from the rolling. In terms of microstructure, the refined region was predominantly ferritic due to the relatively low carbon content of the wire. On the other hand, the non-refined region consists of Widmanstätten and acicular ferrite which is similar to that of the fusion zone.

2.2.4 Fatigue Properties

The fatigue test results obtained by Bartsch et al. [29] consisted of ten samples with different stress ranges. Nine of the samples failed in the centred region of the WAAM part and one sample was considered a runout with 3,580,964 cycles applied and no failure. These test results were plotted in an S-N diagram and statistically evaluated using a method prescribed by the EN 1993-1-9 [34]. The fatigue strength was calculated by conducting a regression analysis to linearly correlate the stress ranges, $\log S$, and the number of cycles, $\log N$. Then, by applying the least-square method, the inverse slope of the regression line, m , was calculated. However, the EN 1993-1-9 [34] specifies fixed values of m ($m = 3$ or $m = 5$). Nevertheless, the statistical evaluation resulted an inverse slope of $m = 6.5$. With these slope values, the fatigue resistance values were found. For an inverse slope of 3, 5, and 6.5, the resulting fatigue resistance (i.e., the stress level corresponding with a fatigue life of 2 million cycles) was 84 MPa, 128 MPa, and 147 MPa, respectively [29]. The resulting S-N curves for the three inverse slope cases are shown in Figure 17 and Figure 18. The slope of $m = 6.5$ has the lowest standard deviation of 0.22. The standard deviation for $m=3$ and 5 was 0.26 and 0.23, respectively. Although, the inverse slope of $m = 6.5$ best fits the data, the other two slopes are applied for design purposes. Therefore, the fatigue resistance of 128 MPa with an inverse slope of $m = 5$ is used to classify the fatigue class to (FAT) 125 [29].

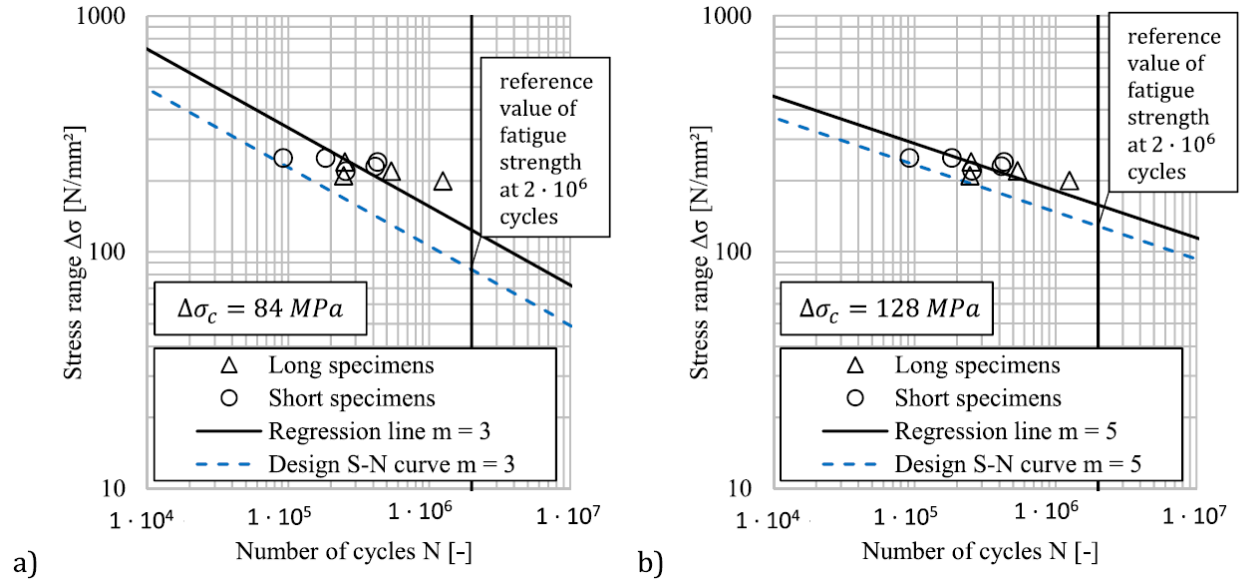


Figure 17: Fatigue test results of all specimens with (a) $m=3$ and (b) $m=5$ (without runout) [29]

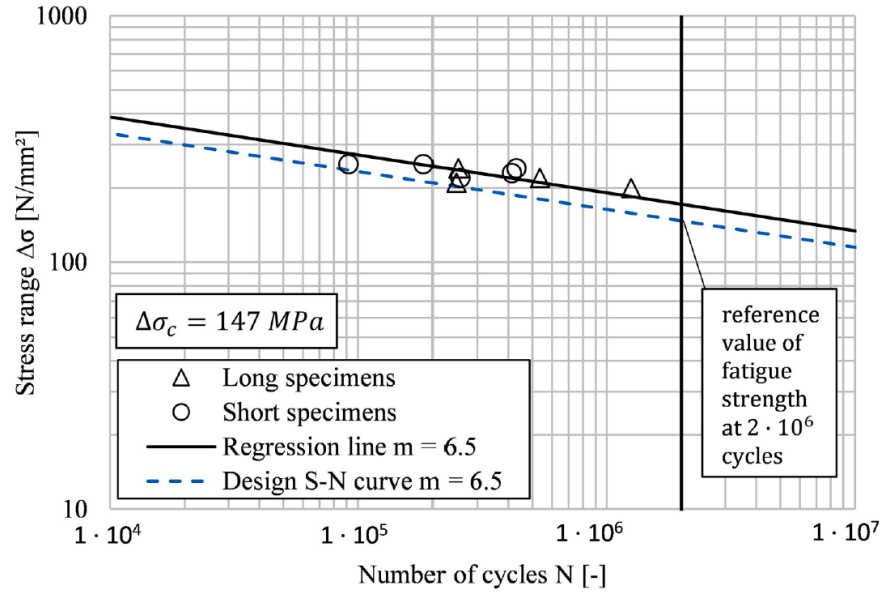


Figure 18: Fatigue test results of all specimens with $m=6.5$ (without runout) [29]

Huang et al. [30] also use S-N diagrams to analyze the fatigue properties of the WAAM structural steel. The same logarithmic approach used by Bartsch et al. [29] in accordance with the EN 1993-1-9 [34] was used to relate the stress and the number of cycles. By means of linear regression, an inverse slope of $m = 2.9$ was determined. Since, this slope is very close to the value $m = 3$

prescribed by EN 1993-1-9 and the IIW Recommendations [35], a slope of $m = 3$ was adopted. This study involved the comparison of as-built WAAM steel as well as machined. Therefore, two S-N diagrams were plotted adopting the same methodology for both cases. It was found that the as-built WAAM specimens had a fatigue endurance limit of 170 MPa while the machined specimens had a greater limit with a 60% increase of 270 MPa [30]. In addition, all test data with finite fatigue lives (discarding runouts) was fitted to an inverse slope of $m = 3.1$. Again, using the recommended value of $m = 3$, the fatigue endurance of all test data was determined as 270 MPa [30].

Comparing the two studies, the fatigue resistance given by Bartsch et al. [29] classified the material as FAT 125 whereas in Huang et al. [30], the as-built samples were classified as FAT 80, the machined samples as FAT 130, and all samples to FAT 135. However, it should be considered that Bartsch et al. [29] performed the analysis with a survival probability of $P_s = 95\%$ while Huang et al. [30] adopted a probability of $P_s = 97.5\%$.

3 Fatigue and Materials Testing

This chapter focuses on the fatigue and material testing procedures and parameters employed in this research project. Chapter 3.1 presents the steps taken to fabricate the WAAM material used to produce the test specimens. Chapter 3.2 described the execution of each test, including the specimen design, frame setup, test procedures, and test parameters.

3.1 Specimen Fabrication

The test specimens were machined from raw WAAM steel plates. These plates were fabricated at the Welding Robotics Laboratory at Conestoga College using a robotic arm as shown in Figure 19. The delivery system chosen for this project was a Fanuc Arc Mate 100-7L/Arc Mate 100iC 6 axis robot with a Lincoln Powerwave R350 power source. Welding took place on mild-steel 360 x 100 x 25 mm plates and the electrode filler metal was 1.14 mm diameter B-G 49A 3 C1 S6 (0.045 in. – ER70S-6). A mixture of 90% Argon and 10% CO₂ was used for the shielding gas. The chemical composition of the Lincoln ER70S-6 SuperArc L-59 wire feedstock that was used in comparison to the requirements for the CSAG40.21 for 350W steel is summarized in Table 1.

Table 1: Chemical composition of wire used for specimen fabrication in comparison to the requirements for 350W steel

Chemical Component	Composition (%)	
	ER70S-6 L-59	350W
C	0.07-0.10	0.50-1.50
Mn	1.42-1.49	<0.40
Si	0.81-0.89	NR
Ni	0.01-0.02	NR
Cr	0.02-0.05	NR
Cu	0.12-0.23	NR
Mo	0.01	NR
V	<0.005	NR
P	0.005-0.010	<0.04
S	0.017-0.027	<0.05

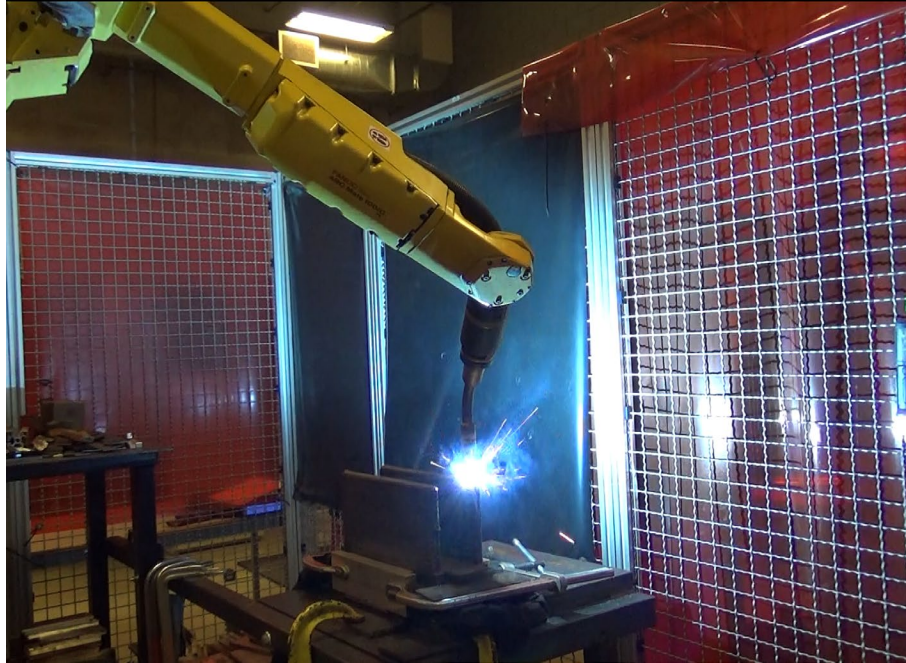


Figure 19: WAAM plates being robotically manufactured at the Welding Robotics Laboratory at Conestoga College

Adopting this method, a total of twelve plates were produced, ten of which are shown in Figure 20. These plates were cut to specimen dimensions to assess material properties, including fatigue and fracture properties.

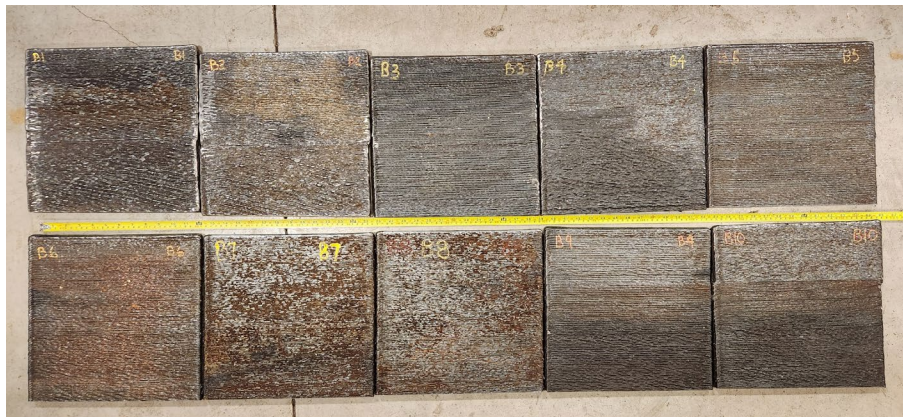


Figure 20: WAAM steel plates produced for test specimens

The planned tests include static tension tests, Charpy V-notch (CVN) tests, compact tension (CT) tests, and fatigue tests for both rough and smooth (milled) specimens. Each of these tests were performed on specimens with the weld bead running in both the parallel and perpendicular directions to the long or loaded axis of the test specimen. The details of each specimen can be found in Appendix A. A summary of the specimen quantities is shown in Table 2.

Table 2: Summary of specimen quantities

Type	Direction	Quantity
Static	Perpendicular	3
	Parallel	3
Charpy	Perpendicular	50
	Parallel	50
CT	Perpendicular	4
	Parallel	4
Cyclic (Smooth)	Perpendicular	10
Fatigue (Rough)	Perpendicular	10
	Parallel	10

Each specimen was given a unique label to properly categorize which plate it originated from, the type of testing, the weld direction, and the associated specimen number. The labelling scheme is summarized in Table 3.

Table 3: Specimen labelling scheme

Block Number	Test Type	Weld Direction	Specimen Number
B##	ST – Static Tensile	N – Perpendicular	##
	CH – Charpy V-Notch	P – Parallel	
	CT – Compact Tension		
	CS – Cyclic (Smooth)		
	FR – Fatigue (Rough)		

3.2 Test Setup and Procedures

3.2.1 Static Tension Test Setup

The static tension test specimens were fabricated and tested according to the ASTM E8/E8M standard [36]. Six specimens were fabricated in total, three of which were machined perpendicular

to the weld bead direction and the remaining three of which were machined parallel to the weld bead direction. An example of a tension specimen is shown in Figure 21.



Figure 21: Static tension test specimen

An MTS 322 test frame and MTS 647 hydraulic wedge grips, as shown in Figure 22a, were used to perform the test. The elongation readings were obtained from a mounted extensometer, as shown in Figure 22b. The strain values were calculated by dividing the elongation reading by the gauge length of 50.8 mm. The stress values were calculated by dividing the load determined by the load cell of the test frame by the initial cross-sectional area of the test region of the specimen.

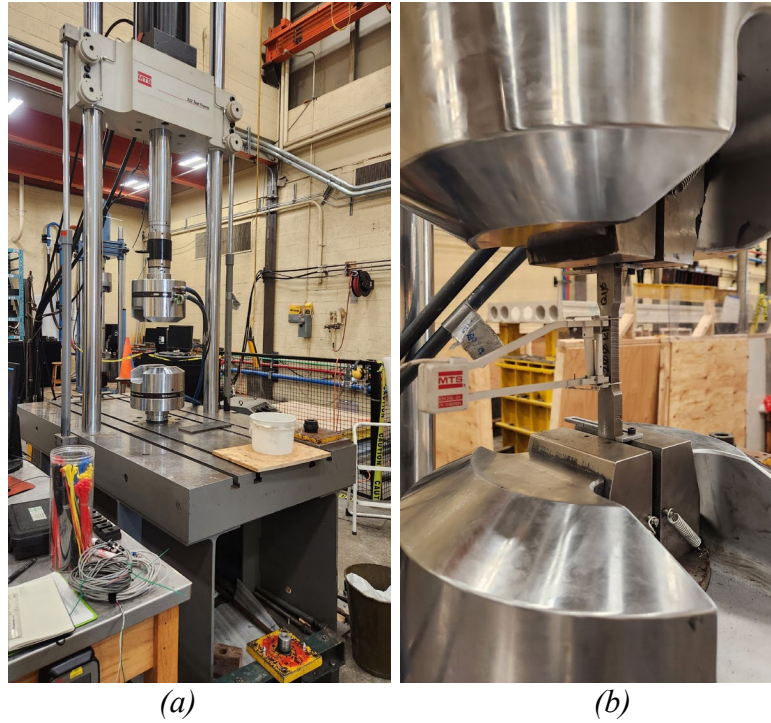


Figure 22: Static tension testing (a) MTS 322 test frame (b) specimen setup with extensometer

In the absence of any specified limitations on speed of testing, the ASTM E8/E8M-22 standard suggests test speeds within the range of strain rates between 0.05 and 0.5 mm/mm of the length of the reduced section per minute. However, in this case the static tests were run under displacement control. The test began with a rate of 0.1 mm/min up to a displacement of 5 mm. Then, in order to ensure a reasonable test duration, a faster rate of 2 mm/min was adopted until fracture. The test results were then compiled to assess the elastic modulus, ultimate tensile stress, and ductility.

3.2.2 Charpy V-Notch Test Setup

The Charpy V-notch (CVN) test is a standardized test to measure the absorbed energy of a notched specimen when struck by a pendulum. In this case, the test was done using the Tinius Olsen's model IT 406 pendulum impact tester shown Figure 23. The test involved 100 CVN specimens with half of them machined in the parallel-to-weld direction and the other half machined in the perpendicular-to-weld direction. The specimens were cut from Blocks 11 and 12, and fabricated

with the notch in the centre where the critical crack is most probable as stated in ASTM A370-23 [37]. A typical specimen before testing is shown in Figure 24.



Figure 23: Tinius Olsen model IT406 pendulum impact tester for Charpy V-notch tests



Figure 24: Charpy Impact (CVN) test specimen (with black marker on face with notch to indicate specimen orientation in testing machine)

The Charpy v-notch specimens were tested in a range of temperatures from -178°C to 80°C to observe the effects of temperature on the absorbed energy at impact. The temperatures were achieved using boiling water for temperatures above room temperature, a dry ice and ethanol solution for temperatures below room temperature. Liquid nitrogen was used to achieve the lowest

temperature of -178°C. To monitor the temperature, an Omega HH501BJK thermometer was used, as shown in Figure 25.



Figure 25: Charpy V-notch temperature control setup

3.2.3 Compact Tension Test Setup

The specimen for the compact tension test was designed, fabricated, and tested according to ASTM E647-23 [38]. The fabricated specimen, shown in Figure 26, was tested to determine the crack growth parameters needed for fatigue life prediction for the WAAM material. The parameters, C and m , are used in the Paris-Erdogan [39] crack growth law to determine the crack propagation under cyclic loading using Equation (1), where a is the crack length, N is the number of cycles, and ΔK is the change in the stress intensity factor.

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

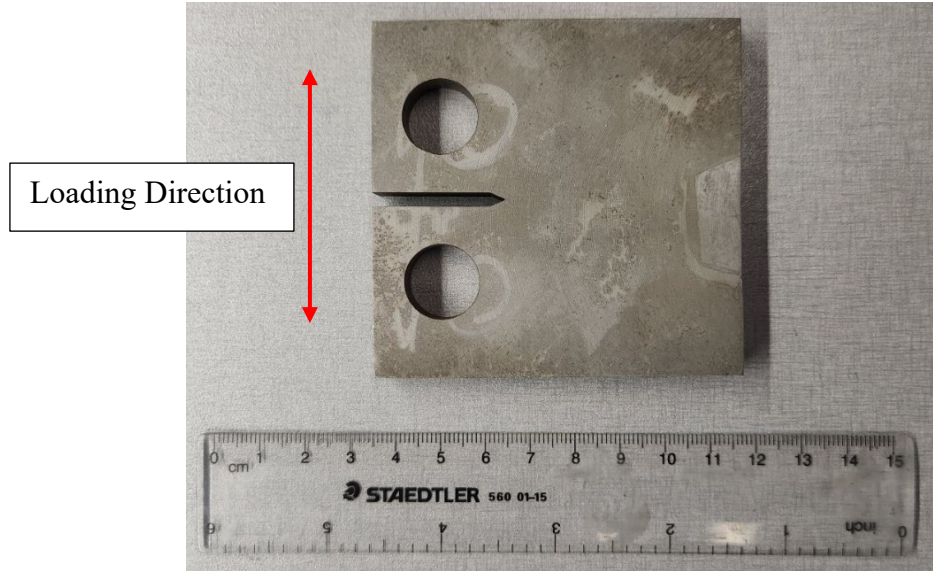


Figure 26: Compact tension test specimen

The specimens were tested in an MTS fatigue testing frame adopting a load ratio, $R = P_{min}/P_{max}$, of 0.8 and a frequency of 100 Hz. The same parameters were used to test four specimens in the perpendicular-to-weld direction and four in the parallel-to-weld direction. Some of the specimens were tested at lower loads to obtain crack propagation rate at lower stress intensities while adopting the same load ratio of 0.8. To obtain the crack mouth opening displacement (CMOD), a clip gauge was placed at the opening end of the notch, shown in Figure 27.



Figure 27: Compact tension test setup

3.2.4 Smooth Cyclic and Fatigue Test Setup

The smooth cyclic specimens were designed and fabricated according to ASTM E606/E606M-21 [40]. The cylindrical specimens were polished smooth to a diameter of 12.7 mm at the grip area and 5 mm at the gauge area shown in Figure 28. This specimen was used for both strain-controlled cyclic and fatigue testing. Both tests were performed using an MTS fatigue testing frame with collet grips to fit the round geometry of the specimens, as shown in Figure 29. An extensometer was placed to capture the strain readings during the test. A coat of “white out” was applied to the areas where the extensometer would be placed to prevent any slippage.

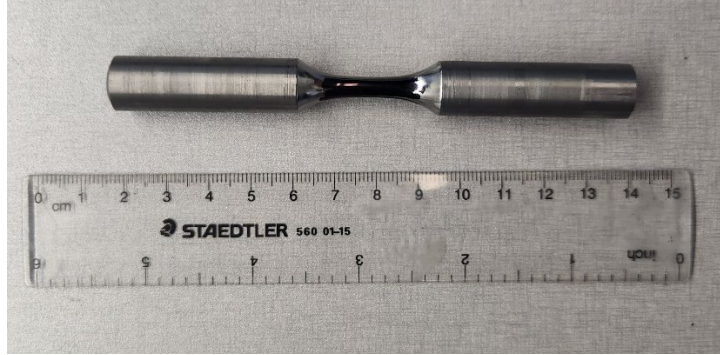


Figure 28: Smooth fatigue test specimen



Figure 29: Smooth cyclic and fatigue test setup

3.2.4.1 Smooth Cyclic Test Parameters

The smooth cyclic test was conducted on three specimens to determine the cyclic Ramberg-Osgood material constants, K' and n' . The tests were performed by imposing strain cycles (10 per strain level) at a load ratio, $R = -1.0$, increasing in increments of 0.1% strain to $\pm 1.0\%$ strain.

3.2.4.2 Smooth Fatigue Test Parameters

Additional tests were conducted on seven smooth specimens to determine the fatigue life of the WAAM material. The tests were conducted under a load control with a load ratio of $R = 0.1$, which is what is generally used for structural applications where the stress range in the actual in-service

structural component may be entirely tensile, or effectively tensile, when welding residual stress are considered. All tests were run at a frequency of 20 Hz.

3.2.5 Rough Fatigue Test Setup

Fatigue tests were conducted on larger specimens with the as-fabricated surface roughness to determine the fatigue life of the WAAM material with no surface improvements (i.e., unmilled). The specimens were designed to the shape of a standard test coupon. The overall length of the specimen was 250 mm with the grip width of 44 mm down to 30 mm at the centre and a thickness of 16.5 mm. The surface of the specimens was left in the as-fabricated state to assess the fatigue failures that may occur due to stress concentrations caused by the surface roughness. Accordingly, two types of rough fatigue specimens were fabricated - ten specimens fabricated in the perpendicular-to-weld direction and ten in the parallel-to-weld direction, shown in Figure 30. The tests were done using the same setup as the static tensile test in Chapter 3.2.2 **Charpy V-Notch Test Setup** using the MTS 322 test frame with the MTS 647 hydraulic wedge grips, shown in Figure 31.

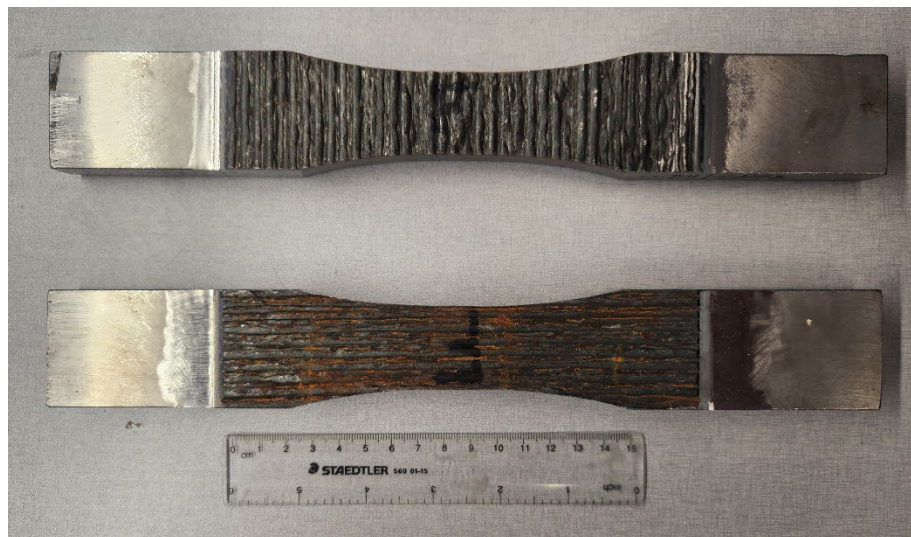


Figure 30: Perpendicular (top) and parallel (bottom) rough fatigue test specimens



Figure 31: Rough fatigue test setup

The tests were performed under load control with a load ratio of $R = 0.1$. Each specimen was tested at a different stress range to determine the fatigue life under different loading conditions. Minimum stress ranges of 100.0 MPa and 164.6 MPa were chosen for the perpendicular- and parallel-to-weld specimens, respectively. The maximum stress ranges were 181.8 MPa and 410.9 MPa, respectively. These values were chosen to obtain a range of fatigue lives between approximately 10,000 cycles and 5 million cycles.

4 Fatigue and Materials Testing Results

This chapter provides experimental results obtained for the various test types described in Chapter 3. First in Chapter 4.1, the stress-strain relationship under static tensile loading is found. In Chapter 4.2, the elastic modulus of the material is determined. This is followed by the ultimate tensile stress, yield stress, and ductility, in Chapter 4.3. In Chapter 4.4, the CVN impact energy and the master curve observing the fracture toughness of the material under different temperatures are shown. Then, in Chapter 4.5, the crack growth observations from the compact tension test are discussed. Chapter 4.6 describes the determination of the Ramberg-Osgood coefficients from the results of the smooth cyclic tests. Finally, in Chapter 4.7 and 4.8 the fatigue life observations from the smooth and rough specimen fatigue tests are discussed, respectively.

4.1 Stress-Strain Relationship

The stress-strain relationship of the tested specimens was calculated by using the extensometer and MTS crosshead displacement readings. The extensometer readings were used up until a strain of approximately 18%. Subsequently, the MTS crosshead displacement readings were used. This was to ensure the fracture of the specimen would not damage the extensometer. The MTS crosshead displacement readings were then corrected to fit the extensometer data. Although six specimens were tested, two encountered issues before failure and were discarded from the ultimate tensile stress and ductility observations. The remaining four are shown in Figure 32. From the figure, it is apparent that although there is visible scatter, the results follow the same general trend. These curves will be used to calculate parameters like the elastic modulus, ultimate tensile strength, and ductility in the following sections.

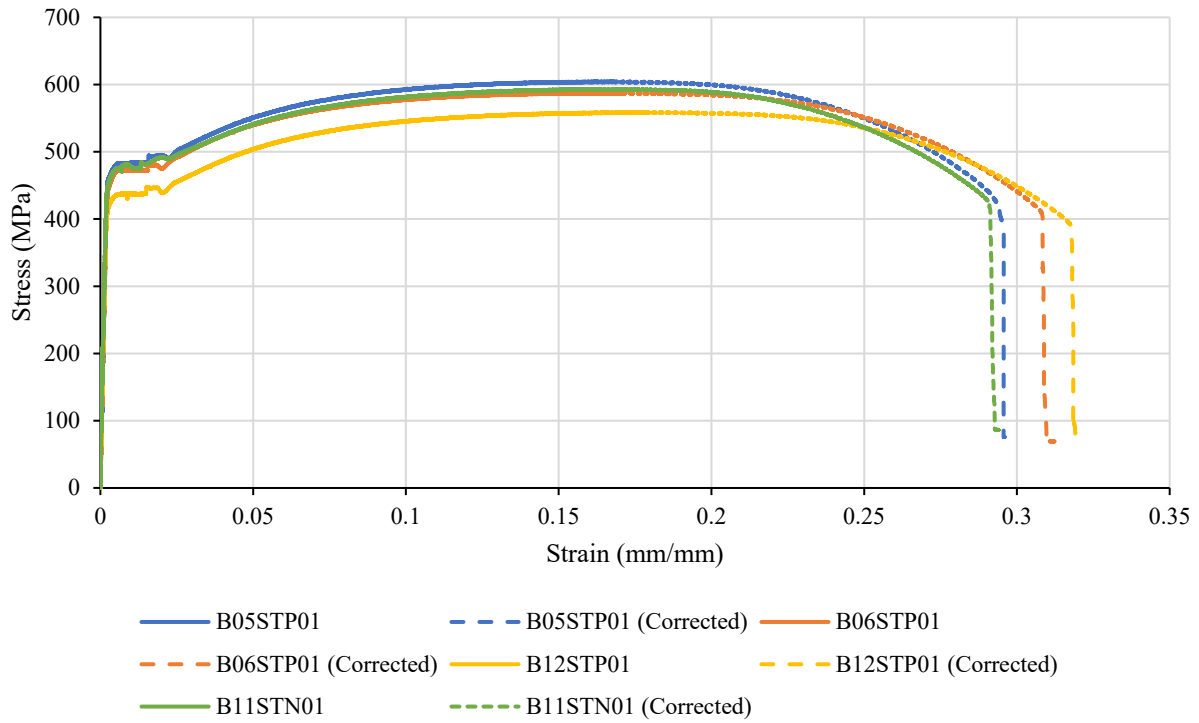


Figure 32: Stress-strain relationship from static tensile tests

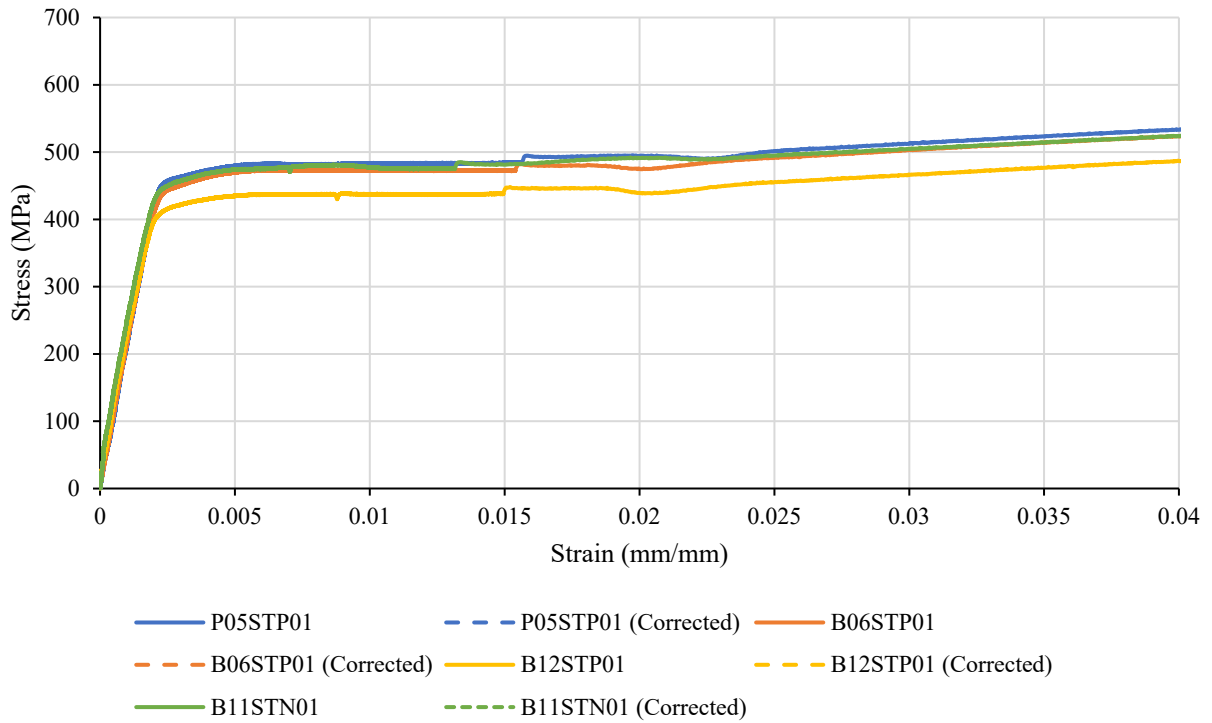


Figure 33: Yield Plateau of stress-strain relationship

4.2 Elastic Modulus

The elastic modulus was calculated by fitting a linear trendline to each stress-strain curve within the elastic region of the stress-strain relationship. A maximum stress level of 200 MPa was used in obtaining the trendline. The plot of the fitted trendline is shown in Figure 34. Using the slope of the trendlines, the elastic modulus of each specimen is summarized in Table 4. The resulting average elastic modulus was approximately 214.9 GPa. Although there is some visible scatter in the plot, based on the coefficient of variance of merely 0.041, it can be determined that the average value is an adequate representation of the elastic modulus of the WAAM steel. Furthermore, it is in proximity to the elastic modulus of steel which is typically approximately 200 GPa.

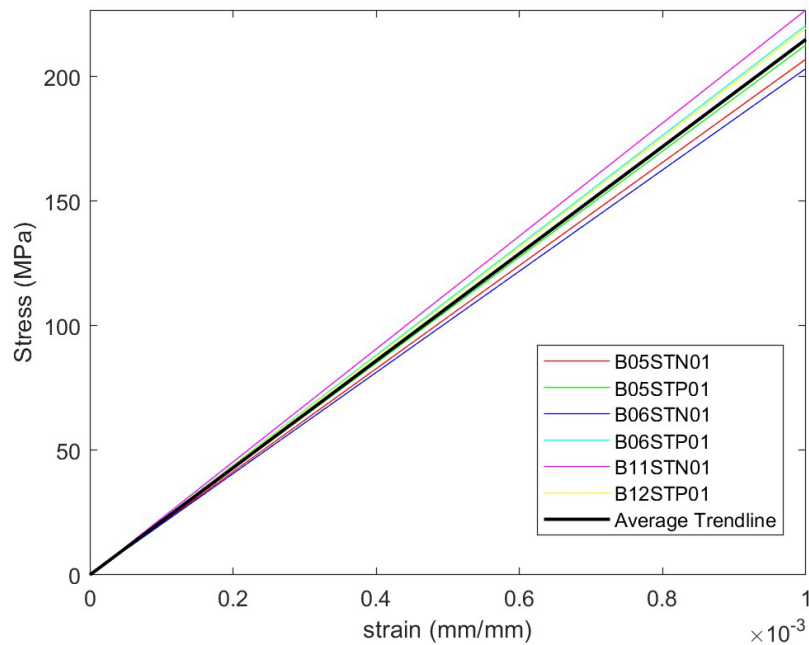


Figure 34: Stress-strain trendlines used to determine elastic modulus

Table 4: Summary of calculated elastic moduli for each static tensile specimen

Specimen	Elastic Modulus (MPa)
B05STN01	206,965
B05STP01	212,608
B05STN01	203,203
B06STP01	220,542

B12STP01	219,404
B11STN01	226,693
Mean	214,903
Standard Deviation	8,902
Coefficient of Variance	0.041

4.3 Ultimate Tensile Stress, Yield Stress, and Ductility

The ultimate tensile stress was taken as the maximum stress resisted during the tensile test. The yield stress was taken using the 0.2% offset method according to the ASTM E8/E8M-22 [36]. This involved offsetting the strain by 0.2% then multiplying with the elastic modulus to find the offset stress. The 0.2% offset strain and stress can be then plotted on the stress-strain relationship to find the intersection point. The stress at this intersection point is determined to be the yield stress. The ductility was taken as the maximum strain based on the 50.8 mm initial gauge length prior to fracture. The ultimate tensile stress, yield stress, and ductility are summarized in Table 5.

Table 5: Summary of the ultimate tensile stress, yield stress, and ductility for each static tensile specimen

Specimen	Ultimate Tensile Stress (MPa)	Yield Stress (MPa)	Ductility (mm/mm)
B05STP01	604.9	477.2	0.294
B06STP01	588.0	462.1	0.308
B12STP01	559.2	427.7	0.317
B11STN01	593.9	468.8	0.291
Mean	586.5	458.9	0.302
Standard Deviation	19.5	21.7	0.012
Coefficient of Variance	0.033	0.047	0.040

The yield stress can also be obtained using the autographic diagram method according to the ASTM E8/E8M-22 [36]. Using this method, the resulting mean lower yield stress (LYS) and upper yield stress (UYS) were approximately 413.2 MPa and 481.0 MPa, respectively. This gave a mean yield stress of approximately 447.1 MPa, which is in proximity to the value determined using the 0.2% method as shown in Table 5.

These properties can be compared to the design values for common mild structural steels such as CSA 350W steel. The comparison of the mechanical properties of WAAM steel found in this study to that of CSA 350W steel from a different study is shown in Table 6. The gathered parameters indicate that WAAM steel has a greater yield stress at 458.9 MPa compared to the 350W steel with a yield stress of 356.0 MPa. However, the UTS of WAAM steel is lower than the CSA 350W steel at 586.5 MPa but it is still within the typical range of 450 - 650 MPa. The ductility WAAM steel is on average similar to that of 350W steel.

Table 6: Comparison of the mechanical properties of WAAM steel vs. CSA 350W steel

Parameter	Units	WAAM	CSA 350W [41]
E	<i>GPa</i>	214.9	208.1
σ_y	<i>MPa</i>	458.9	356.0
σ_u	<i>MPa</i>	586.5	616.0
<i>Ductility</i>	-	0.302	0.320

4.4 CVN Impact Energy and Master Curve

The Charpy impact energy was obtained from the pendulum impact tester and recorded manually. The impact tester generated values of absorbed energy in joules. The Charpy impact energy-temperature relationship was plotted, as shown in Figure 35. On the same plot, an S-shaped curve is plotted. From the curve, three regions can be identified – the lower shelf, transition, and upper shelf regions. In the lower shelf, the material performs in a brittle manner under lower temperatures where less energy is absorbed on impact. In contrast, in the upper shelf region, the material absorbs a greater amount of energy on impact and undergoes ductile fracture (preceded by significant plastic deformation). Accordingly, it is important to identify the temperature in which the material will undergo a mixture of ductile and brittle failure, known as the transition region.

To capture the transition region of the WAAM material, the CVN test results were calibrated to an empirical hyperbolic tangent function, as shown in Equation (2). This S-shaped curve

captures the mean data in the three regions [42]. Using this curve, T_{27J} , the temperature at which the CVN impact energy is 27 Joules was obtained to be at -132 °C and -98 °C for perpendicular-to-weld and parallel-to-weld specimens, respectively. The CSA S16:19 indicates that the minimum mean daily temperatures in Canada are around -60°C [4]. Based on the results of the CVN test, WAAM steel would likely have satisfactory brittle fracture performance for use anywhere in the country.

$$KV = A \left(1 + \tanh \left(\frac{T_{KV} - B}{C} \right) \right) \quad (2)$$

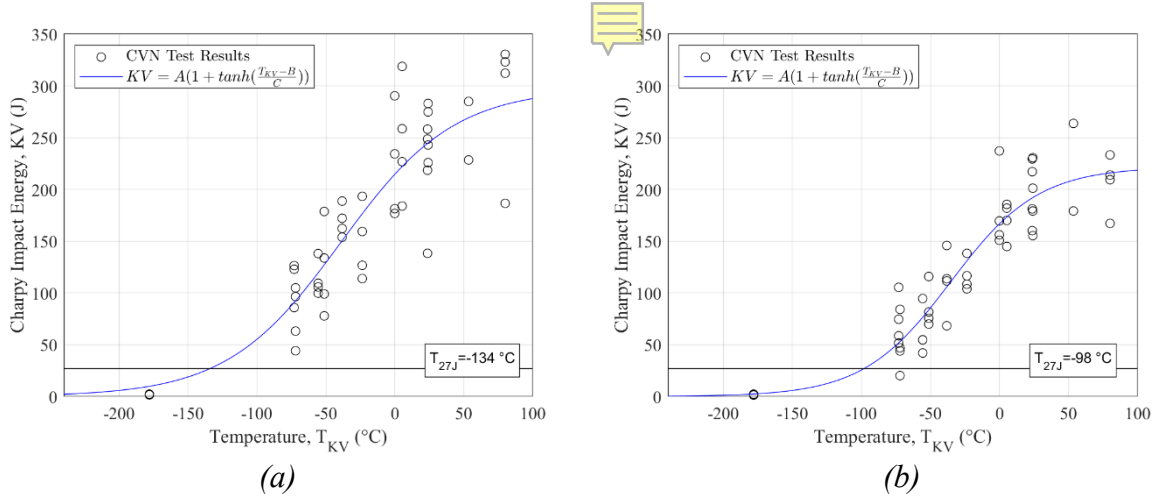


Figure 35: Charpy v-notch impact energy for (a) perpendicular-to-weld and (b) parallel-to-weld specimens

To estimate the fracture toughness of the WAAM steel, the modified Sanz correlation can be used along with the Master curve developed by Wallin [43]. Using the modified Sanz correlation shown in Equation (3), T_{27J} is used to calculate the T_0 which is the temperature at which the fracture toughness, K_{IC} , is $100 \text{ MPa}\cdot\text{m}^{0.5}$. The T_0 values for the perpendicular- and parallel-to-weld specimens was -152°C and -116°C, respectively. The T_0 temperature can then be used to calculate the fracture toughness using the Wallin empirical relationship, shown in Equation (4). The fracture toughness-temperature relationship is shown in Figure 36.

$$T_o = T_{27J} - 18^\circ\text{C} \pm 13^\circ\text{C} \quad (3)$$

$$K_{IC} = 31 + 77e^{0.019(T-T_o)} \quad (4)$$

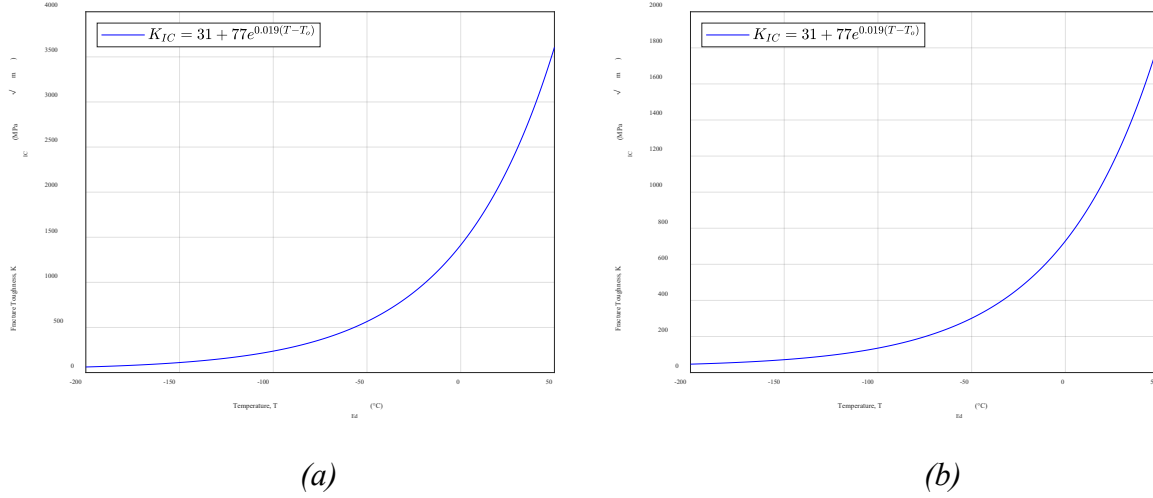


Figure 36: Charpy v-notch Master curve showing fracture toughness-temperature relationship for (a) perpendicular-to-weld and (b) parallel-to-weld specimens

4.5 Crack Growth Observations

The crack growth behaviour of the WAAM steel was monitored according to the ASTM E647-23 [38], as mentioned in Chapter 3.2.3. The CMOD measurements taken by the crack gauge were converted into crack length, a , using Equation (5) and (6) from ASTM E647-23 [38].

$$\alpha = \frac{a}{W} = C_0 + C_1 u_x + C_2 u_x^2 + C_3 u_x^3 + C_4 u_x^4 + C_5 u_x^5 \quad (5)$$

$$u_x = \left\{ \left[\frac{EvB}{P} \right]^{\frac{1}{2}} + 1 \right\}^{-1} \quad (6)$$

where W is the length from the end of the specimen to the loading location. C_i are the coefficients based on the measurement location as shown in Figure 37, which in this case was V_0 . The coefficients used are shown in Table 7, where v is the collected CMOD data.

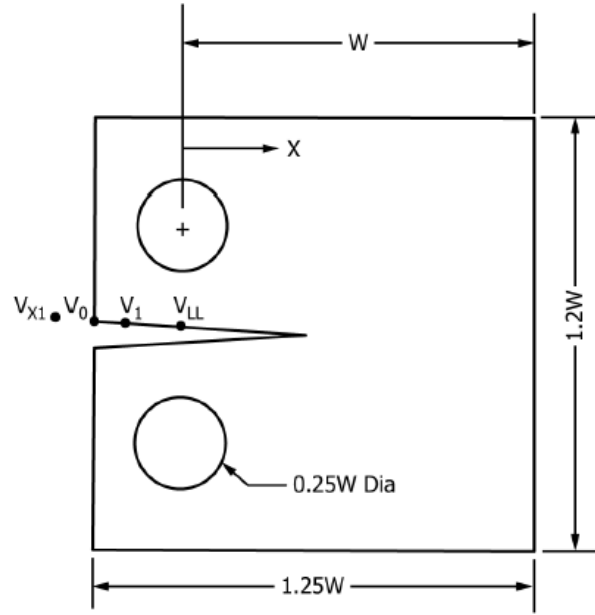


Figure 37: CMOD data measurement location [38]

Table 7: Coefficients to determine crack length based on the CMOD measurement location [38]

Meas. Location	C_0	C_1	C_2	C_3	C_4	C_5
V_0	1.0010	-4.6695	18.460	-236.82	1214.9	-2143.6

The crack length values were then filtered and only the measurements with a $\Delta a \geq 0.25 \text{ mm}$ were taken to limit the noise in the data. Using this filtration, the resulting crack length, a , and number of cycles, N , were plotted for all tested specimens, as shown in Figure 38. Generally, the crack fully propagated between 1,000,000 and 10,000,000 cycles.

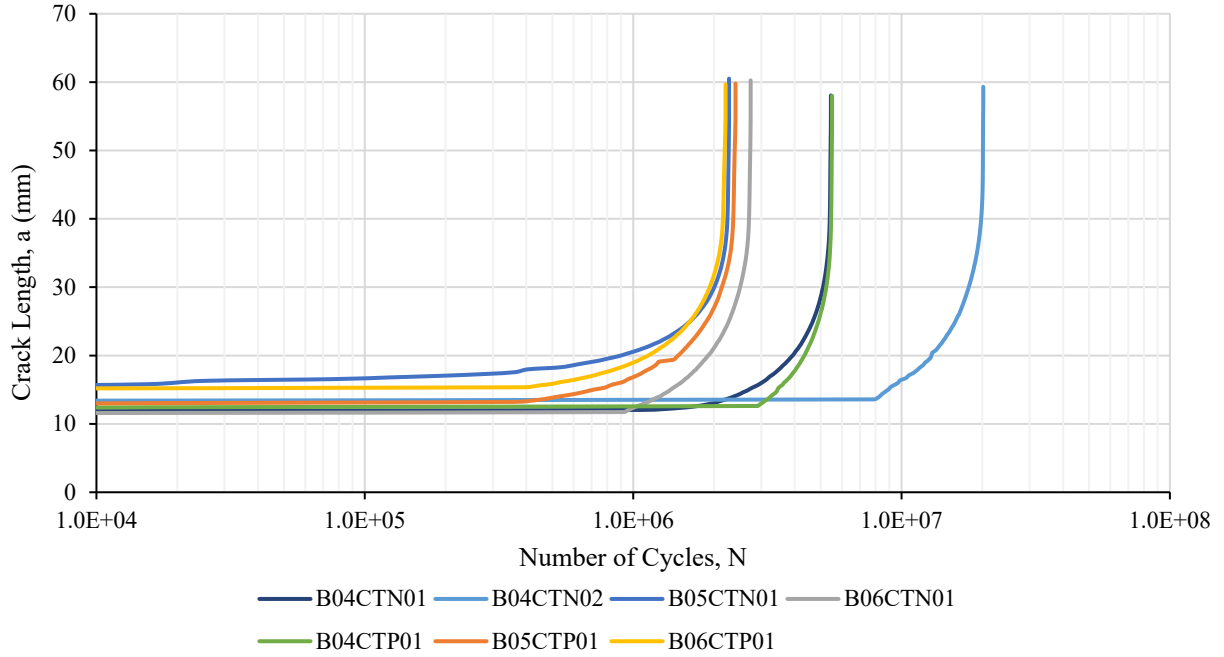


Figure 38: Crack growth curves for compact tension specimens

According to the ASTM 647-23 [38] standards, the crack growth rate, da/dN , can be obtained using two different methods. One method is the secant method, and the other is the incremental polynomial method.

The secant or the point-to-point technique method involves determining the slope of a line by connecting two adjacent data points on the a vs. N curve, shown in Figure 38. It is expressed using Equation (7) [38].

$$(da/dN)_a = (a_{i+1} - a_i) / (N_{i+1} - N_i) \quad (7)$$

The equation calculates the da/dN as an average rate over the $(a_{i+1} - a_i)$ increment, hence the average crack size, $\bar{a} = \frac{1}{2}(a_{i+1} + a_i)$, is used to find ΔK , using Equation (8) [38].

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2 + \alpha)}{(1 - \alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \quad (8)$$

where $\alpha = \bar{a}/W$.

Adopting this method, the da/dN versus ΔK relationship was determined and plotted in Figure 39.

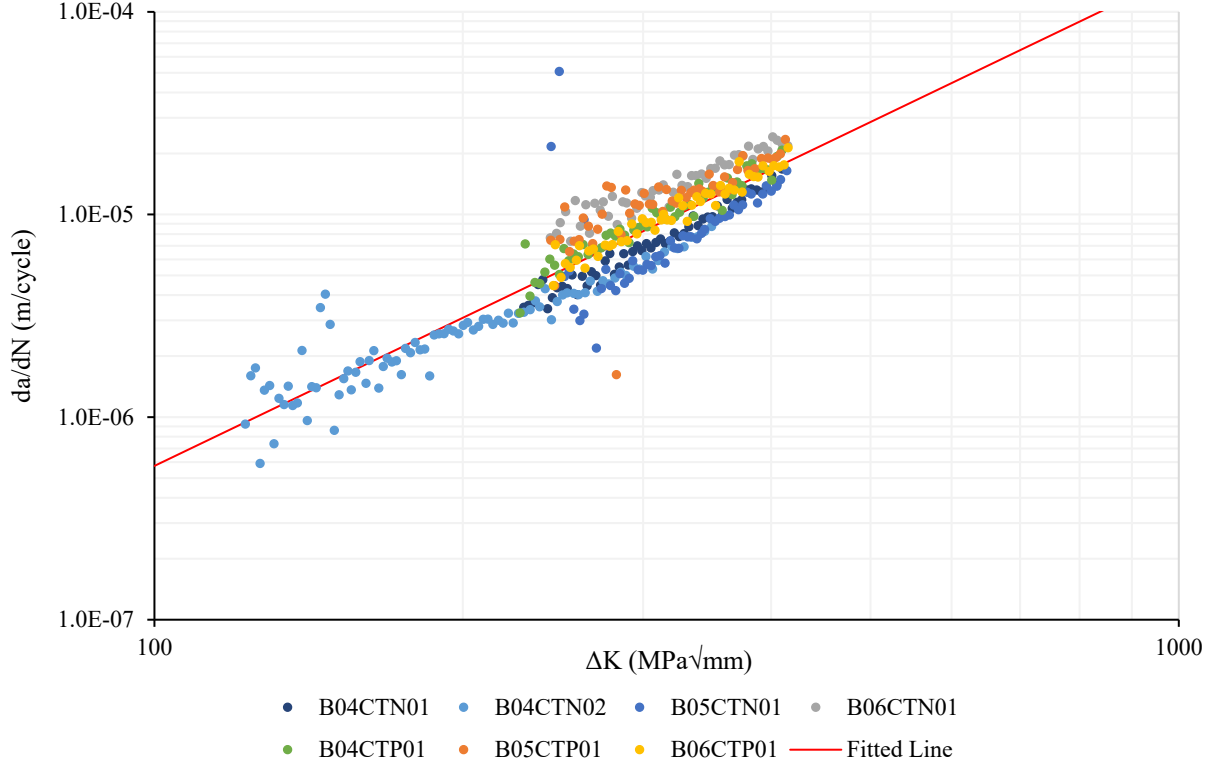


Figure 39: da/dN versus ΔK relationship plotted using the secant method

The incremental polynomial method computes da/dN by fitting a second-order polynomial to sets of $(2n + 1)$ successive data points. The parameter n is usually equal to 1, 2, 3, or 4, but in this case $n = 3$ was used. The local fit is expressed using Equation (9) [38].

$$\bar{a} = b_0 + b_1 \left(\frac{N_i - C_1}{C_2} \right) + b_2 \left(\frac{N_i - C_1}{C_2} \right)^2 \quad (9)$$

where b_0 , b_1 , and b_2 are the regression parameters determined by the least squares method. $\bar{a}$ is the fitted value of crack size at N_i that is also used to calculate ΔK using Equation (8). The parameters C_1 and C_2 are used to scale the input data to avoid numerical difficulties that arise in determining the regression parameters. These parameters can be expressed using Equation (10) and Equation (11).

$$C_1 = \frac{1}{2}(N_{i-n} + N_{i+n}) \quad (10)$$

$$C_2 = \frac{1}{2}(N_{i+n} - N_{i-n}) \quad (11)$$

The derivative of the parabola given by (9) can be used to determine the rate of crack, da/dN at N_i , expressed using Equation (12).

$$(da/dN)_{\bar{a}_i} = (b_1)/(C_2) + 2b_2(N_i - C_1)/C_2^2 \quad (12)$$

Similarly, the da/dN versus ΔK relationship was determined and plotted in Figure 40.

Comparing the two methods (see Figure 39 and Figure 40), it is apparent that the incremental polynomial method leads to reduced noise or scatter in the crack growth data.

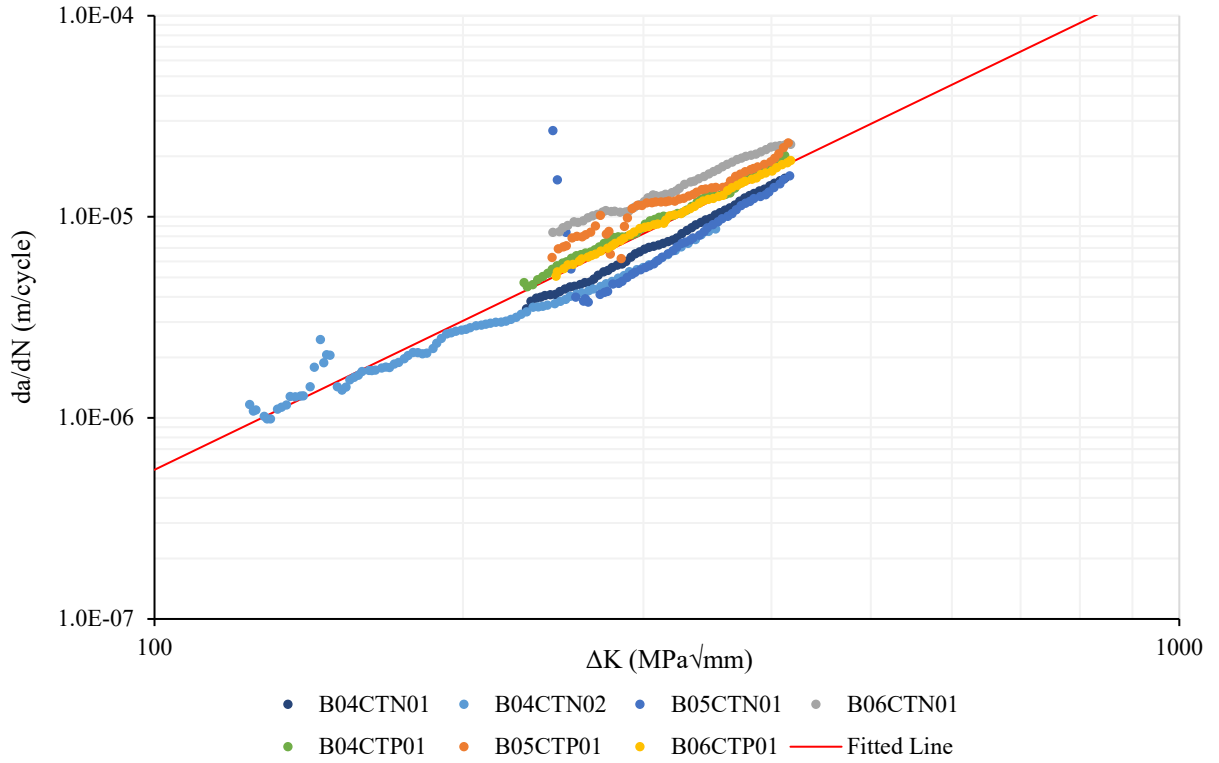


Figure 40: da/dN versus ΔK relationship plotted using the incremental polynomial method

The Paris Law constants can be determined by fitting a line onto the da/dN versus ΔK plot. Table 8 shows the crack growth parameters summarize for both methods.

Table 8: Crack growth relationship parameters

Parameter	Units	Magnitude
C (Secant Method)	N, mm	$8.00 \cdot 10^{-12}$
m (Secant Method)	-	2.428
C (Incremental Polynomial Method)	N, mm	$6.61 \cdot 10^{-12}$
m (Incremental Polynomial Method)	-	2.461

4.6 Ramberg-Osgood Coefficients

The Ramberg-Osgood coefficients were taken from the data obtained from the smooth cyclic test, mentioned in Chapter 3.2.4. The data collected from the test can be used to plot the stress-strain relationship. Since the specimens undergoes cycles of loading and unloading, the plot gives what is referred to as *hysteresis loops* for each strain increment, as shown in Figure 41.

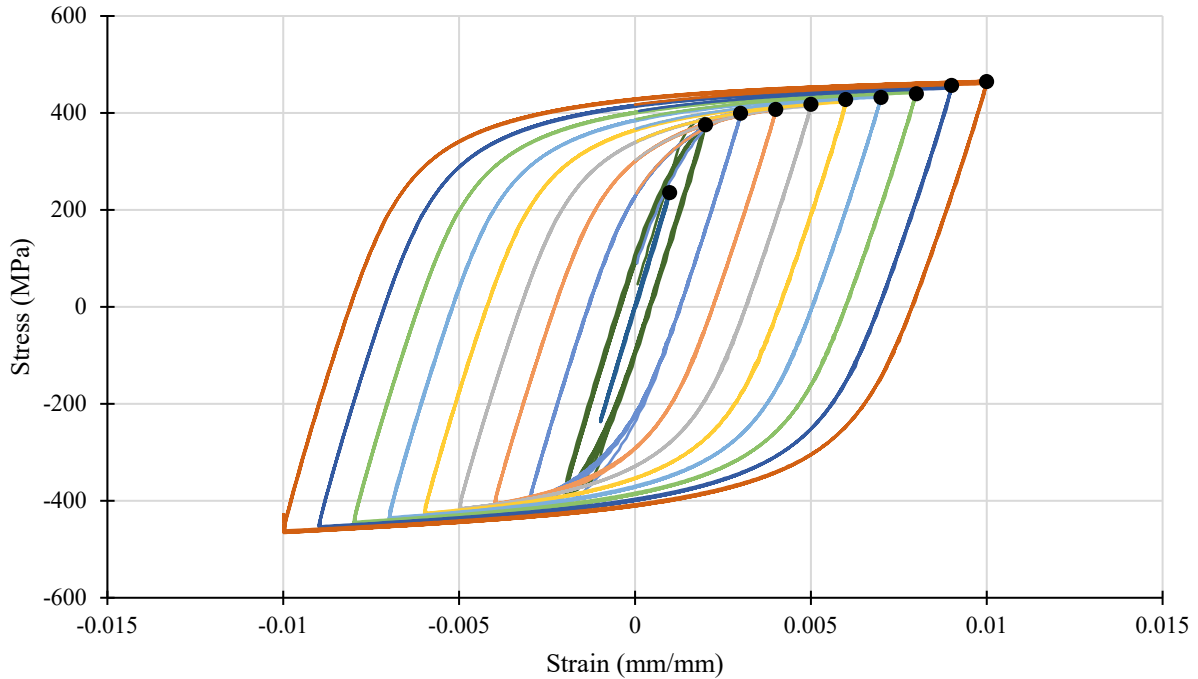


Figure 41: Stress-Strain plot showing hysteresis loops for specimen CS1

The peaks of the hysteresis loops can be found and used to find the maximum plastic strain at each strain increment. This can be done by subtracting the elastic strain from the total strain using Equation (13).

$$\varepsilon_p = \varepsilon - \frac{\sigma}{E} \quad (13)$$

where ε_p is the plastic strain, ε and σ are the peak strain and stress, respectively. E is the elastic modulus of the material determined from the static tensile tests, shown in Table 4.

The plastic strain and their associated stress can be plotted, as shown in Figure 42. The Ramberg-Osgood coefficients, K' and n' , were determined by fitting line on the plot. The smooth cyclic test results are summarized in Table 9.

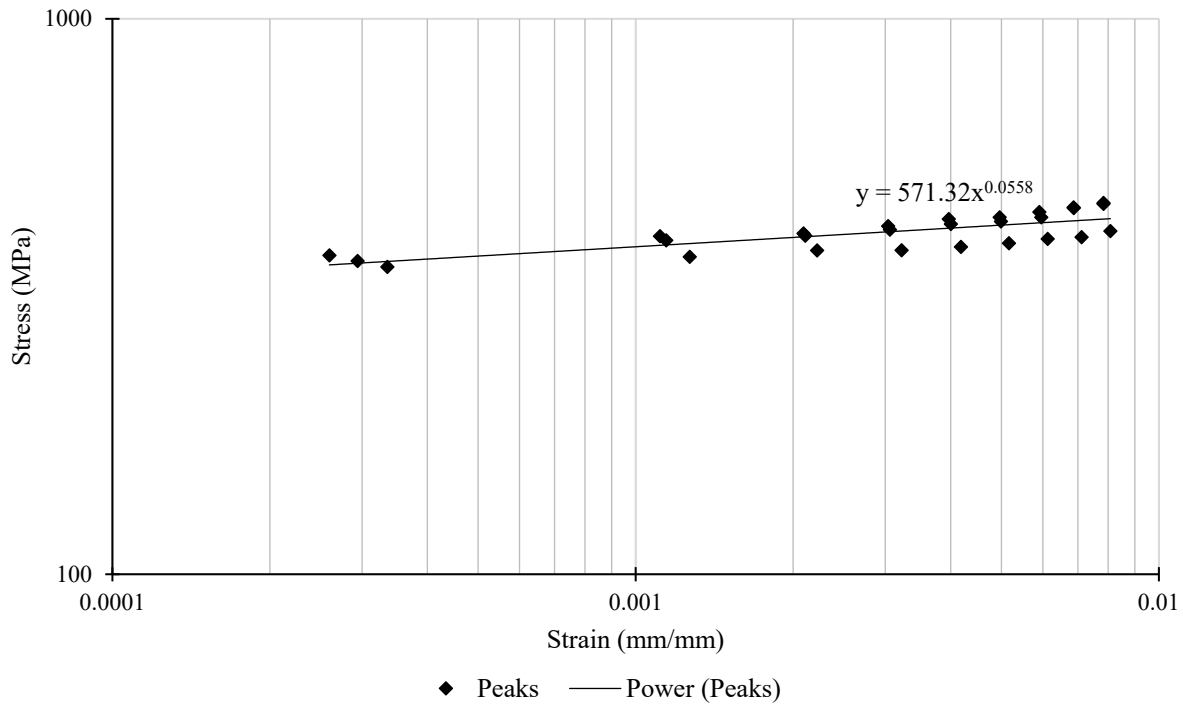


Figure 42: Hysteresis loop peaks for all three CS specimens

Table 9: Smooth cyclic test results

Parameter	Units	Value
K' (cyclic)	MPa	571.32
n' (cyclic)	-	0.0558

The determined Ramberg-Osgood coefficients can be validated by plotting the true stress-true strain curve using the Ramberg-Osgood relationship, shown in Equation (14) [44]. It is shown that the results of one specimen, CS3, exhibits some deviation from the remaining two specimens. Therefore, more accurate results for the K' and n' parameters may be obtained by omitting the CS3 results from the calculation, but more tests are needed to confirm.

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{1/n'} \quad (14)$$

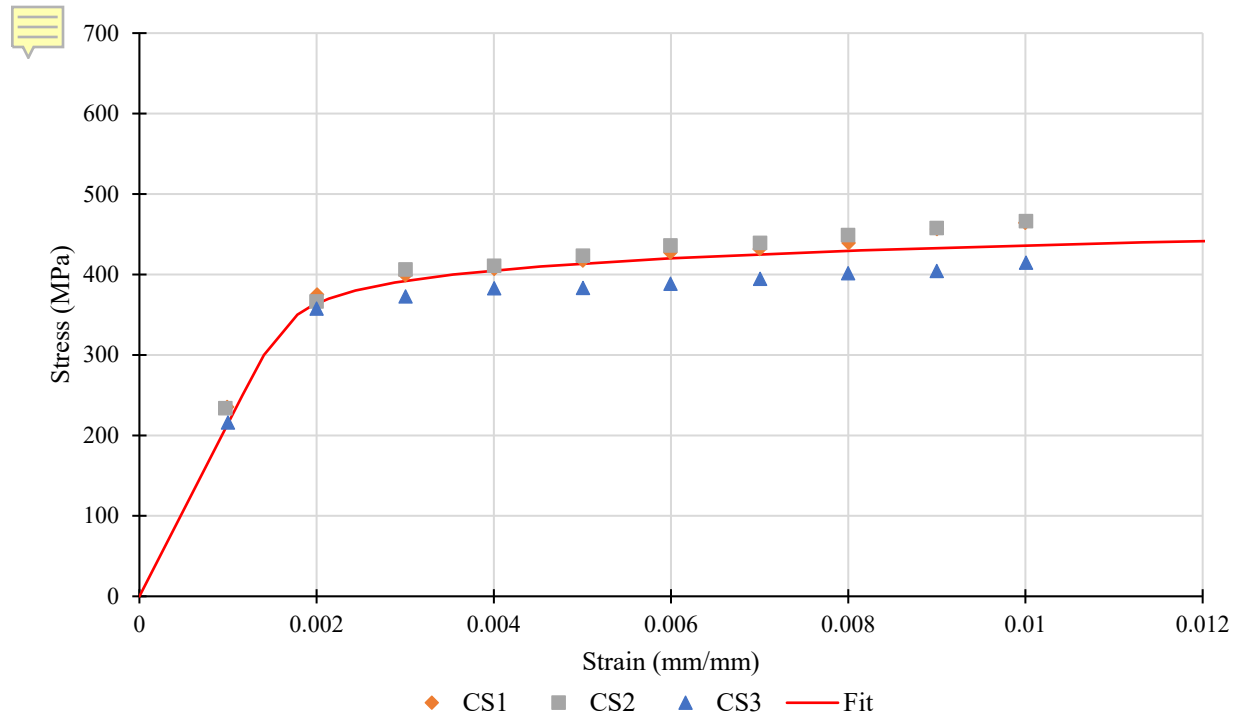


Figure 43: Ramberg-Osgood relationship fitted on test data points

4.7 Fatigue Life Observation from Smooth Specimens

Fatigue tests for the smooth specimens were conducted using the parameters discussed in Chapter 3.2.4. Seven smooth specimens were tested with at various stress ranges. The first test was performed at a stress range with the maximum stress at 229 MPa which was approximately half of the yield stress determined through the static tensile test, shown in Table 5. Observing that the material effectively had an infinite (runout) life at this stress range, the stress ranges were increased accordingly. The summary of the stress ranges and the resulting number of cycles is shown in Table 10. The resulting S-N curve is plotted in Figure 44. From the S-N curve, it was determined that that the constant amplitude fatigue limit (CAFL) of the WAAM material in its milled state is approximately 360 MPa.

Table 10: Summary of smooth fatigue test results

Stress Range MPa	Number of Cycles
462	95,539
417	260,713
390	186,314
367	1,567,114
344	Runout
321	Runout
229	Runout

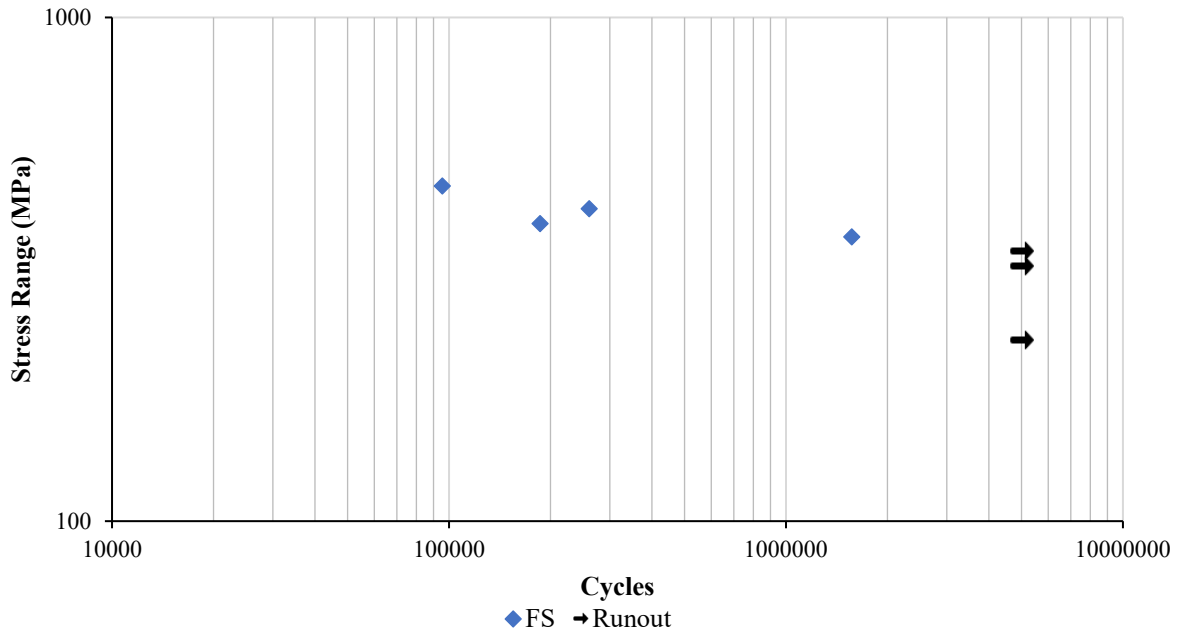


Figure 44: S-N curve obtained from smooth fatigue testing

4.8 Fatigue Life Observations from Tests on Rough Specimens

The fatigue tests for the rough specimens were done according to the parameters discussed in Chapter 3.2.5. The theoretical central cross section area of the specimen of 495 mm², was used as the area to calculate the stress ranges to be tested. It was predicted that the parallel-to-weld specimens would have longer fatigue lives since the welds ran parallel to the load implying that there should be less influence from the local stress concentrations. To ensure that this was the case, both specimen types were first run at a stress range of 163.6 MPa with a Pmax and a Pmin of 90.0 kN and 9.0 kN, respectively. This resulted in a fracture at approximately 300,000 cycles for the perpendicular-to-weld specimen, while the parallel-to-weld specimen effectively had an infinite (runout) fatigue life. To establish the S-N behaviour of each type of specimen, the stress was lowered for the perpendicular-to-weld specimens and increased for the parallel-to-weld specimens accordingly. The results of the rough fatigue test are summarized in Table 11 and Table 12.

Table 11: Summary of perpendicular-to-weld rough fatigue test results

Specimen	Stress Range <i>MPa</i>	Pmax <i>kN</i>	Pmin <i>kN</i>	Cycles
B07FRN02	181.8	100	10	182,323
B11FRN01	163.6	90	9	344,065
B07FRN04	154.5	85	8.5	488,953
B07FRN01	145.5	80	8	431,145
B07FRN06	136.4	75	7.5	264,237
B07FRN03	127.3	70	7	540,224
B05FRN02	118.2	65	6.5	909,219
B05FRN01	109.1	60	6	543,664
B07FRN05	100.0	55	5.5	Runout

Table 12: Summary of parallel-to-weld rough fatigue test results

Specimen	Stress Range <i>MPa</i>	Pmax <i>kN</i>	Pmin <i>kN</i>	Cycles
B08FRN02	410.9	226	22.6	160,304
B08FRP03	365.5	201	20.1	181,008
B12FRP02	325.5	179	17.9	358,124
B12FRP01	282.8	155	15	511,216
B06FRP02	270.0	148.5	14.85	737,758
B08FRP05	258.2	142	14.2	1,568,371
B08FRP04	230.9	127	12.7	Runout
B06FRP01	181.8	100	10	Runout
B08FRP01	163.6	90	9	Runout

The resulting S-N data for the rough specimens is plotted in Figure 45. It can be determined from the plot that the constant amplitude fatigue limit (CAFL) of the WAAM material in its unmilled state is approximately 110 MPa and 260 MPa for the perpendicular- and parallel-to-weld specimens, respectively.

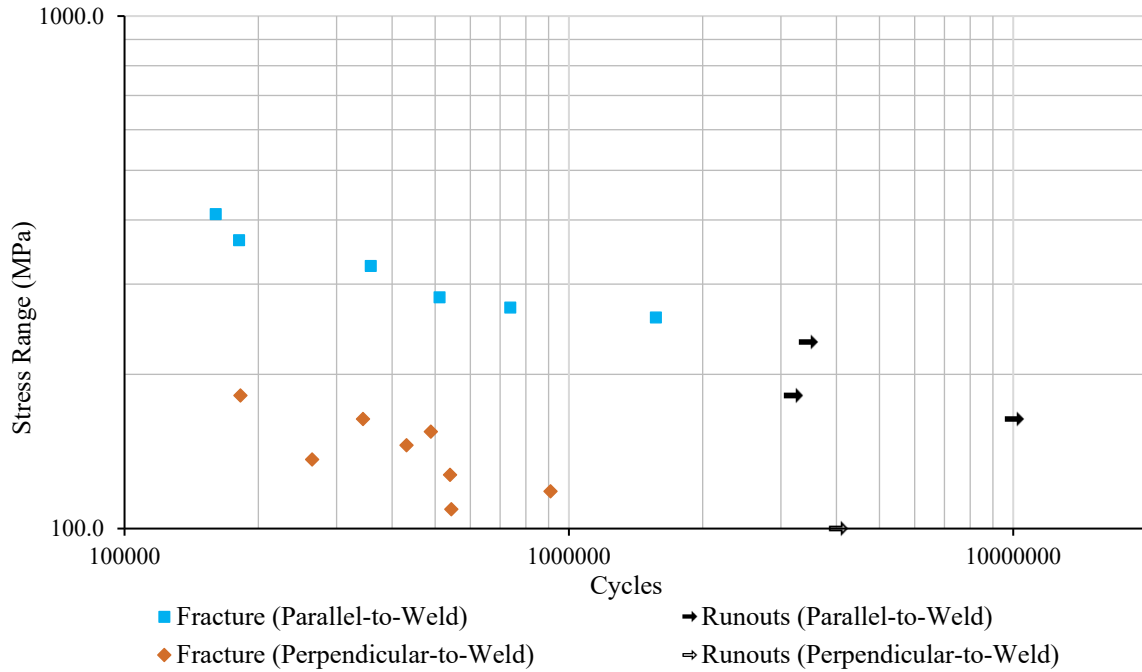


Figure 45: *S-N data obtained from rough fatigue specimen testing*

Two crack shapes were observed amongst the rough fatigue tests. One was a semi-elliptical surface crack, and the other was the semi-elliptical corner crack. The crack shapes can be used to predict fatigue life using analytical methods such as fracture mechanics. Examples of fracture surfaces for each crack type are shown in Figure 46.

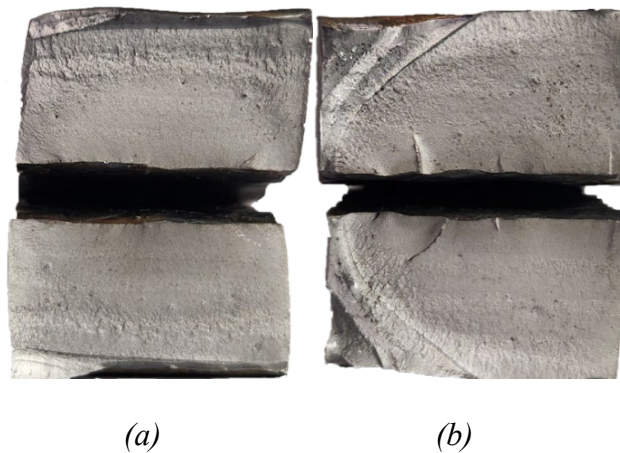


Figure 46: Cross-section of (a) semi-elliptical surface crack taken from B11FRN01 and (b) semi-elliptical corner crack take from B05FRN01

5 Metallurgical Analysis

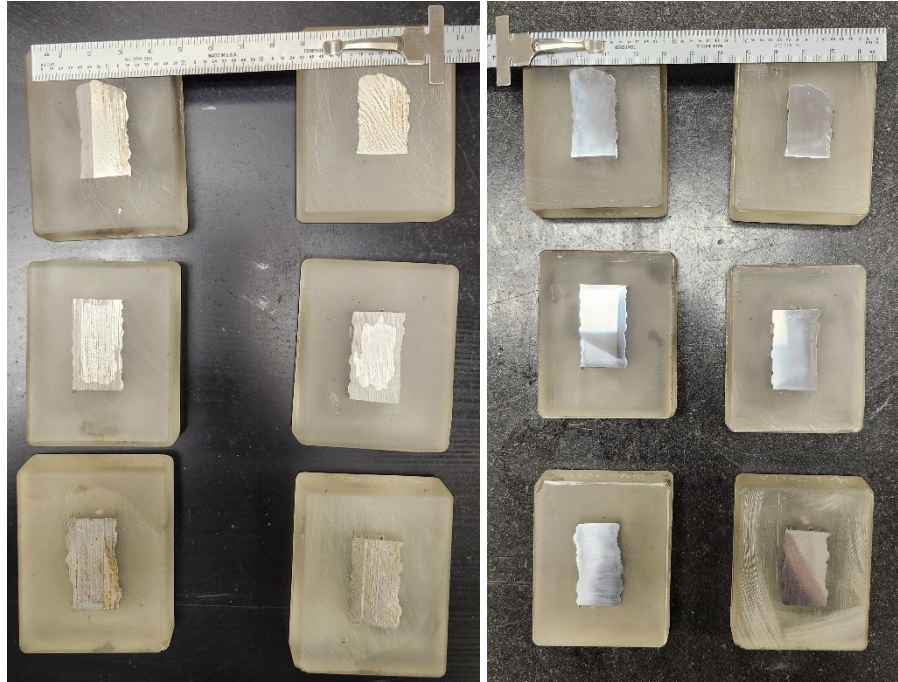
As mentioned in the literature review in Chapter 2.2.3, the mechanical properties of the material are influenced by the microstructural properties. Therefore, it is important that a metallurgical study is conducted to investigate the grain boundaries and sizes of the WAAM steel. This chapter will go through the steps taken to perform the metallurgical analysis. Chapter 5.1 presents the preparation of the WAAM specimens and the setup used to observe the microstructure. In Chapter 5.2, observations based on the results of the analysis will be presented.

5.1 Specimen Preparation and Setup

The specimens for the metallurgical analysis originated from one of the welded plates used to extract specimens for mechanical and fatigue testing, shown in Figure 20. A total of six specimens were extracted from plate four, three from the as-built material and the other three from samples where the surface had been impact treated by “needle peening”.

Needle peening is a type of surface treatment used to improve the fatigue performance of welds by introducing compressive residual stresses at the treated surface. It helps reduce crack growth rates at the smaller crack depths [45]. Needle peening was used in this study to evaluate the effects of surface treatment on the fatigue life of WAAM steel. Originally, surface treated specimens were fabricated for fatigue testing, but it was prevented due to lab delays. The fatigue testing and analysis of the needle peened specimens is an area for future research.

Each specimen came from different locations within the plate, including the top, middle, and bottom. This was done to examine any differences between the grains within the weld passes as well as the edges. The specimens were embedded in an epoxy “puck” with uniform thickness and smooth surfaces, shown in Figure 47a. They were then ground and polished using standard steel grinding/polishing procedures. The polished specimens are shown in Figure 47b.

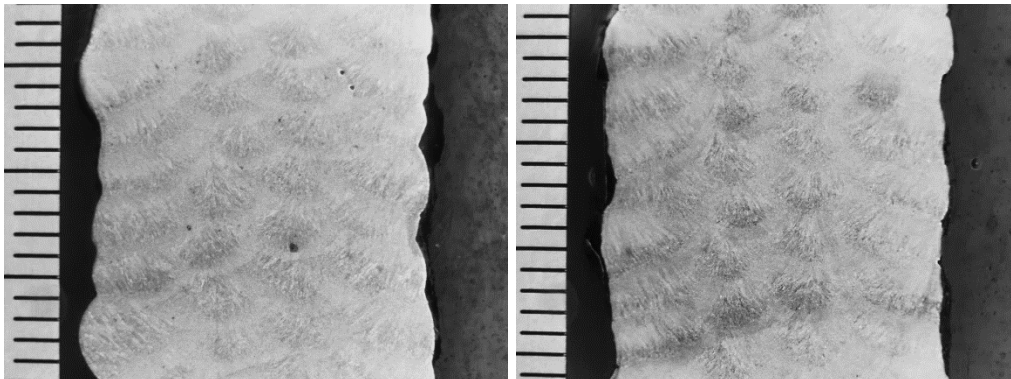


(a)

(b)

Figure 47: (a) As-built (left) and impacted treated (right) specimens prepared in epoxy for metallurgical analysis, (b) grinded and polished specimens

The last step of the preparation process was to etch the specimens. This was done using 3% Nital as the reagent. The final etched specimens are shown in Figure 48. To observe the microstructure, a Reichert Jung MeF3 microscope, shown in Figure 49, was used.



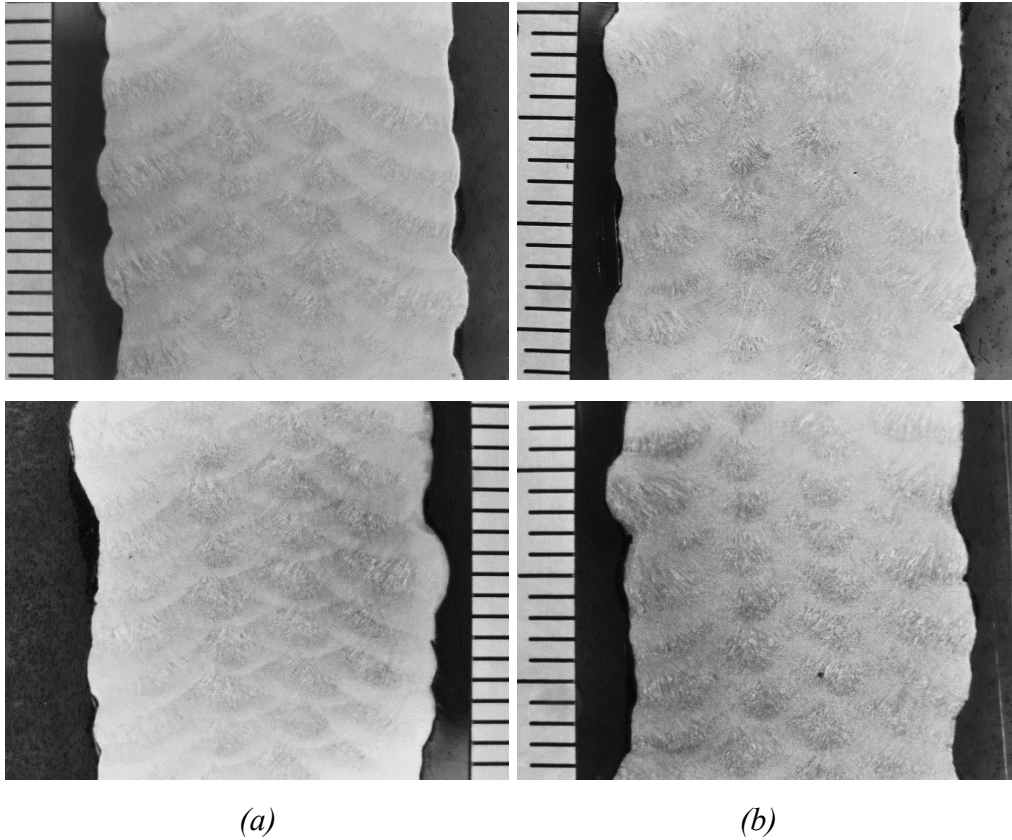


Figure 48: (a) As-built and (b) impacted treated etched specimens for metallurgical analysis



Figure 49: Reichert Jung MeF3 microscope used for microstructural observations

5.2 Microstructural Observations

The microstructure of these materials can be classified into two different zones, identified herein as the as-deposited and the reheated weld metal. The as-deposited zones consist of regions where the weld material placed and not significantly disturbed/reheated by the subsequent deposition of additional layers. The reheated zones are regions where the addition of a new layer heats the previous layer resulting in a much finer grain size. From the etched surfaces, it can be observed that each layer has four weld passes each consisting of these zones. In Figure 50, the as-deposited zones are darker near the interior of each weld pass.

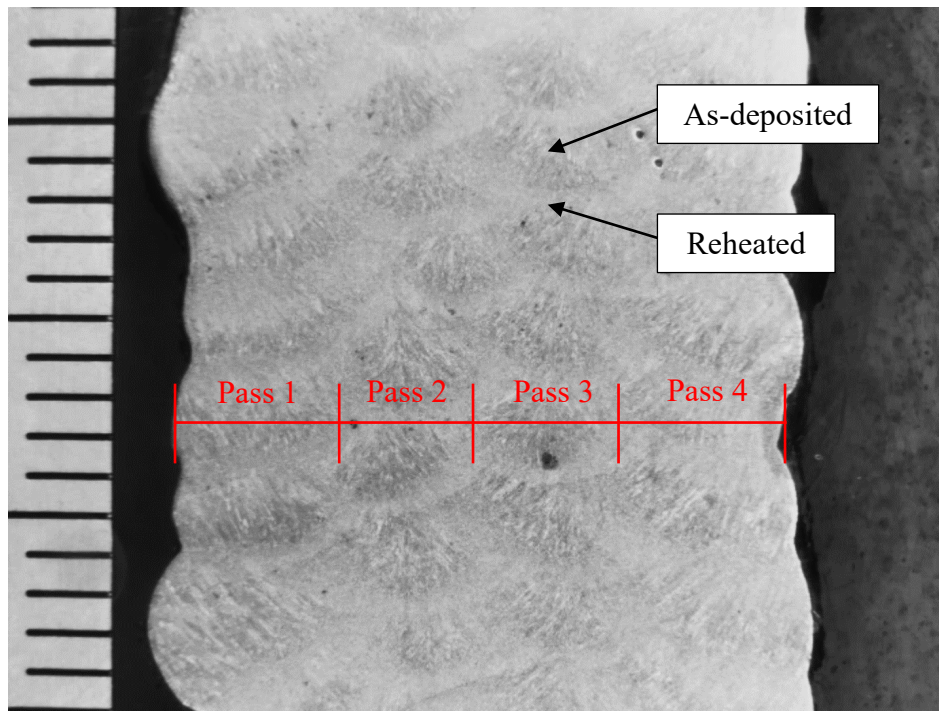


Figure 50: Example of microstructure showing as-deposited and reheated zones. Four weld passes are shown in each layer (red)

Upon closer examination, it becomes obvious that these zones show differences in grain size as well as microconstituents. The as-deposited microstructure at 500x zoom, in Figure 51, shows the presence of relatively coarser grains compared to the reheated zone, shown in Figure 52, with the

presence of acicular ferrite which is the most desirable constituent due to its fine grain size and interlocking structure. The high angle boundaries of the acicular ferrite provide the material its high impact toughness [46]. On the other hand, the reheated microstructure consists of finer grains with the presence of fine polygonal ferrite and lamellar pearlite. The overall microstructure is similar as that of welded steel found in other references [27, 46].

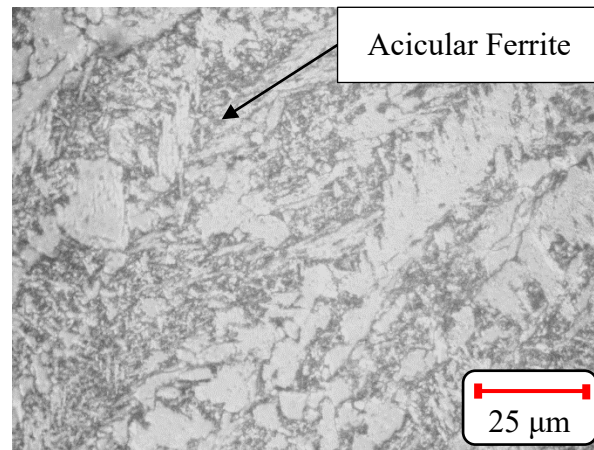


Figure 51: Higher magnification of as-deposited microstructure

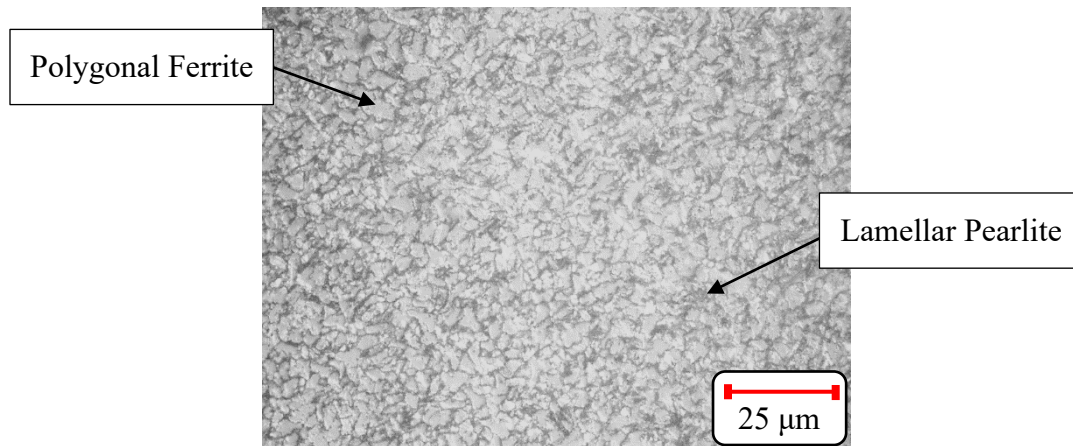


Figure 52: Higher magnification of reheated microstructure

Another observation that can be made using the metallurgical analysis concerns the formations of defects within the specimen. Defects such as porosity that are present within the material can influence the fracture toughness and the fatigue performance of the material. Upon visual

inspection, holes associated with porosity were found in the specimens. The size of these whole varies from approximately 0.2-0.5 mm in diameter. These defects can also be used to model the crack propagation by using the size of these defects as the initial crack size.

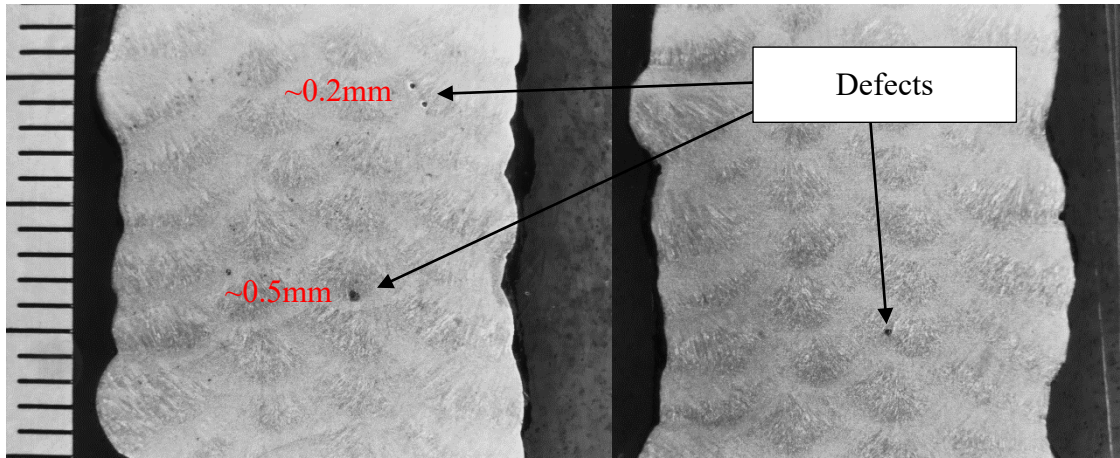


Figure 53: Defects found within WAAM steel specimens

Lastly, the edges of the as-built and the impact treated specimens can be compared to examine the effects of the peening on the surfaces. As shown in Figure 54, the grains of the needle peened surface are flattened in comparison to the grains of the as-built surface. This provides evidence that the surface treatment induced plastic deformation in the specimen and thus the compressive residual stresses were effectively introduced at the peened surface.

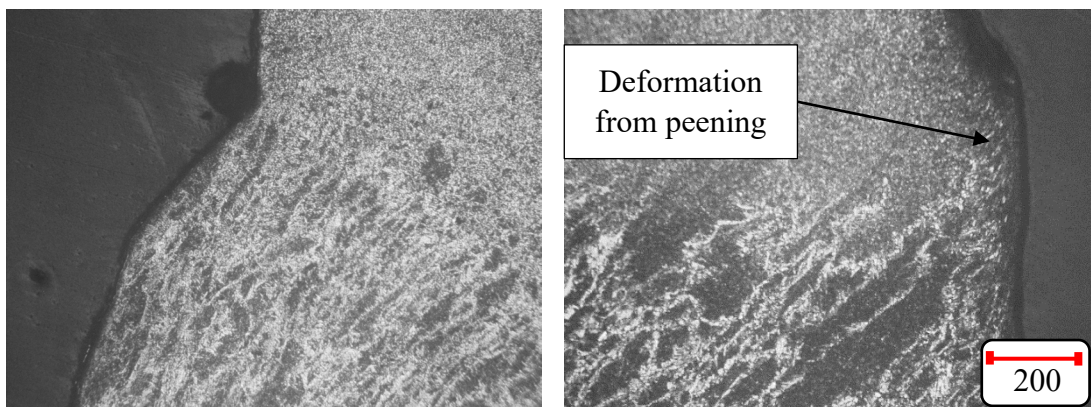


Figure 54: Surface of as-built specimen (left) and needle peened specimen (right)

6 Analysis

This chapter presents the analyses performed to evaluate and validate the experimental results. First, Chapter 6.1 will go through the statistical analysis recommended by the International Institute of Welding (IIW) on fatigue test data. Then in Chapter 6.2, the characteristic curve determined from the analysis in Chapter 6.1 is compared to the CSA S6 design curves. Lastly, Chapter 6.3 describes a fracture mechanics approach taken to analyze the fatigue test data.

6.1 IIW Statistical Analysis of Rough Fatigue S-N curves

According to the IIW Fatigue Recommendations [35], there are three ways of testing a limited number of samples from a larger population: 1) a specimen to failure, 2) first specimen to failure, and 3) p specimens to failure amongst n specimens. Although many methods of statical evaluation of fatigue data are available, the IIW recommends that it is most common to fit S-N curves by regression analysis, taking $\log(N)$ as the dependent variable. Then, the characteristic values are determined for the design curve by adopting a curve lying k standard deviations of the dependent variable below the mean. In addition, the analysis evaluates the different statistical effects such as: variance of data, probability distribution of the mean value by its confidence interval, probability distribution of the variance by its confidence interval, difference of the distribution of the whole set of data and the distribution of the sample, and the deviation from the assumed Gaussian distribution which can be evaluated by a likelihood or a χ^2 test [35].

For the experimental results of the rough fatigue test described in Chapter 4.8, the approach used to determine the characteristic curves followed the recommendations prescribed in the IIW Fatigue Recommendations [35]. Before performing recommended steps, the experimental data was corrected by finding actual cross-sectional area at the crack and then computing the stress accordingly. To accurately find the cross-sectional area, the FARO Edge 3D scanner, shown in

Figure 55a, was used to scan the rough fatigue specimens. Then, each fatigue specimen with a finite fatigue life (discarding runouts) was imported to a modelling software called *Blender* where the physical location of the crack was measured and located on the software, shown in Figure 55b. Finally, the area was measured on the software, shown in Figure 55c.

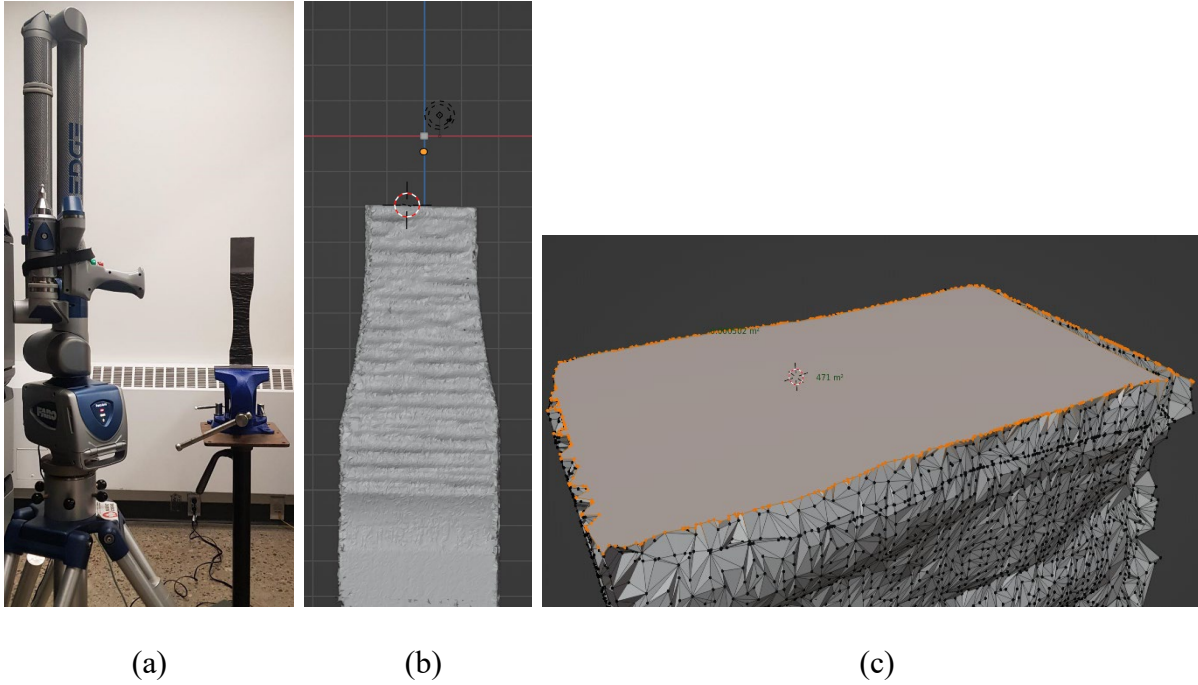


Figure 55: (a) Faro Edge 3D Scanner, (b) location of crack located on Blender, and (c) area of crack cross-section

Although the stress ranges were determined using a nominal area of 495 mm^2 in Chapter 4.8, these values were corrected to the cross-sectional areas of the crack location to find the characteristic S-N curve. The stress range for the specimens considered runouts were determined by using the average cross-sectional area of the failed specimen, which was 497 mm^2 .

With this corrected set of data, S-N data was plotted allowing the IIW recommendations to be applied. The process involved calculating the $\log_{10}$ of the data including the stress range, $\Delta\sigma$, and the number of cycles N . Then the exponent, m , and constants, $\log C$, from Equation (15) is determined using linear regression taking the stress as the independent variable [35].

$$\log N = \log C - m \cdot \log \Delta\sigma \quad (15)$$

Using the obtained values for m and $\log C$, the mean, x_m , and standard deviation, $Stdv$, was determined using Equation (16).

$$x_m = \frac{\sum x_i}{n}, \quad Stdv = \sqrt{\frac{\sum (x_m - x_i)^2}{n-1}} \quad (16)$$

Finally, the characteristic values x_k was calculated using Equation (17).

$$x_k = x_m - k \cdot Stdv \quad (17)$$

The k factor considers the different statistical effects mentioned previously. This factor depends on the minimum value of the mean confidence interval, and the maximum value of the variance confidence interval [35]. The general formula, given by Equation (18), considers the probability distribution of the mean using a Student Law (t-distribution) and of the variance using a Chi-square law (χ^2) [35].

$$k = \frac{t_{(p,n-1)}}{\sqrt{n}} + \Phi_{(alpa)}^{-1} \cdot \sqrt{\frac{n-1}{\chi^2_{(\frac{1+\beta}{2}, n-1)}}} \quad (18)$$

Adopting this procedure, the mean curve and the characteristic curve were plotted on top of the experimental data. As recommended a survival probability of $\alpha=95\%$ was adopted [35]. The resulting inverse slopes from the linear regression for the perpendicular- and the parallel-to-weld tests were $m=2.1$ and $m=4.5$, respectively. These curves for the perpendicular- and the parallel-to-weld test data are shown in Figure 56 and Figure 57, respectively.

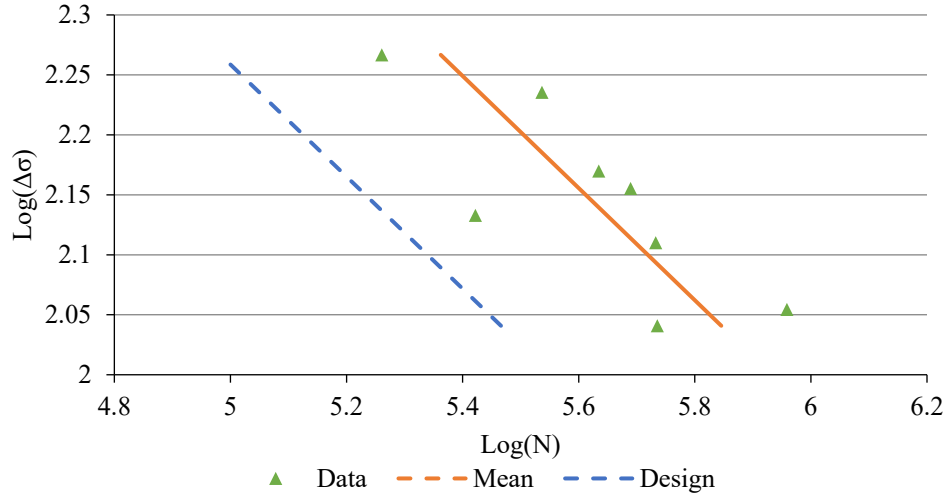


Figure 56: Mean and characteristic curves of perpendicular-to-weld rough fatigue test data ($m = 2.1$)

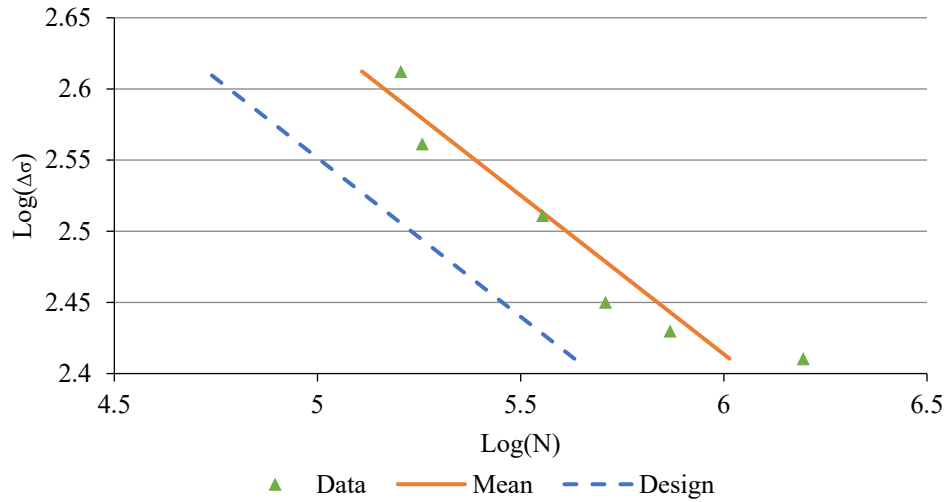


Figure 57: Mean and characteristic curves of parallel-to-weld rough fatigue test data ($m = 4.5$)

In addition, the IIW recommends an inverse slope of $m=3$ for steel as used in other studies [7, 30]. Therefore, another set of S-N curves was determined for a fixed inverse slope of $m = 3$ for the perpendicular- and parallel-to-weld rough fatigue specimens, shown in Figure 58 and Figure 59, respectively.

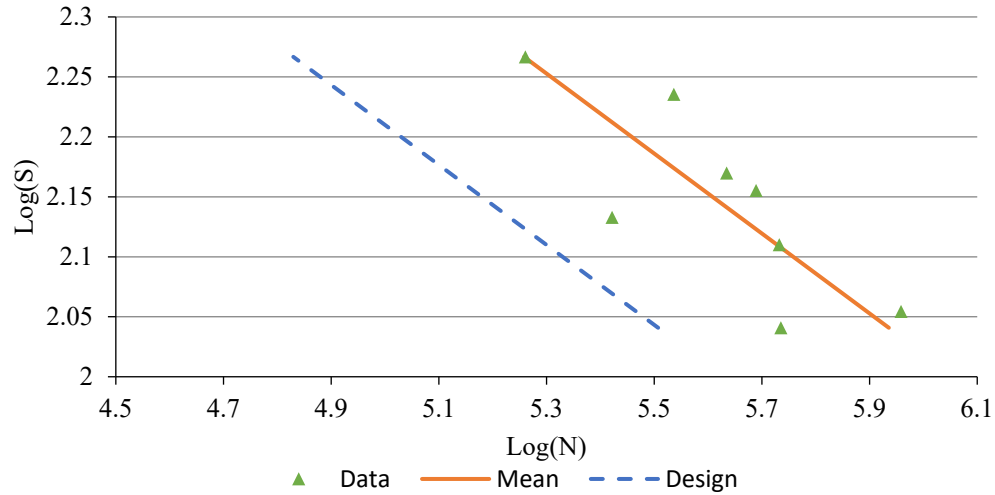


Figure 58: Mean and characteristic curves of perpendicular-to-weld rough fatigue test data ($m = 3$)

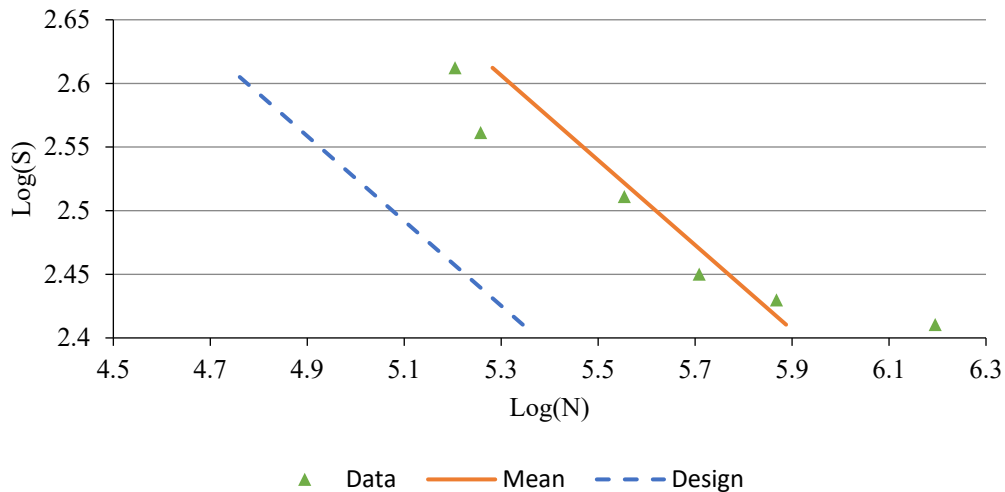


Figure 59: Mean and characteristic curves of parallel-to-weld rough fatigue test data ($m = 3$)

6.2 CSA S16 Design Curve Comparison

The characteristic curves obtained from Chapter 6.1 can be plotted along the CSA S16:19 [4] design curves to verify which weld detail category applies for the WAAM steel samples. The Detail Category S-N curves were plotted using the equations found in Chapter 26.3.3 of the CSA S6 [4], shown in Equations (19) and (20).

$$N_{fi} = \gamma f_{sri}^{-3} \quad \text{for } f_{sri} \geq F_{srt} \quad (19)$$

$$N_{fi} = \gamma' f_{sri}^{-5} \quad \text{for } f_{sri} \leq F_{srt} \quad (20)$$

where N_{fi} is the number of cycles, γ and γ' are the fatigue constants given in Table 9 of CSA S16:19, f_{sri} is the stress range, and F_{srt} is the constant amplitude threshold stress range also given in Table 9 of CSA S16:19 [4].

The mean and design curves of both, the perpendicular- and the parallel-to-weld rough fatigue specimens, were plotted on top the CSA S16:19 Detail Category S-N curves. Figure 60 shows the mean and design curves determined with an inverse slope obtained through regression of $m = 2.1$ and $m = 4.5$ for the perpendicular- and parallel-to-weld specimens, respectively. Figure 61 shows the mean and design curves determined with a fixed inverse slope of $m = 3$. For design purposes, the design curves associated with an inverse slope of $m = 3$ was used to classify the detail category of the WAAM structural steel component.

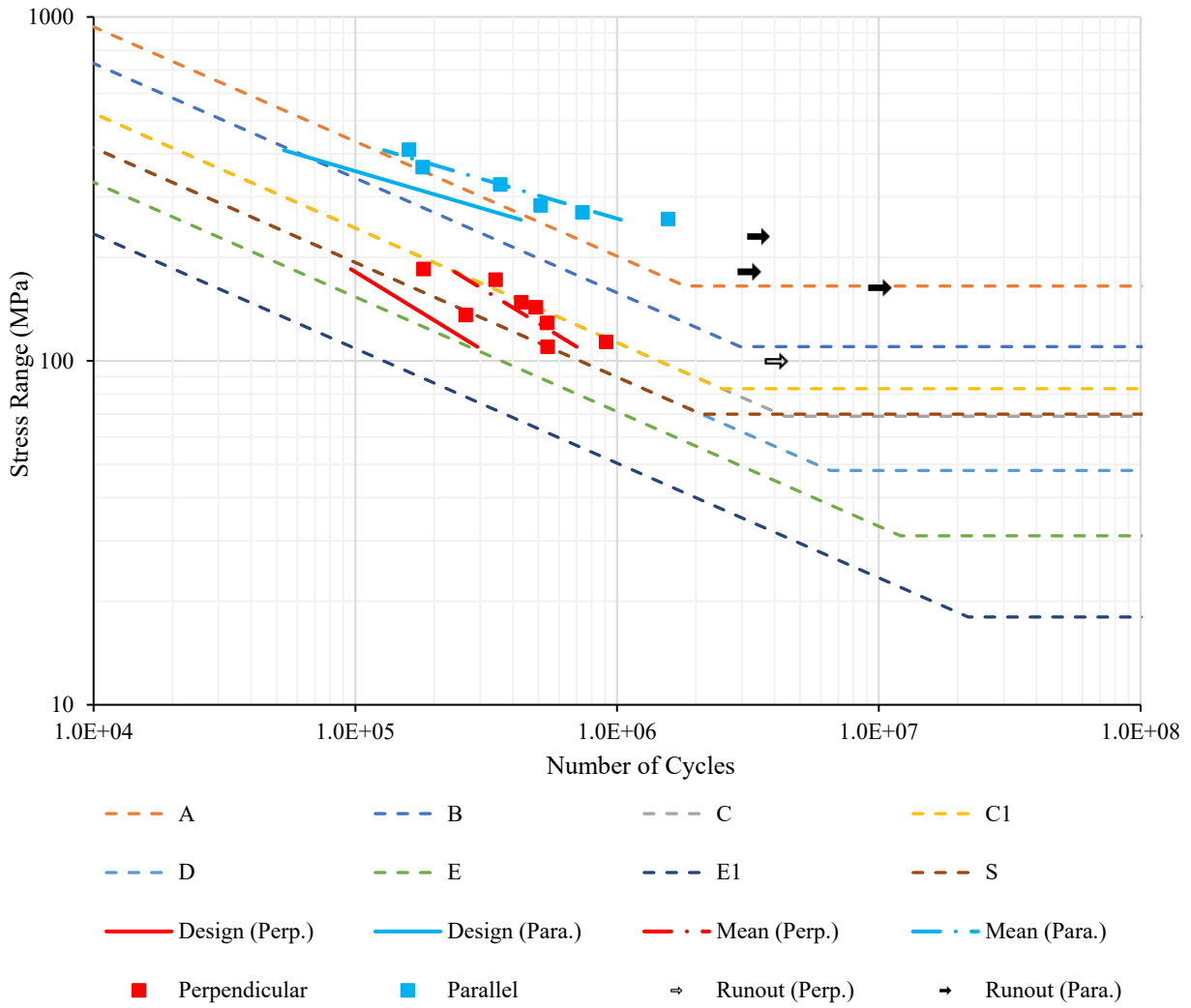


Figure 60: S-N Curve showing design curve obtained from rough fatigue test results compared with CSA S6 Detail Categories - with statistically determined inverse slopes

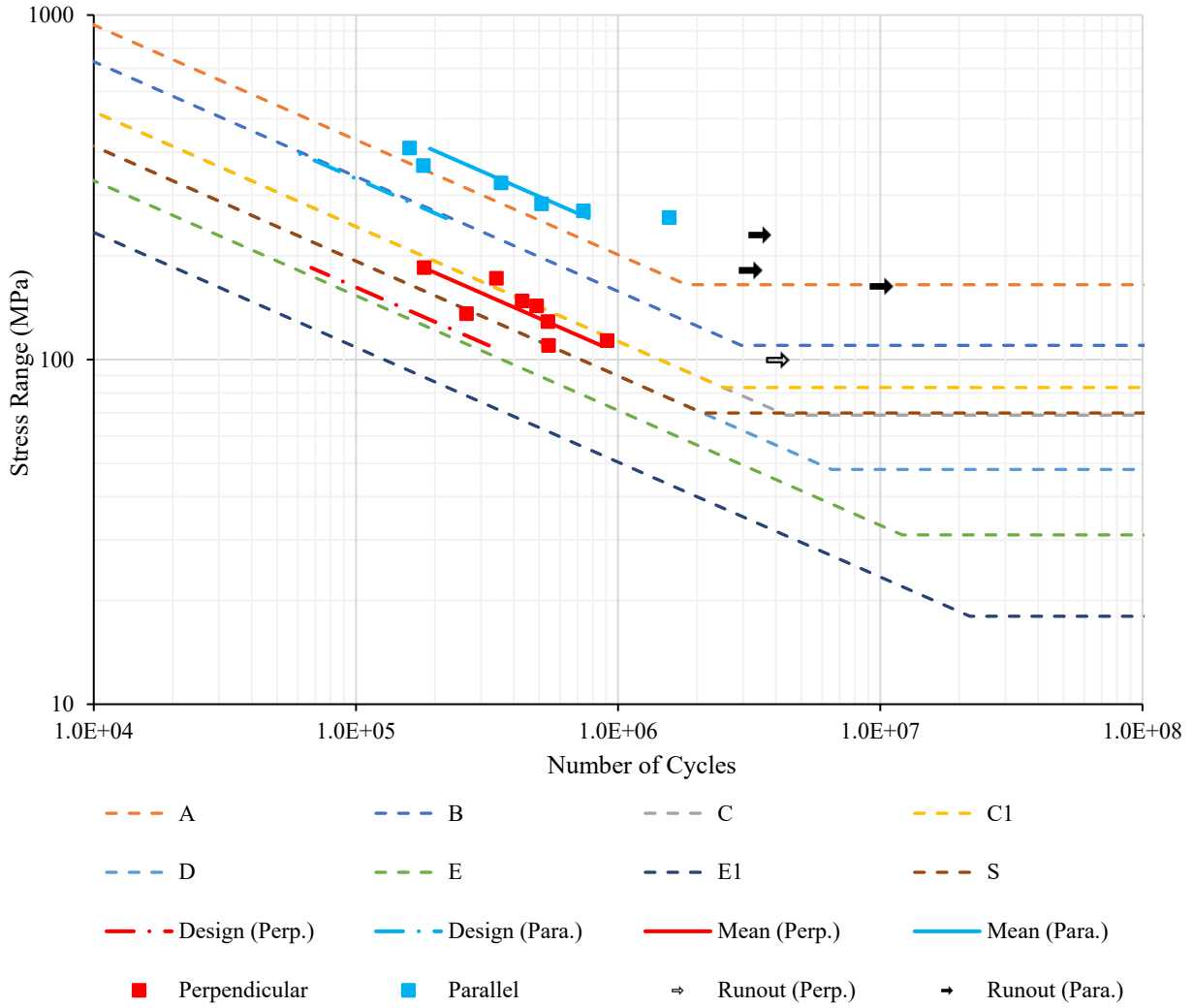


Figure 61: S-N Curve showing design curve obtained from rough fatigue test results compared with CSA S6 Detail Categories - with fixed inverse slope of $m = 3$

From Figure 61, it is apparent that the parallel-to-weld WAAM specimens lie close to Detail Category B. According to the CSA S16:19 [4], detail category B represents built up members with base metal and weld metal in components, without attachments, connected by either continuous full-penetration groove welds with backing bars removed, or continuous fillet welds parallel to the direction of applied stress, as shown in Figure 62a. It can also be compared to groove-welds in the direction of the applied stress with the welds ground flush, as shown in Figure 62b. These comparisons are adequate when applied to the parallel-to-weld specimens as the detail category

illustrates the member to have weld connections in parallel to the stress or normal but grinded to limit stress concentrations.

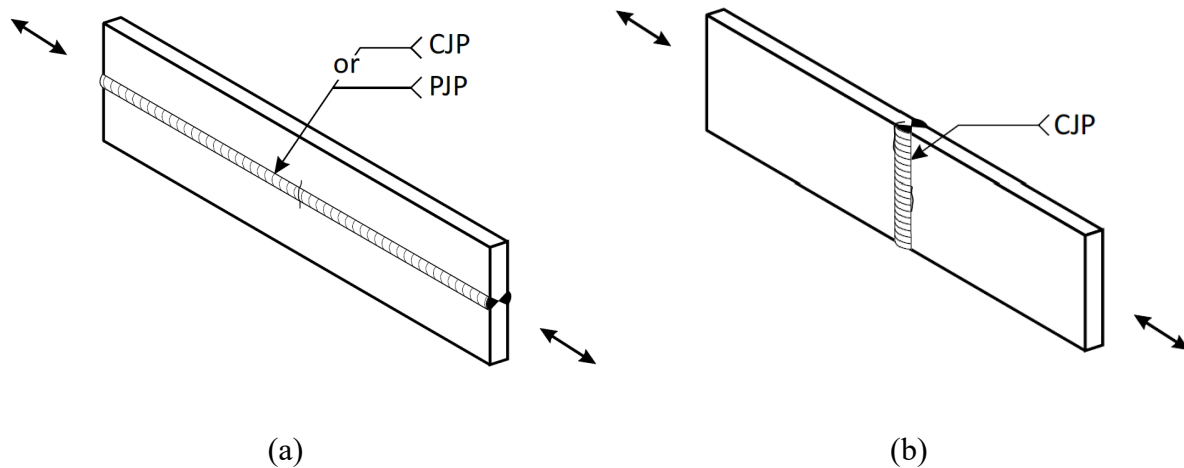


Figure 62: Example of CSA S16:19 Category B detail with built-up members (a) connected by continuous fillet welds parallel to the direction of applied stress, and (b) groove-welds ground flush in the direction of applied stress [4]

On the other hand, the perpendicular-to-weld WAAM fatigue results show proximity to CSA S16:19 Detail Category E. This can be compared to built-up members where the base metal are at ends of partial-length cover plates that are narrower than the flange, with or without end welds, or wider than the flange with ends welds for the case that the flange thickness is less than or equal to 20 mm [4], shown in Figure 63. The crack typically forms at the toe of the fillet weld and is perpendicular to the applied stress as present in the perpendicular-to-weld fatigue specimens. Although, the detail category for the perpendicular-to-weld fatigue specimens is not as illustrative as the parallel-to-weld specimens, it can be concluded that it is generally representative of cases of small transition radii and non-ground attachments. Nevertheless, more testing is necessary to accurately classify the material along with conventional structural components used up to date.

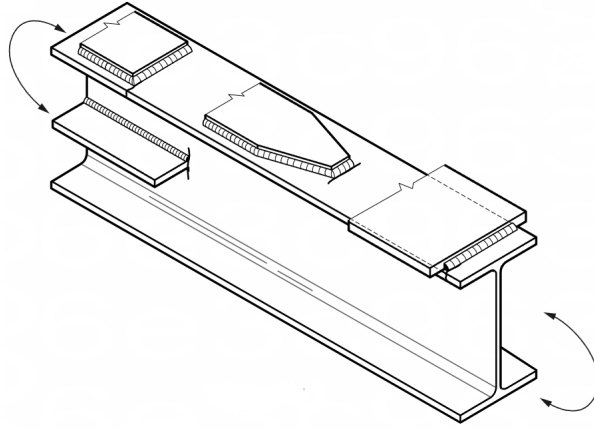


Figure 63: Example of CSA S16:19 Category E detail [4]

6.3 Linear Elastic Fracture Mechanics Analysis

In addition to experimental methods and statistical analysis of test data, a variety of analytical means for predicting fatigue performance exist, including local stress and strain approaches. One of the commonly used tools for predicting fatigue life is linear elastic fracture mechanics (LEFM). LEFM is useful in determining the behaviour of cracked materials under stress while assuming that the material acts linear-elastically. Therefore, the deformation is proportional to the applied load and the original geometry can be restored once the load is removed.

An LEFM analysis was performed for the current study using the Paris-Erdogan crack growth law [39], modified to consider a threshold stress intensity factor, as shown in Equation (21).

$$\frac{da}{dN} = C \cdot \max[(\Delta K - \Delta K_{th})^m, 0] \quad (21)$$

where a is the crack length, N is the number of cycles, C and m are the Paris-Erdogan crack law constants estimated from the compact tension test in Chapter 4.5 Crack Growth Observations, ΔK is the stress intensity factor for the assumed crack size and loading, and ΔK_{th} is the threshold stress intensity factor.

By integrating Equation (21) over the crack depth range of a_i (initial crack depth) to a_c (critical crack depth), the number of cycles to failure, N , can be estimated, as shown in Equation (22).

$$N = \int_{a_i}^{a_c} \frac{da}{C \cdot \max[(\Delta K - \Delta K_{th})^m, 0]} \quad (22)$$

The stress intensity factor, ΔK , was determined using the stress intensity factor equations by Newman and Raju [47]. Two crack shapes were observed from the experimental fatigue testing, a semi-elliptical surface crack and a semi-elliptical corner crack. The stress intensity factor equations of the two crack shapes are shown in Equation (23).

$$\Delta K_I = \Delta S \sqrt{\pi \frac{a}{Q}} F_{s,c} \quad (23)$$

where ΔS is the stress range, Q is the shape factor for an ellipse given by empirical expressions shown in (24), $F_{s,c}$ (F_s for surface crack and F_c for corner crack) is the correction factor that accounts for the crack shape.

$$\begin{aligned} Q &= 1 + 1.464 \left(\frac{a}{c}\right)^{1.65} \text{ for } \frac{a}{c} \leq 1 \\ Q &= 1 + 1.464 \left(\frac{c}{a}\right)^{1.65} \text{ for } \frac{a}{c} > 1 \end{aligned} \quad (24)$$

The crack shape correction factors for the surface and corner crack are shown in Equation (25) and (26), respectively.

$$F_s = \left[M_1 + M_2 \left(\frac{a}{t}\right)^2 + M_3 \left(\frac{a}{t}\right)^4 \right] g f_\phi f_w \quad (25)$$

$$F_c = \left[M_1 + M_2 \left(\frac{a}{t}\right)^2 + M_3 \left(\frac{a}{t}\right)^4 \right] g_1 g_2 f_\phi f_w \quad (26)$$

where M_i and g_i are curve fitting functions, f_ϕ is the angular function derived from the embedded elliptical crack solution, and f_w is the finite-width correction factor.

For $a/c = 1$, the curve fitting functions M_i and g for the semi-elliptical surface crack are given in Equations (27) to (30).

$$M_1 = 1.13 - 0.09 \left(\frac{a}{c} \right) \quad (27)$$

$$M_2 = -0.54 + \frac{0.89}{0.2 + \left(\frac{a}{c} \right)} \quad (28)$$

$$M_3 = 0.5 - \frac{1}{0.65 + \left(\frac{a}{c} \right)} + 14 \left(1 - \frac{a}{c} \right)^{24} \quad (29)$$

$$g = 1 + \left[0.1 + 0.35 \left(\frac{a}{t} \right)^2 \right] (1 - \sin \phi)^2 \quad (30)$$

where ϕ is the parametric angle of the ellipse ($\phi = 0^\circ$ for surface and $\phi = 90^\circ$ for depth).

For the same crack depth to length ratio, the curve fitting functions M_i and g for the semi-elliptical corner crack are given in Equations (31) to (35).

$$M_1 = 1.08 - 0.03 \left(\frac{a}{c} \right) \quad (31)$$

$$M_2 = -0.44 + \frac{1.06}{0.3 + \left(\frac{a}{c} \right)} \quad (32)$$

$$M_3 = -0.5 + 0.25 \left(\frac{a}{c} \right) + 14.8 \left(1 - \frac{a}{c} \right)^{15} \quad (33)$$

$$g_1 = 1 + \left[0.08 + 0.4 \left(\frac{a}{t} \right)^2 \right] (1 - \sin \phi)^3 \quad (34)$$

$$g_2 = 1 + \left[0.08 + 0.15 \left(\frac{a}{t} \right)^2 \right] (1 - \cos \phi)^3 \quad (35)$$

The angular function, f_ϕ , and the finite-width correction factor, f_w , are given in Equations (36) and (37) for both crack shapes.

$$f_\phi = \left[\left(\frac{a}{c} \right)^2 \cos^2 \phi + \sin^2 \phi \right]^{1/4} \quad (36)$$

$$f_w = \left[\sec \left(\frac{\pi c}{2b} \sqrt{\frac{a}{t}} \right) \right]^{1/2} \quad (37)$$

For every stress range investigated in the experimental program for the rough fatigue specimens, the number of cycles to failure was calculated using this approach. To account for the surface characteristics of the WAAM steel, a stress concentration factor, K_t , was applied to the nominal stress ranges. This allowed the consideration of stress concentrations found in the roughness and waviness of the surface. The K_t values were determined using the 3D scanned models of the rough fatigue specimens discussed in Chapter 6.1 IIW Statistical Analysis of Rough Fatigue S-N curves. These

scans were modelled using finite element methods (FEM) through a software called *ANSYS* (ANSYS workbench - ver. 2022) [48] to locate stress concentrations zones of the WAAM rough fatigue specimens. The K_t values were taken as the maximum values from the contour plots shown in Figure 64. Originally, the cross sectional area that was inputted to the model was 610 mm^2 . Hence the results were corrected to a nominal cross sectional area of 495 mm^2 by multiplying each K_t value by $495/610$.

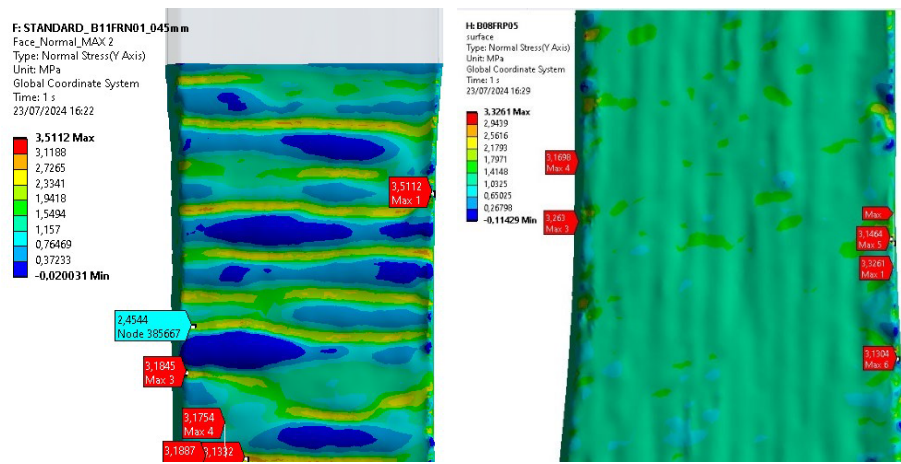


Figure 64: Contour plots showing maximum stress concentration factors (K_t) for perpendicular- (left) and parallel-to-weld (right) rough fatigue specimens

The maximum K_t values were obtained for each specimen, summarized in Table 13 and Table 14. It should be noted here that the ANSYS analysis to obtain the K_t values was performed by another member of the research group working on this project - Dr. Eduardo Martins Fontes do Rego. In this thesis, the K_t results are simply used as an input for the LEFM analysis, which was performed by the thesis author.

Table 13: Maximum K_t values for perpendicular-to-weld rough fatigue specimens

Specimen	K_t
B11FRN01	2.85
B07FRN01	4.05
B07FRN02	2.73
B07FRN03	3.89
B07FRN01	3.60
B07FRN05	5.14
B11FRN02	3.01
B05FRN02	4.14
B07FRN04	3.69
B07FRN06	4.35
Min	2.73
Max	5.14
Average	3.74

Table 14: Maximum K_t values for parallel-to-weld rough fatigue specimens

Specimen	K_t
B08FRP01	3.21
B06FRP01	3.04
B12FRP01	3.39
B06FRP02	2.92
B08FRP02	2.02
B08FRP03	3.31
B08FRP04	2.96
B08FRP05	2.70
B08FRP06	3.01
B12FRP02	3.39
Min	2.02
Max	3.39
Average	3.00

A summary of the input parameters used for the LEFM model is shown in Table 15. The assigned values are obtained from the current study, unless noted otherwise.

Table 15: Assigned values of LEFM model input parameters

Input Parameter	Assignment Value	Units	Source
$2 \cdot b$	30	mm	
T	16	mm	
a/c	1	-	
a_i	0.15	mm	[49]
a_c	8	mm	[49]
C	6.61E-12	N, mm	
m	2.461	-	
Average K_t ($\perp$)	3.74	-	
Average K_t ($\parallel$)	3.00	-	
ΔK_{th}	80	MPa $\cdot\sqrt{mm}$	[49]

The plate width, $2 \cdot b$, was taken as 30 mm. The thickness, T , was taken as the nominal thickness of the specimen (16 mm). The initial crack depth was taken as the 0.15 mm, which is a commonly assumed value for steel components [49]. The critical crack depth was taken as half of the specimen nominal thickness. The parametric angle of the ellipse, ϕ , was taken as $\pi/2$ (90°) to account for the deepest part of the crack. The K_t values were taken as the average values of the obtained maximum stress intensity factors found in Table 13 and Table 14. Lastly, a typical value from the literature was assumed for the threshold stress intensity factor, ΔK_{th} [49]. For simplification, the model assumed that the stress was uniform throughout the crack depth, crack closure effects were neglected, and residual stresses were not considered.

With these parameters, the LEFM results were compared to the experimental results, shown in Figure 65 and Figure 66.

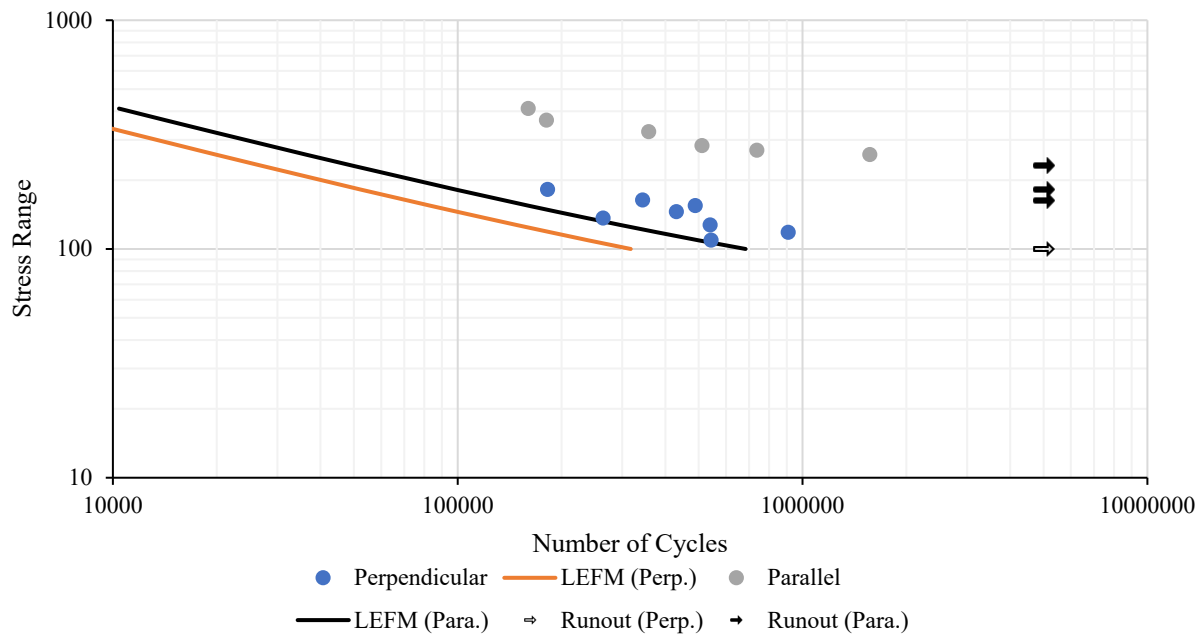


Figure 65: LEFM and experimental fatigue results assuming semi-elliptical surface crack (K_t values obtained by laser scanning and ANSYS analysis)

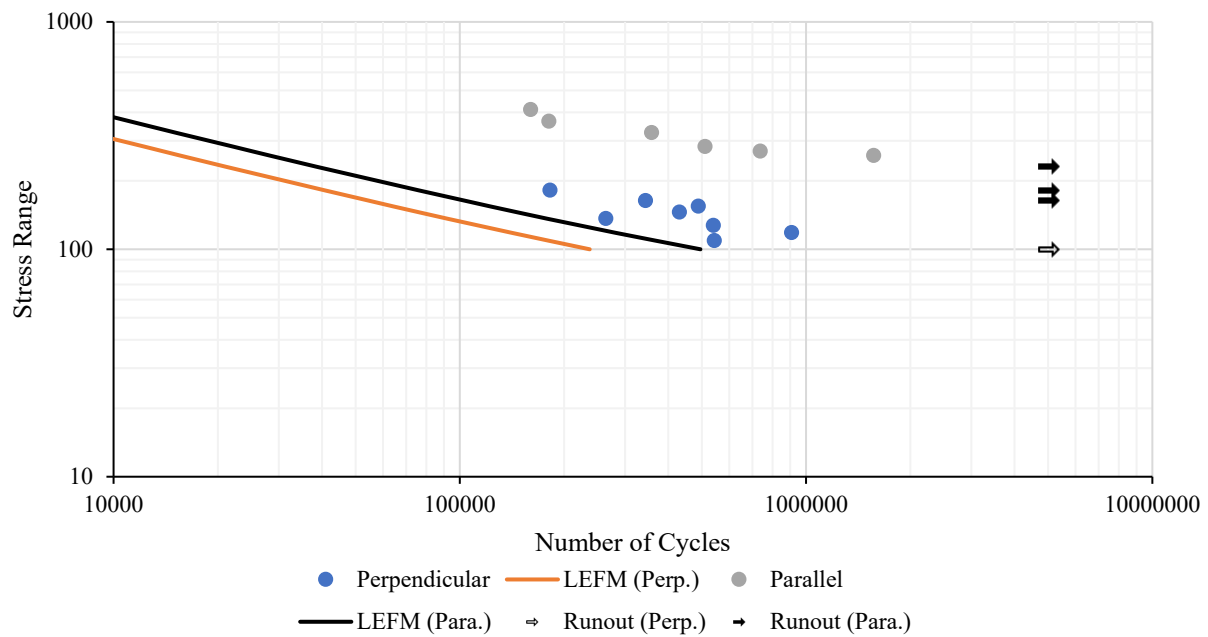


Figure 66: LEFM and experimental fatigue results assuming semi-elliptical corner crack (K_t values obtained by laser scanning and ANSYS analysis)

Looking at this figure, it can be seen that the LEFM predictions made using the K_t values obtained by laser scanning and ANSYS analysis resulted in highly conservative predictions. On this basis, another set of analyses were performed where K_t was varied for each data set to find values that led to accurate predictions of the fatigue test results. In this way, it was found that for a semi-elliptical surface crack, K_t values of 2.5 and 1.1 for the perpendicular- and parallel-to-weld specimens, respectively, best matched the experimental results. Whereas for a semi-elliptical corner crack, K_t values of 2.2 and 1.0 for the perpendicular- and parallel-to-weld specimens, respectively, best matched the experimental results as shown in Figure 67 and Figure 68.

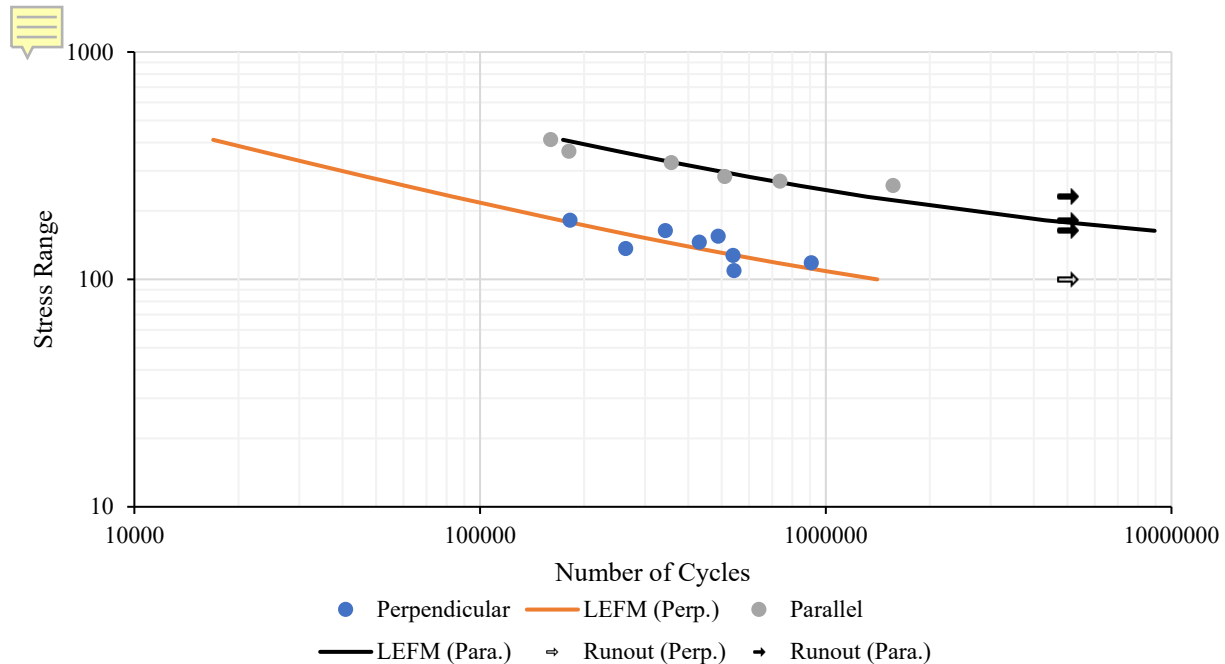


Figure 67: LEFM and experimental fatigue results assuming semi-elliptical surface crack (estimated K_t values)

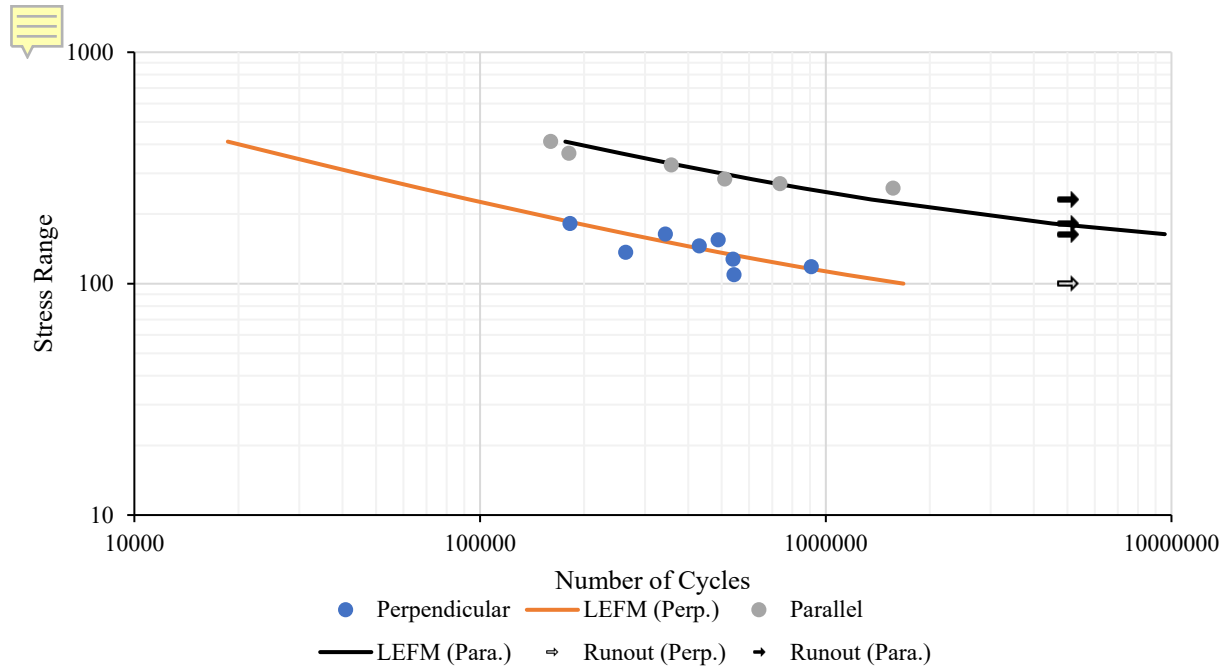


Figure 68: LEFM and experimental fatigue results assuming semi-elliptical corner crack (estimated K_t values)

Based on the LEFM result, predicting the fatigue life of the WAAM structural steel components using LEFM is possible but is highly dependent on the choice of input parameters. In this study, it was found that the K_t values obtained by laser scanning and ANSYS analysis led to very conservative fatigue life predictions. Better results were achieved with back-calculated K_t values, which were generally lower than maximum values obtained by laser scanning and ANSYS analysis. There are several possible explanations for this result, and further investigation will be needed to better understand which explanation or combination of explanations is correct. One explanation is that using the maximum K_t value is conservative because as the crack grows into regions where K_t is lower, the crack growth may slow. Another possible explanation is that the regions with high K_t values in the case of the perpendicular specimens generally stretch across the specimen width, whereas they tend to be more localized in the case of the parallel specimens. Lastly, it is possible that lack of fusion defects – if present – tend to run parallel to the weld bead, which means they

will have a bigger impact on the perpendicular fatigue tests. This would mean that the same values for a_i may not be appropriate for predicting fatigue life in the two directions.

7 Conclusions and Recommendations for Future Work

7.1 Conclusions

This chapter presents conclusions drawn from the research work done for this thesis. It is divided into three main parts: Chapter 7.1.1, Chapter 7.1.2, and Chapter 7.1.3.

7.1.1 Experimental Testing

The following conclusions are drawn based on the experimental program discussed in Chapter 3 and the results presented in Chapter 4:

- The mechanical properties of the WAAM structural steel components were determined through material testing. These tests included static strength tests to determine the mechanical properties under tensile loading such as the modulus of elasticity, yield stress, ultimate tensile stress, and the ductility. Cyclic material properties were obtained from the smooth cyclic test. From these tests, the average material properties were: $E = 214.9$ GPa, $\sigma_y = 458.9$ MPa, $\sigma_u = 586.5$ MPa, $K' = 571.3$ MPa, and $n' = 0.0558$. The % elongation at fracture was found to be 30.2% on average. These values were found to be similar to design values for common mild structural steels such as CSA 350W steel.
- The fracture toughness properties of the WAAM structural steel component were determined through Charpy v-notch (CVN) testing. Based on the CVN test results, the material possesses excellent fracture toughness with a T_{27J} of -134 °C and -98 °C for the perpendicular- and parallel-to-weld specimens, respectively.
- The crack propagation properties were gathered through the compact tension test. The test was done to capture the crack growth of the WAAM structural steel component. Based on the results, the Paris-Erdogan constants, C and m , were determined to be $6.61 \cdot 10^{-12}$ (N, mm) and 2.461, respectively.

- The fatigue properties of the WAAM structural steel component were determined through fatigue testing of both smooth and rough (as-fabricated) material samples. From the smooth specimen tests, a constant amplitude fatigue limit (CAFL) of approximately 370 MPa was obtained. On the other hand, the material exhibited an overall drop in the fatigue performance in the as fabricated state. The CAFL of the rough fatigue specimens was approximately 110 MPa and 260 MPa for the perpendicular- and parallel-to-weld specimens, respectively. Moreover, it can also be concluded that the material possesses better fatigue properties when oriented parallel to the weld direction.
- Mechanical properties of the WAAM structural steel components indicate that the material is isotropic when the surface is milled (smooth). However, when the components are in its as-deposited state (rough), the material exhibits anisotropic behaviour.
- Based on the fatigue test observations, the WAAM structural steel was classified based on the CSA detail categories. The perpendicular-to-weld specimens results suggested design should be done in this case using CSA Detail Category E, whereas the parallel-to-weld specimens achieved a performance consistent with CSA Detail Category B.

7.1.2 Metallurgical Analysis

The following conclusions are drawn based on the metallurgical analysis discussed in Chapter 5:

- The weld deposition layers were observed through the microstructure of the WAAM structural steel cross-sections. Within the layers, the as-deposited zones and the reheated zones can be distinguished. As expected the grain sizes were much finer in the reheated zones near the edges of each weld pass in contact with subsequent weld passes.
- Based on the microstructure, the microconstituents can be determined. The microconstituents were in general agreement with what has been reported in similar

studies. It was found that the as-deposited microstructure consisted of acicular ferrite. Whereas the reheated zones consisted of polygonal ferrite and lamellar pearlite. It can be inferred that the characteristics of these microconstituents, such as the acicular ferrite, provide the material with its high impact toughness.

- The metallurgical analysis also revealed defects within the material such as porosity

7.1.3 Linear Elastic Fracture Mechanics Model

The following conclusions are drawn based on the metallurgical analysis that is discussed in Chapter 6.3:

- The linear elastic fracture mechanics (LEFM) model showed some correlation with the experimental fatigue results. With the chosen surface stress concentration factors, K_t , of 3.74 and 3.00 for the perpendicular- and parallel-to-weld fatigue specimens, respectively, obtained through laser scanning and finite element (FE) analysis using the software ANSYS, the LEFM model was found to produce highly conservative results.
- The analysis was performed again with “back-calculated” K_t values that were much lower than the ones obtained by laser scanning and FE analysis. The results were more representative of the experimental data. The new K_t values were 2.5 and 1.1 for the perpendicular- and parallel-to-weld fatigue specimens, respectively, for the semi-elliptical surface crack. For the semi-elliptical corner crack, K_t values of 2.2 and 1.0 were used for the perpendicular- and parallel-to-weld fatigue specimens, respectively
- It was concluded that LEFM can be used to predict the fatigue life of the WAAM structural steel, but the selection of input parameters can significantly influence the results.

7.2 Recommendations for Future Work

This chapter presents the recommendations for future works based on the findings of this thesis.

7.2.1 Experimental Testing

The following recommendations for future research are made based on the experimental results:

- Fatigue testing on more complex and large-scale specimens, such as connection joints, is recommended to study the size and shape effects of the components. This will also serve to introduce the various loading schemes that occur in real structural connections.
- Fatigue testing of post-processed WAAM steel, such as with steel samples subjected to impact treating, is recommended to study the benefits of post-processing.
- Fatigue testing of WAAM steel with varying deposition parameters is recommended to find the optimal parameters that may improve fatigue life. These can be the altering of the interlayer temperatures to reduce surface roughness, altering wire feed rate, etc.
- Further fatigue testing to more accurately classify the WAAM structural steel component into current codes and regulations such as the CSA codes is recommended.

7.2.2 Metallurgical Analysis

The following recommendations for future research are made based on the microstructural results:

- Hardness testing of the as-deposited and reheated regions to better understand the variation of the strength properties within a volume of WAAM steel is recommended.

7.2.3 Linear Elastic Fracture Mechanics Model

The following recommendations for future research are made based on the linear elastic fracture mechanics analysis results:

- A more in depth fracture mechanics analysis should be conducted to assess the effects of the non-linear stress distribution, crack closure effects, and residual stresses.
- The effects of different crack shape (a/c) ratios should be considered in future analysis.
- Further investigation is recommended to determine more accurate surface stress intensity factors, K_t , for both the perpendicular- and parallel-to-weld WAAM components.

References

- [1] R. Kühne, M. Feldmann, S. Citarelli, U. Reisgen, R. Sharma and L. Oster, "3D printing in steel construction with the automated Wire Arc Additive Manufacturing," *ce/papers*, no. 3, pp. 577-583, 2019.
- [2] B. Wu, Z. Pan, D. Ding, D. Cuiuri, H. Li, J. Xu and J. Norrish, "A review of the wire arc additive manufacturing of metals: properties, defects and quality improvements," *Journal of Manufacturing Processes*, no. 35, pp. 127-139, 2018.
- [3] CSA Group, "CSA S6:19," in *Canadian Highway Bridge Design Code*, 2019.
- [4] CSA Group, "CSA S16:19, Design of steel structures," in *Handbook of Steel Construction*, 2021.
- [5] M. Dinovitzer, X. Chen, J. Laliberte, X. Huang and H. Frei, "Effect of wire and arc additive manufacturing (WAAM) process parameters," *Additive Manufacturing*, no. 26, pp. 138-146, 2019.
- [6] M. Srivastava, S. Rathee, A. Tiwari and M. Dongre, "Wire arc additive manufacturing of metals: A review on processes, materials and their behaviour," *Materials Chemistry and Physics*, no. 294, 2023.
- [7] E. Brandl, B. Baufeld, C. Leyens and R. Gault, "Additive manufactured Ti-6Al-4V using welding wire: comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications," *Physics Procedia*, vol. 5, pp. 595-606, 2010.
- [8] J. Xiong, G. Zhang, H. Gao and L. Wu, "Modeling of bead section profile and overlapping beads with experimental validation for robotic GMAW-based rapid manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 29, no. 2, pp. 417-423, 2013.
- [9] P. A. Colegrove, H. E. Coules, J. Fairman, F. Martina, T. Kashoob, H. Mamash and L. D. Cozzolino, "Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling," *Journal of Materials Processing Technology*, vol. 213, no. 10, pp. 1782-1791, 2013.
- [10] F. Montevercchi, G. Venturini, A. Scippa and G. Campatelli, "Finite Element Modelling of Wire-arc-additive-manufacturing Process," *Procedia CIRP*, vol. 55, pp. 109-114, 2016.
- [11] A. Lopez, R. Bacelar, I. Pires, T. G. Santos, J. P. Sousa and L. Quintino, "Non-destructive testing application of radiography and ultrasound for wire and arc additive manufacturing," *Additive Manufacturing*, vol. 21, pp. 298-306, 2018.

- [12] N. Kumar, H. Bhavsar, P. V. Mahesh, A. K. Srivastava, B. J. Bora, A. Saxena and A. R. Dixit, "Wire Arc Additive Manufacturing – A revolutionary method in," *Materials Chemistry and Physics*, no. 285, 2022.
- [13] K. Treutler and V. Wesling, "The current state of research of wire arc additive manufacturing (WAAM): A Review," *Applied Sciences*, vol. 18, no. 11, September 2021.
- [14] V. Kumar, A. Mandal, A. K. Das and S. Kumar, "Parametric study and characterization of wire arc additive manufactured steel structures," *The International Journal of Advanced Manufacturing Technology*, no. 115, pp. 1723-1733, 2021.
- [15] T. A. Rodrigues, V. Duarte, R. M. Miranda, T. G. Santos and J. P. Oliveira, "Current Status and Perspectives on Wire and Arc Additive Manufacturing (WAAM)," *Materials* 12, no. 7: 1121, 2019.
- [16] O. V. Panchenko, L. A. Zhabrev, D. V. Kuruskin and A. A. Popovich, "MACROSTRUCTURE AND MECHANICAL PROPERTIES OF Al – Si, Al – Mg – Si, AND Al – Mg – Mn ALUMINUM ALLOYS, PRODUCED BY ELECTRIC ARC ADDITIVE GROWTH," *Metallovedenie i Termicheskaya Obrabotka Metallov*, no. 11, pp. 63-69, 2018.
- [17] C. Buchanan and L. Gardner, "Metal 3D printing in construction: A review of methods, research,," *Engineering Structures*, no. 180, pp. 332-348, 2019.
- [18] L. Gardner, P. Kyvelou, G. Herbert and C. Buchanan, "Testing and initial verification of the world's first metal 3D printed bridge," *Journal of Constructional Steel Research*, no. 172, 2020.
- [19] M. Chaturvedi, E. Scutelnicu, C. C. Rusu, L. R. Mistodie, D. Mihailescu and A. V. Subbiah, "Wire Arc Additive Manufacturing: Review on Recent Findings," *Metals*, no. 11, 2021.
- [20] R. Kawalkar, H. K. Dubey and S. P. Lokhande, "Wire arc additive manufacturing: A brief review on advancements in," *Materials Today: Proceedings*, no. 50, pp. 1971-1978, 2022.
- [21] J. Wang, Z. Pan, D. Cuiuri and H. Li, "Phase constituent control and correlated properties of titanium aluminide intermetallic alloys through dual-wire arc additive manufacturing," *Materials Letters*, no. 242, pp. 111-114, 2019.
- [22] H. Geng, J. Li, J. Xiong, X. Lin and F. Zhang, "Geometric Limitation and Tensile Properties of Wire and," *Journal of Materials Engineering and Performance*, vol. 26, no. 2, pp. 621-629, 2017.

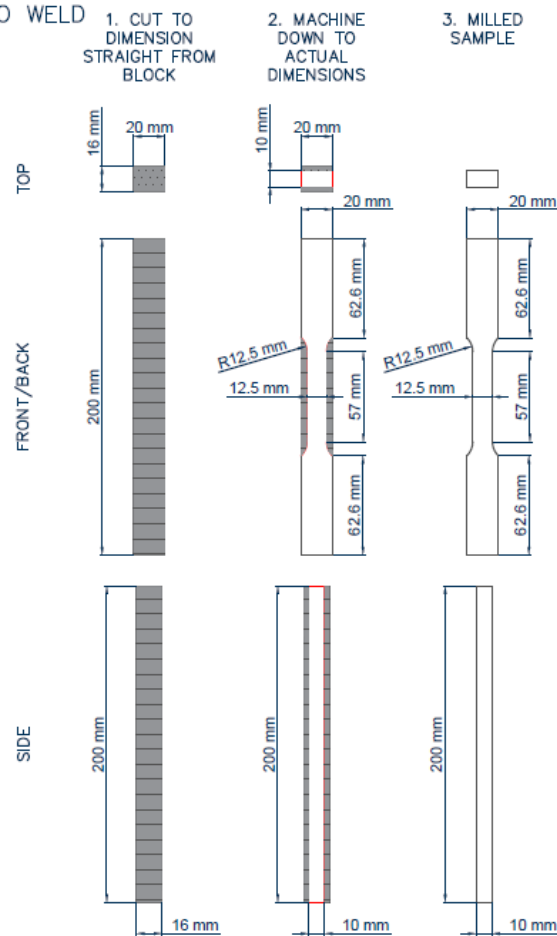
- [23] J. Ge, J. Lin, Y. Chen, Y. Lei and H. Fu, "Characterization of wire arc additive manufacturing 2Cr13 part: Process stability, microstructural evolution, and tensile properties," *Journals of Alloys and Compounds*, vol. 748, pp. 911-921, 2018.
- [24] J. F. Wang, Q. J. Sun, G. Wang, J. P. Liu and J. C. Feng, "Effect of location on microstructure and mechanical properties of additive layer manufactured Inconel 625 using gas tungsten arc welding," *Materials Science and Engineering: A*, vol. 676, pp. 395-405, 2016.
- [25] I. Jurić , I. Garašić, M. Bušić and Z. Kožuh , "Influence of Shielding Gas Composition on Structure and Mechanical Properties of Wire and Arc Additive Manufactured Inconel 625," *The Journal of The Minerals, Metals & Materials Society (TMS)*, vol. 71, pp. 703-708, 208.
- [26] J. Guo, Y. Zhou, C. Liu, Q. Wu, X. Chen and J. Lu, "Wire Arc Additive Manufacturing of AZ31 Magnesium Alloy: Grain Refinement by Adjusting Pulse Frequency," *Materials*, vol. 9, no. 10, p. 823, 2016.
- [27] M. Rafieazad, M. Ghaffari, A. V. Nemani and A. Nasiri, "Microstructural evolution and mechanical properties of a low-carbon," *Microstructural evolution and mechanical properties of a low-carbon* *Microstructural evolution and mechanical properties of a low-carbon*, no. 105, p. 2019, 2121-2134.
- [28] P. Moore, A. Addison and M. Nowak-Coventry, "Mechanical properties of wire plus arc additive manufactured steel," *Welding in the World*, no. 63, pp. 1521-1530, 2019.
- [29] H. Bartsch, R. Kuhne, S. Citarelli, S. Schaffrah and M. Feldmann, "Fatigue Analysis of Wire Arc Manufactured (3D Printed) Components with Unmilled Surface," *Structures*, pp. 576-589, 2021.
- [30] C. Huang, L. Li, N. Pichler, E. Ghafoori, L. Susmel and L. Gardner, "Fatigue testing and analysis of steel plates manufactured by wire-arc," *Additive Manufacturing*, no. 73, 2023.
- [31] CEN (European Committee for Standardization), "EN ISO 6892-1:2016," *Metallic materials - Tensile testing - Part 1: method of test at room temperature*, 2016.
- [32] American Society of Testing Materials (ASTM), "Standard guide for preparation of metallographic specimens," in *ASTM E3-11*, West Conshohocken, ASTM International, 2011.
- [33] American Society of Testing Materials (ASTM), "Standard practice for conducting force controlled constant amplitude axial fatigue tests of metallic materials," in *ASTM E466-21*, West Conshohocken, ASTM International, 2021.
- [34] European Committee for Standardization, "Eurocode 3: Design of Steel Structures - Part1-9: Fatigue," in *EN 1993-1-9*, 2005.

- [35] International Institute of Welding, in *IIW Fatigue Recommendations*, 2005, pp. 91-94, 137-140.
- [36] American Society of Testing Materials (ASTM), "Standard Test Methods for Tension Testing of Metallic Materials," in *ASTM E8/E8M-22*, West Conshohocken, PA: ASTM International, 2022.
- [37] American Society of Testing Materials (ASTM), "Standard Test Methods and Definitions for Mechanical Testing of Steel Products," in *ASTM A370-23*, West Conshohocken, ASTM International, 2023.
- [38] American Society of Testing Materials (ASTM), Standard Test Method for Measurement of Fatigue Crack Growth Rates, West Conshohocken: ASTM International, 2023.
- [39] P. Paris and F. Erdogan, "A critical analysis of crack propagation laws," in *Journal of Basic Engineering*, ASME, 1963, pp. 528-534.
- [40] American Society of Testing Materials (ASTM), "Standard Test Method for Strain-Controlled Fatigue Testing," in *ASTM E606/E606M-21*, West Conshohocken, ASTM International, 2021.
- [41] K. Ghahremani, "Fatigue Assessment of Repaired Highway Bridge Welds Using Local Approaches," University of Waterloo, Waterloo, 2015.
- [42] M. Feldmann, B. Eichler, B. Kühn, N. Stranghöner, W. Dahl, P. Langenberg, J. Kouhi, R. Pope, G. Sedlacek, P. Ritakallio, G. Iglesias, R. Puthli, J. Packer and J. Krampen, "Choice of Steel Material to Avoid Brittle Fracture for Hollow Section Structures," EUR 25400 EN, 2012.
- [43] G. Golisch, "Evaluation of the Lower Shelf Toughness Properties of High Strength Steels Using Fracture and Damage Mechanics Approaches," RWTH Aachen University, Guben, 2018.
- [44] P. S. Patwardhan, R. A. Nalavde and D. Kujawski, "An Estimation of Ramberg-Osgood Constants for Materials with and without Luder's Strain Using Yield and Ultimate Strengths," *Procedia Structural Integrity*, no. 17, pp. 750-757, 2019.
- [45] K. Ghahremani and S. Walbridge, "Fatigue testing and analysis of peened highway bridge welds under in-service," *International Journal of Fatigue*, vol. 33, pp. 300-312, 2011.
- [46] J. Jorge, L. Souza, M. Mendes, L. Bott, L. Araujo, V. Santos, J. Rebello and G. Evans, "Microstructure characterization and its relationship with impact toughness of CeMn and high strength low alloy steel weld metals e a review," *Journal of Materials Research and Technology*, no. 10, pp. 471-501, 2021.

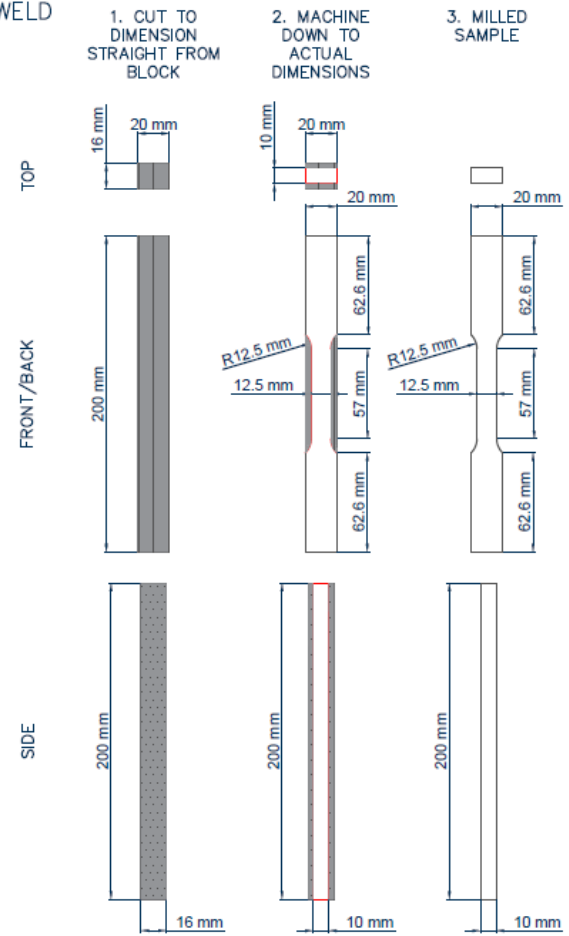
- [47] J. C. Newman, Jr. and I. S. Raju, "Stress-Intensity Factor Equations For Cracks In Three-Dimensional Finite Bodies," *NASA Technical Memorandum*, 1981.
- [48] ANSYS Inc., "Ansys," 2024. [Online]. Available: <https://www.ansys.com/products/ansys-workbench>.
- [49] S. Walbridge, "Fatigue analysis of post-weld fatigue improvement treatments using a strain-based fracture mechanics model," *Engineering Fracture Mechanics*, vol. 75, pp. 5057-5071, 2008.
- [50] Y. Wang, X. Chen, S. Konovalov, C. Su, A. N. Siddiquee and N. Gangil, "In-situ wire-feed additive manufacturing of Cu-Al alloy by addition of silicon," *Applied Surface Science*, vol. 487, pp. 1366-1375, 2019.

Appendix A – Specimen Details

PERPENDICULAR TO WELD



PARALLEL TO WELD



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Revisions			

Drawn On 26-Oct-22

Drawn By Jun Seo Lee

Client

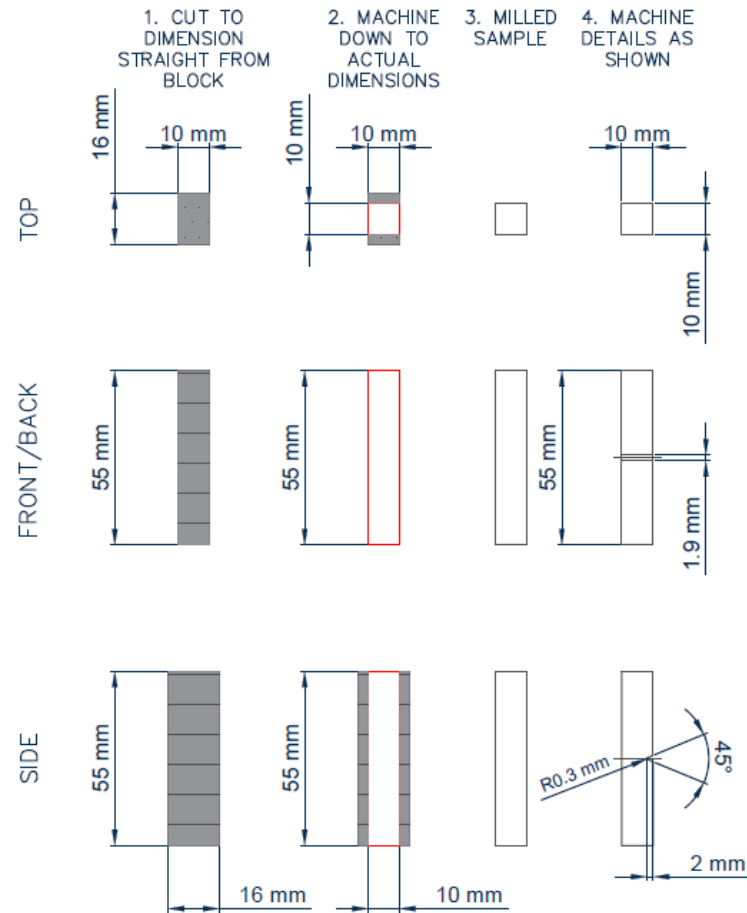


Project Fatigue & Fracture of WAAM Steel Products

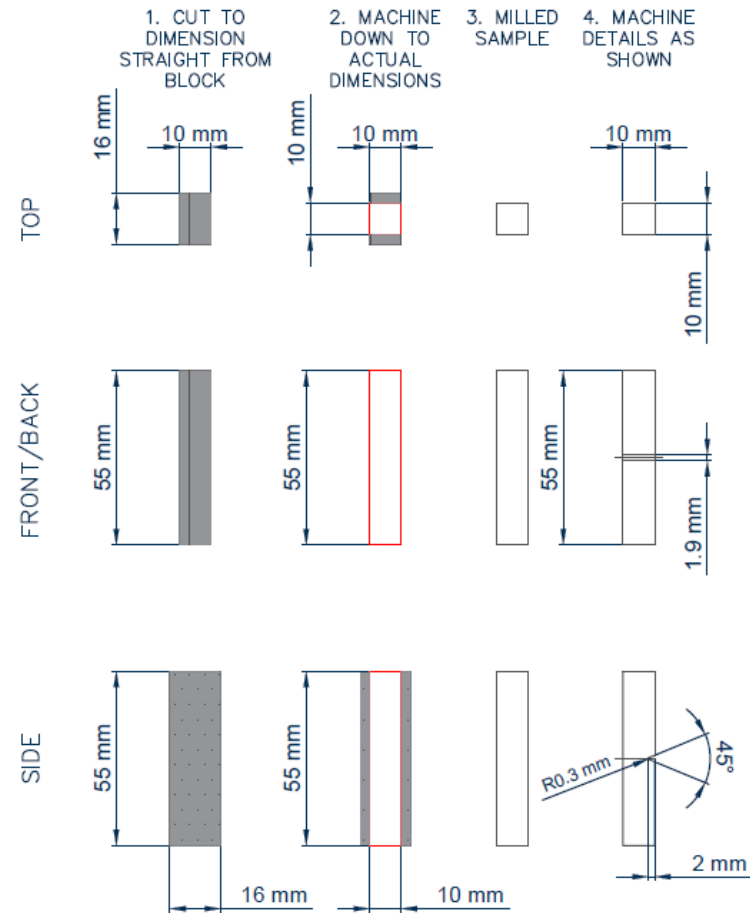
Drawing Specimen Detail Static Tension

Scale 1:4

PERPENDICULAR TO WELD



PARALLEL TO WELD



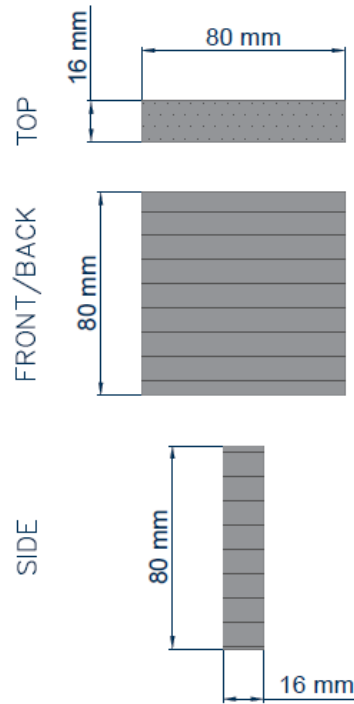
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Revisions			

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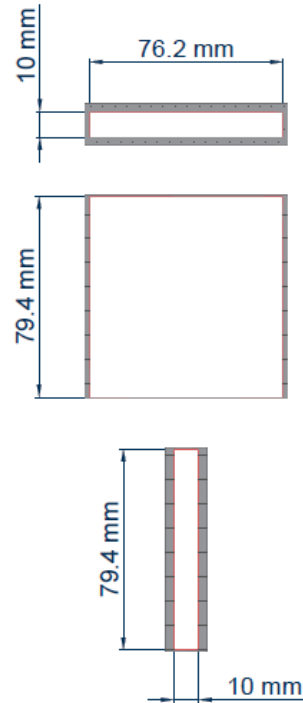


Project Fatigue & Fracture of WAAM Steel Products
 Drawing Specimen Detail Charpy
 Scale 1:2

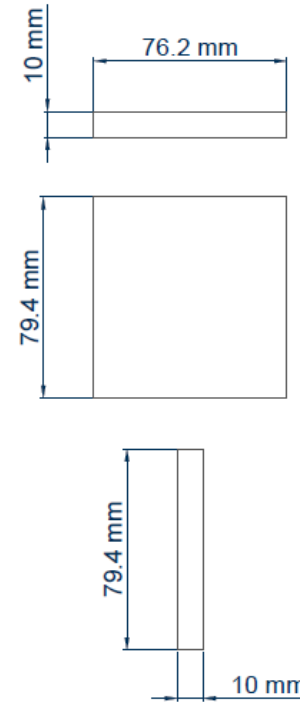
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STRAIGHT FROM BLOCK



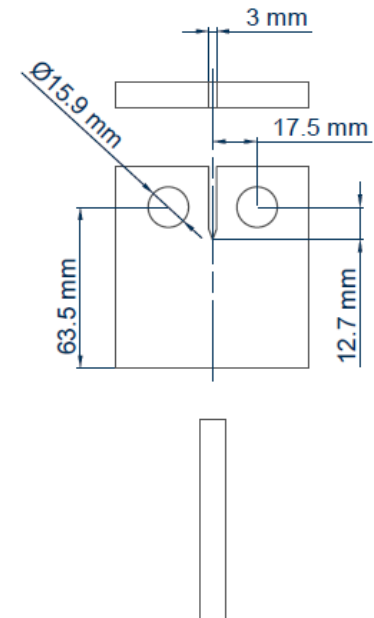
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ACTUAL DIMENSIONS



3. MILLED SAMPLE



4. MACHINE DETAILS
AS SHOWN



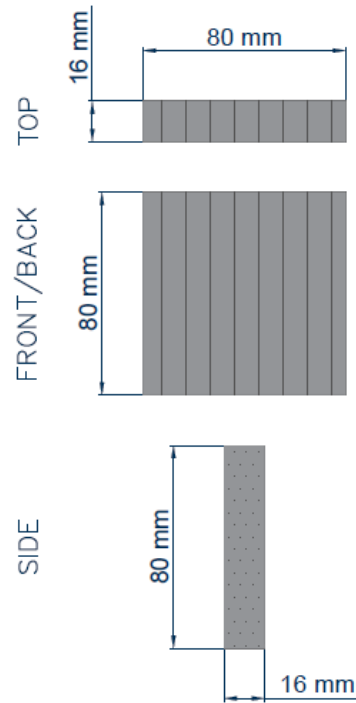
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Revisions			

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Client	

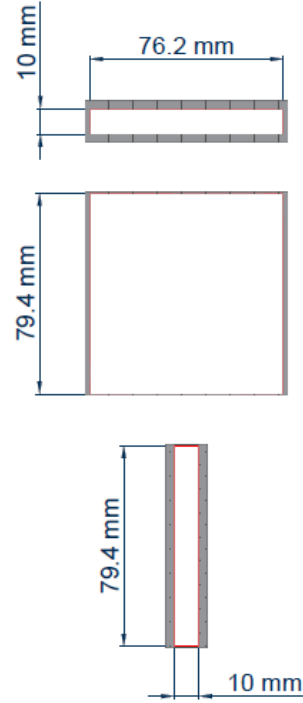


Project	Fatigue & Fracture of WAAM Steel Products
Drawing	Specimen Detail CT (Perp.)
	Scale 1:1.25

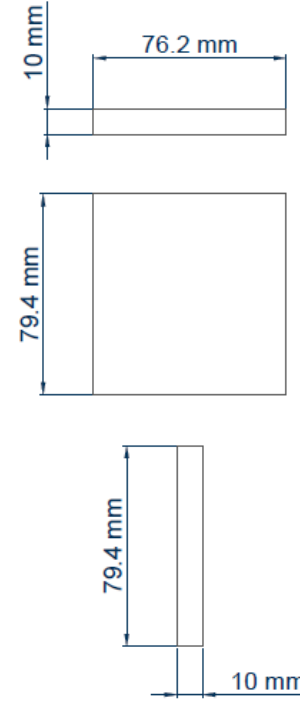
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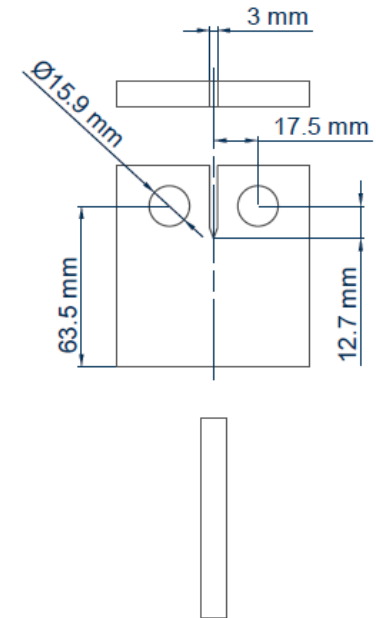
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ACTUAL DIMENSIONS



3. MILLED SAMPLE



4. MACHINE DETAILS
AS SHOWN

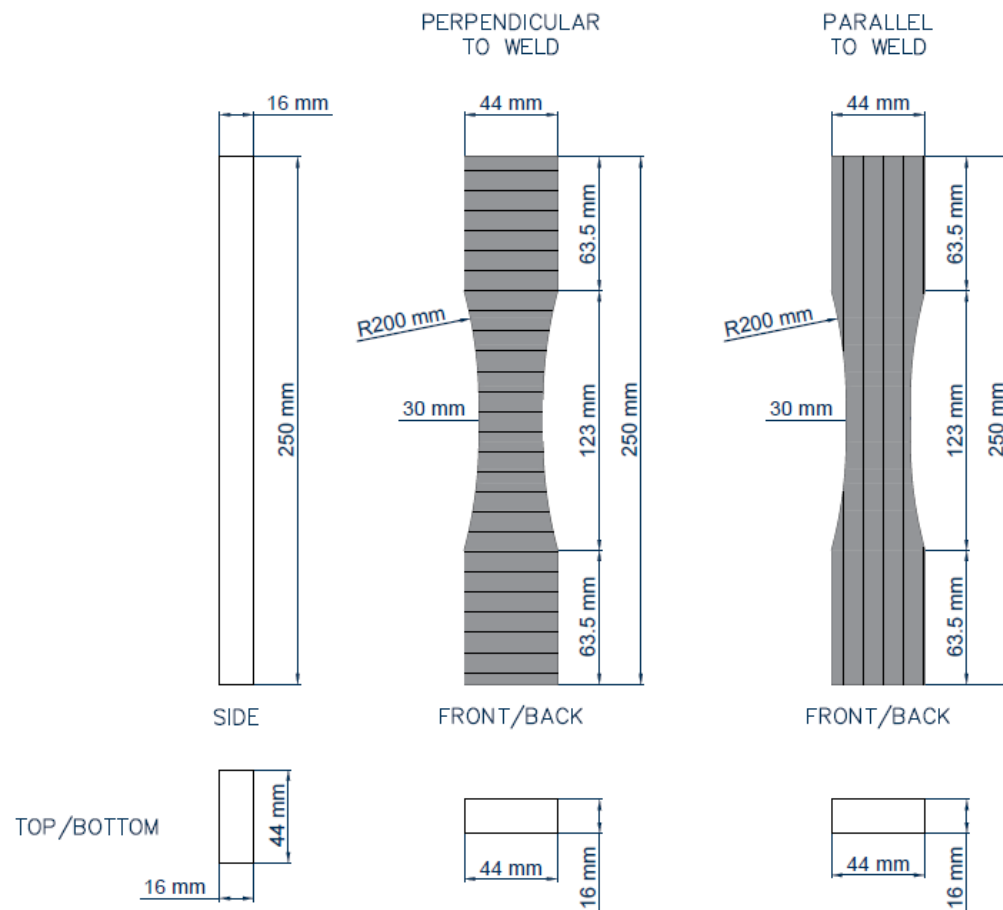


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Revisions			

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Client	



Project	Fatigue & Fracture of WAAM Steel Products
Drawing	Specimen Detail CT (Parallel)
	Scale 1:1.25

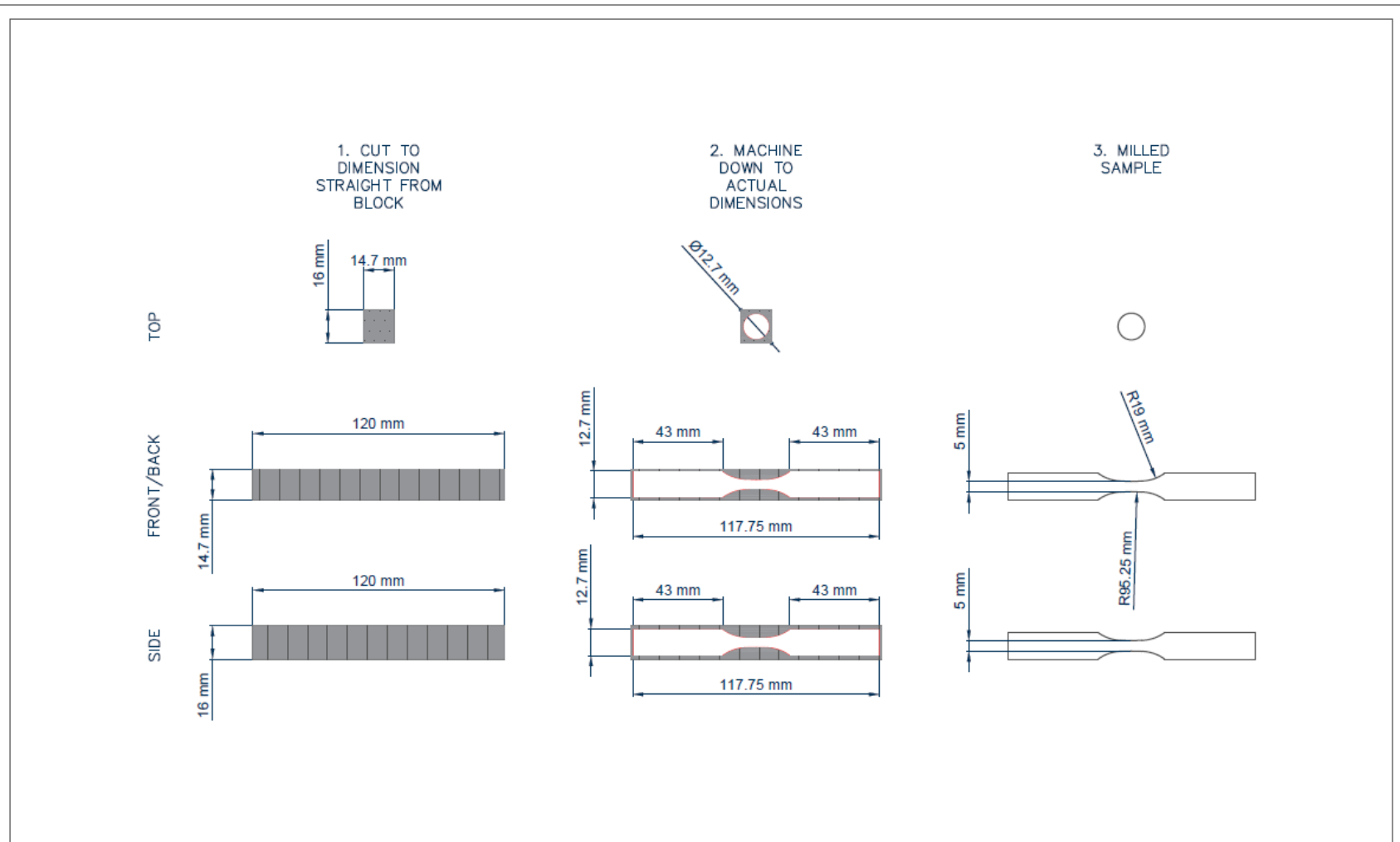


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Revisions			

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Client	



Project	Fatigue & Fracture of WAAM Steel Products
Drawing	Specimen Detail Fatigue
	Scale 1:3



Rev	Note		
00	INITIAL DRAWING RELEASE		10/26
Revisions			

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Client	



Project	Fatigue & Fracture of WAAM Steel Products
Drawing	Specimen Detail Fatigue (Smooth)
	Scale 1:2

Appendix B – Images of Fractured Fatigue (Rough) Specimens

Fractured Specimen

Cross-Section of Crack

B05FRN01



B05FRN02



B07FRN01



B07FRN02



B07FRN03



B07FRN04



B07FRN06



B11FRN01

