

Fatigue of Aluminum Gas Metal Arc Welds in Electric Vehicle Battery Pack

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This paper is co-authored by my supervisor Dr Hamid Jahed, Dr. Andrew Gryguc who is a post-doctoral fellow, Yi-Hsin Chen, Marie Mills, Lisa Pasqualotto, Mingchao Guo, Mario Virgilio Durando, Daniele Rossi, Chandra Thandhayuthapani, Yi Liu, Robert Ruokolainen, Eniyavan Subramanian, Wensheng Zhang, and Justin Hunt who are all members of Stellantis. I wrote the thesis, conducted the lab experiments, the fracture analysis and the finite element modeling. Dr. Jahed and Dr. Gryguc supervised the experiments and gave guidance on how to carry out the analysis and the testing. Alan Woo provided guidance for fixturing methods during welding and mechanical testing and supervised mechanical testing. Yi-Hsin Chen, Marie Mills, Lisa Pasqualotto, Mingchao Guo, Mario Virgilio Durando, Daniele Rossi, Chandra Thandhayuthapani, Yi Liu, Robert Ruokolainen, Eniyavan Subramanian, Wensheng Zhang, and Justin Hunt helped to guide the research which would not have been possible without the help of Stellantis.

Abstract

Aluminum extrusions, when strengthened with precipitation hardening, are an ideal material for lightweight structures. The gas metal arc welding (GMAW) process offers a cost effective and high-volume method of joining mating plates for large structural components. As the automotive industry is looking for lightweight structures to offset the increased weight of electric vehicle battery packs, it is crucial to understand the process limitations and resulting fatigue properties of aluminum GMA welds to ensure the structure outlasts the battery chemistry and warranty.

High volume manufactured aluminum welds are controlled with weld acceptance criteria, which are in turn predicted with statistical representation of randomly tested samples. This research investigated the aluminum GMAW process window that consistently produces welds within the industry partner acceptance criteria and resulting microstructure. This research performed component level testing of 2.3 mm AA-6061-T6 mating plates in the tee joint and lap configurations under quasi static and cyclic loading conditions. The quasi-static testing revealed the influence of porosity on the maximum load before rupture of lap shear joints, and the failure location of the joint and lap joint geometries. The cyclic test results showed crack initiation behavior through the thickness of the heat affected zone (HAZ) when observed by digital image correlation (DIC) during testing. Fracture surface analysis revealed crack initiation zones along existing defects and preexisting cracks attached to the root area of the weld for both tee joint and lap joint samples.

Structural stress methods are employed to correlate far field nodal force and moment derived stresses to the observed failure locations in thin sheet aluminum welds, excluding local effects. Load life data is translated to structural stress life data for 2.3 mm thick tested samples, as well as for additional 4mm and 8 mm thick samples provided by the industry partner. Stress life data is segregated based on a bending stress to total stress bending ratio into two distinct structural stress curves. Power law regression is used to calculate a line of best fit through each curve.

Random samples configurations are excluded from a separate regression, which is used to predict the life of the excluded samples within 3 folds (3x) from tested sample life. Mean stress corrections are used to further collapse test data into single membrane and bending curves but applied thickness corrections increased observed scatter amongst test data.

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1. Introduction

Canada's commitment to achieving net-zero emissions by 2050 underscores the importance of the automotive industry in Southwestern Ontario, a vital contributor to this national goal. As the electric vehicle (EV) revolution accelerates, with Canada aiming for EVs to dominate all new vehicle sales by 2035, the durability and safety of EV battery packs have become critical areas of research. The battery pack, the heart of an EV, demands lightweight yet robust structural components that can endure the vehicle's lifespan, surpassing the chemical degradation timeline of the battery itself. These structures must not only support individual battery cells but also provide a sealed enclosure to contain thermal runaway events. Lastly the structure must be compatible with high volume manufacturing to meet the rising demand for EVs and support the added weight during a crash event.

Aluminum extrusions, due to their high stiffness and strength, have emerged as a key material in meeting these lightweighting objectives. However, the seam welded joints needed for sealing and structural joining are susceptible to fatigue under repeated loading conditions seen during normal road use. The high strength of heat-treated aluminum is further compromised with the heat input during all welding processes. Recent advancements in aluminum GMAW have enhanced the process's stability, addressed common fatigue-inducing defects and increasing compatibility with automation. These improvements position GMAW as a crucial technique for fabricating EV battery enclosures, yet the fatigue behavior of such welds requires thorough investigation to ensure long-term durability and safety, and to update any modeling methods to predict the life of component level designs.

1.1. Objective

The objective of this thesis is to implement and validate the Volvo life estimation method for the fatigue performance of thin sheet aluminum to aluminum gas metal arc welds with modern process optimization, as utilized in electric vehicle battery packs. To achieve this, the thesis will:

1. Conduct a comprehensive literature review on the application of aluminum GMAW in the automotive industry, followed by aluminum fatigue mechanisms and the modeling of aluminum weld fatigue.
2. Optimize GMAW parameters for consistent welds that meet industry partner acceptance criteria.
3. Investigate the fatigue behavior of aluminum GMAW in various cyclic loaded test configurations relevant to EV battery pack structures.
4. Implement numerical methods and FEM to analyze the structural stresses in these welded joints under fatigue loading.
5. Validate the Volvo method for fatigue life prediction and propose any necessary modifications to enhance its applicability to EV battery pack design.

1.2. Outline

Chapter 2 outlines readily available practices for fillet weld design fabrication and fatigue analysis and digs into the recent literature developments for fatigue characterization of aluminum fillet welds. Chapter 3 details the methodologies used in the experimental campaign. Chapter 4 reports the tested weld parameters and resulting optimized parameters for fabricating fatigue test samples, with insights into precipitation hardened aluminum weld microstructure. Chapter 5 outlines the quasi-static and cyclic load testing of lap and tee joint samples, with a fractography overview. Chapter 6 converts the tested load life data into structural stress life and applies corrections for mean and thickness effects to collapse test data into the Volvo method bending and membrane curves. Chapter 6 further verifies the method by predicting sample lives of samples kept out of the regression.

2. Background and Literature Review

This chapter establishes a brief history of the origin and background for Gas Metal Arc Welding (GMAW), and considerations for welding aluminum alloys. Optimization techniques are discussed, as well as the most recent developments and technologies. Fatigue and fracture mechanics behaviors of aluminum seam welds are discussed alongside microstructure influences. Lastly the current methods for modeling the fatigue performance of aluminum GMA welds are discussed. This area is of particular interest to the automotive industry, as aluminum GMA welds offer a comparative lightweight joint when the welding process is properly controlled [1].

2.1. Aluminum Gas Metal Arc Welding

GMAW welding provides high deposition rates and an automation friendly process that continues to be adopted with recent advances in quality control and prediction. The commercially viable process surfaced around 1948, where high current density coupled with a small diameter weld metal electrode protected by an inert or active gas gave rise to the name [2]. GMAW welding can join carbon, high strength, and stainless steels, as well as aluminum, copper, titanium, and nickel alloys. The process is adaptable to construction and semi-automatic applications and enjoys widespread use in the automotive industry due to continued improvements in weld quality and automation integration.

2.1.1. *Process Parameters and Optimization*

In the GMAW process shown in Figure 2-1, the primary goal is to transfer electrode weld material to the molten weld pool, while providing shielding to avoid impurities and slag formation.

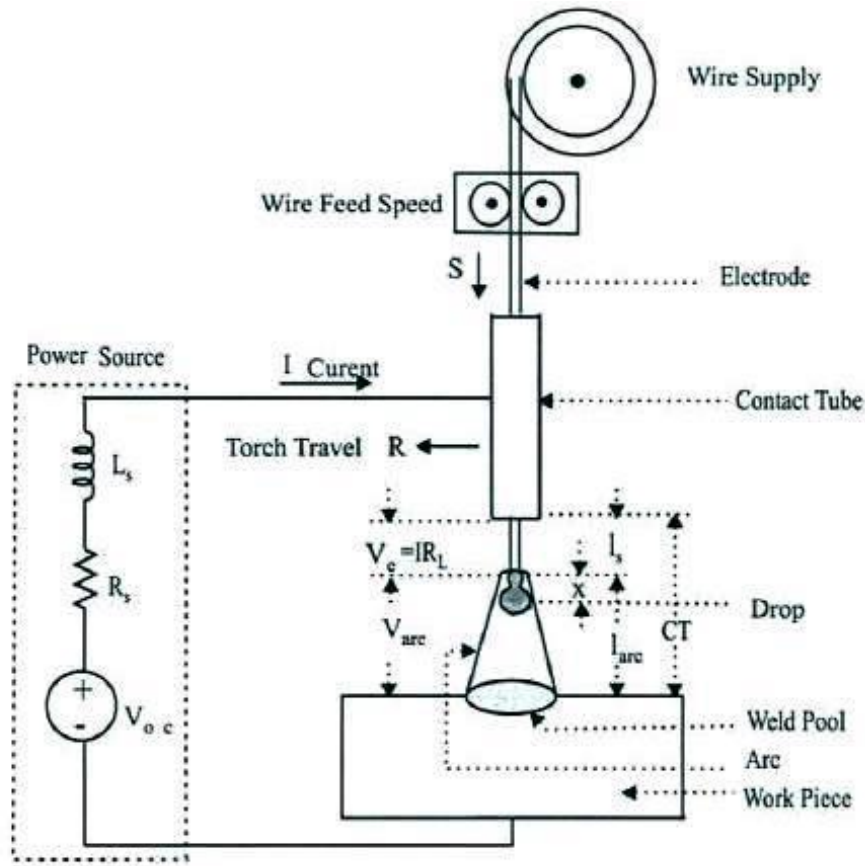


Figure 2-1: Schematic of the GMAW process. Obtained from Bera et al. [3]

The governing process parameters are as follows:

1. Wire feed speed (WFS): WFS controls the electrode feeding rate. The WFS is kept in tandem with current to maintain a consistent arc length.
2. Voltage: Voltage is usually selected as a nominal value based on the WFS. The arc characteristics can be modified for a given process window by increasing or decreasing voltage.
3. Travel speed (TS): TS controls the velocity of the torch. Modifying TS while keeping other parameters constant will have a large impact on the heat input and amount of filler material deposition per unit length of welding.
4. Torch angle and position: The orientation and distance from the torch to the workpiece plays a large role in gas coverage, heat input and weld puddle dynamics. Torch angle is especially sensitive for thin sheet welding.

5. Shielding gas: Shielding gas selection is based on the base material reactivity. Argon and inert gas mixtures are used for sensitive materials, while CO₂ mixtures are used for steel welding.

2.1.2. Metal Transfer Modes

GMAW metal transfer can largely be grouped as free flight or short circuit methods [4]. The mode used is determined by voltage and current, as well as the capabilities of the power supply, as shown in Figure 2-2. Free flight transfer is further divided as globular, spray, short circuiting, or slag protected transfer.

Gravitational, electromagnetic, and surface tension forces all impact material transfer, with some influence from the input current. Projected spray is an attractive transfer mode for automotive applications due to the low splatter and fume levels, coupled with the high heat input and deposition rates the high required current levels generate.

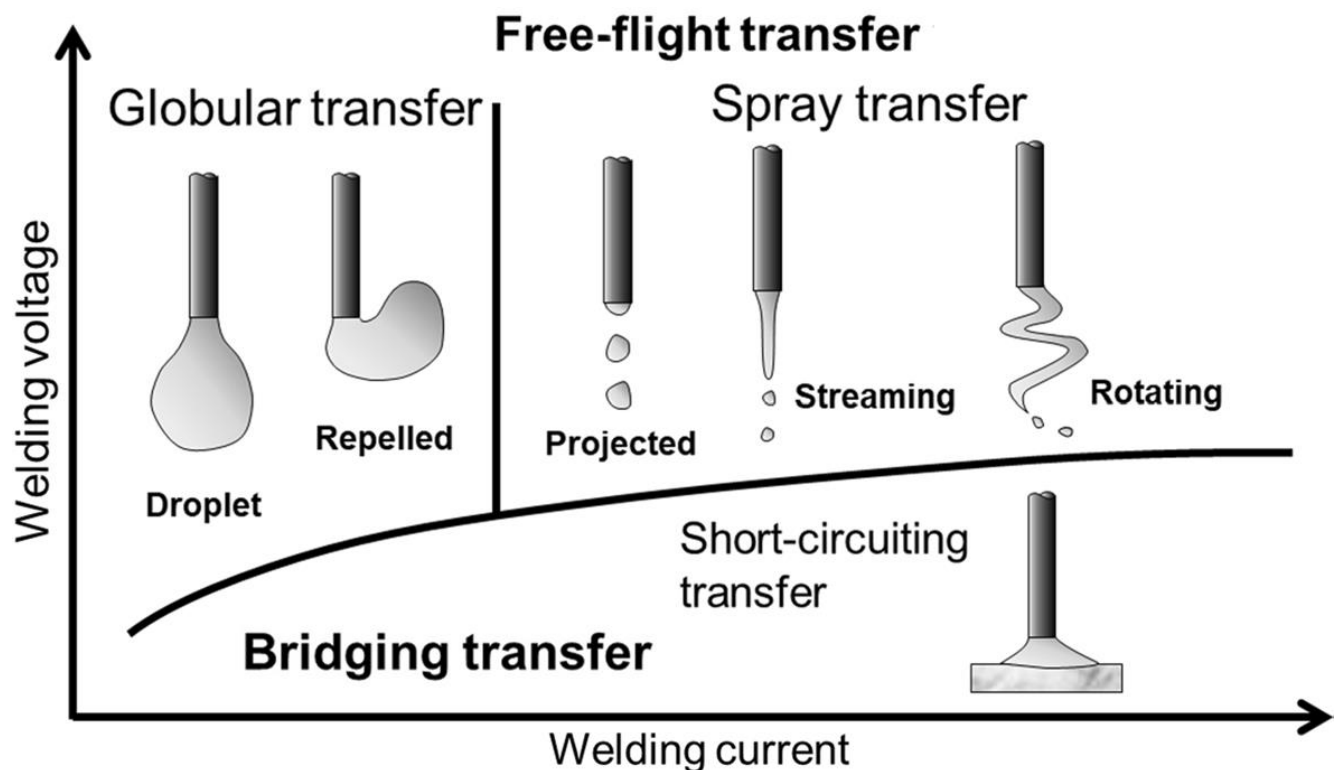


Figure 2-2: Classification of transfer modes in GMAW process. Obtained from Ogino et al. [5]

2.1.3. Technological Advancements and Challenges

Recent GMAW process developments aim to further control material transfer, while improving process stability control and tolerances. Commercial electronic power sources now allow for pulsed spray transfer, which is a key technology to consistently weld thin sheets. Recent advancements in pulsed spray transfer for GMAW have significantly enhanced the control over heat input and metal transfer, particularly benefiting aluminum weldability. Izeda et al. [6] optimized pulsed spray transfer parameters to weld aluminum 6082-T6. By fine-tuning pulse frequencies and currents, the welds exhibited improved mechanical properties and reduced defects, leading to more consistent and higher-quality welds. Zhai et al. [7] studied the effect of additional droplets detaching for a single cycle and a single droplet detaching over multiple cycles. Shallow penetration is observed when multiple droplets are detached in a single cycle, since the droplets are slower and do not have a large impact on the weld pool. Multiple cycle droplets experience overheating, increasing the required current and lowering penetration. One drop per cycle transfers displayed superior weld appearance, deeper penetration, and better mechanical properties compared to other modes. Advancements in droplet transfer control reduce spatter and improve overall arc stability. The use of alternating currents in the pulsed spray transfer of aluminum, such as the Lincoln AC aluminum pulse mode, is important to ensure fusion and puddle control without the additional heat input that causes burn through and distortion [8].

Hybrid Laser Arc Welding (HLAW) is emerging as a separate process that combines GMAW or other arc processes with laser welding. It is discussed in brevity to show the maturation of the GMAW process. Recent advancements in HLAW have focused on optimizing welding parameters to improve the quality and performance of aluminum welds. Du et al. [9] conducted a study on laser-MIG hybrid welding for high-speed train aluminum components. The study optimized welding speed, laser power, and arc current parameters, resulting in weld quality and mechanical property improvements. Xu et al. [10] explored the application of hybrid laser-GMAW in additive manufacturing, highlighting its potential to produce high-quality tailored aluminum components without significant defects.

Aluminum alloys are categorized based on their main alloying elements, each with unique welding challenges. The nearly pure aluminum 1000 series offers excellent corrosion resistance but is soft and has low strength, requiring low heat input to avoid warping [11]. The 2000 series, alloyed primarily with copper, provides high strength but is prone to hot cracking and requires precise control over heat input. The 3000 series, with manganese as the main alloying element, offers good corrosion resistance and moderate strength with porosity challenges. The 4000 series, containing silicon, is often used as filler material due to its low melting point, but results in a brittle joint. The 5000 series, with magnesium, provides excellent weldability and strength but is susceptible to stress corrosion cracking if not welded correctly. The 6000 series, with magnesium and silicon, is widely used for structural applications but requires careful heat management to avoid softening in the HAZ and cracking. The 7000 series, primarily alloyed with zinc, offers the highest strength but presents significant challenges due to its susceptibility to cracking and sensitivity to heat, necessitating precise control over the welding parameters. Finally, the 8000 series, used mainly for specialized applications like electrical conductors, is less common in structural welding and requires attention to its specific alloying elements, which can introduce unique challenges like poor weldability and reduced mechanical properties.

Each series demands tailored approaches in the welding process to overcome its inherent challenges. The general approach to welding each Al series is careful control of the required heat input, as well as careful selection of the filler wire to avoid solidification cracking. The soft nature of 1XXX Al requires a lower heat input to avoid excessive distortion. The increased performance of recent Al GMAW techniques is offset by the growing need for lightweight structures with improved mechanical performance. The foundational and recent developments are summarized in Table 2-1 to show the trend between process improvements and stringent acceptance requirements. The packaging and strength requirements that dictate base plate thickness alter the welding access and power input into the joint. Welded aluminum joints are observed to fail consistently within the softened HAZ [12].

An optimized weld therefore has minimized porosity, a narrow HAZ, and sufficient reinforcement and penetration. Each new thickness must be optimized separately, as the input parameters for the desired penetration will change. Further the welding setup is influenced by the thickness of the plate and clamping conditions, as cantilever supported thin sheets have reduced stiffness to resist thermal deflection and the resulting localized plastic strain [13].

Table 2-1: Available literature for GMA Al welding, detailing process improvements and optimization challenges.

Ref	Authors	Title	Year	Aluminum Alloy	Key Findings
[12]	V Malin, et al.	Study of Metallurgical Phenomena in the HAZ of 6061-T6 Aluminum Welded Joints An area of minimum hardness in the HAZ appears to be the location of initial failure regardless of welding variables	1995	AA-6061-T6	Minimum hardness is adjacent to the FZ in the HAZ. An exposure of 464°C to 716°C removes B' phase and hardness. Weld strength is increased by reducing width of minimum hardness zone and locating it as close to the weld as possible.
[14]	S Subramaniam, et al.	Droplet Transfer in Pulsed Gas Metal Arc Welding of Aluminum Droplet transfer modes in pulsed GMAW of aluminum are identified and a method for characterizing one droplet per pulse is described	1998	AA-4047	Pulse parameters control droplet transfer mode, heat input, droplet size and droplet velocity
[15]	C. Huang, et al.	Liquation cracking in partial penetration aluminum welds: Assessing tendencies to lique, crack and backfill	2004	AA-2024-T351, AA-6061-T651 and AA-7075-	Wavy weld root showed inconsistent penetration in the weld length. The weld metal pulls the PMZ near the weld root.

Table 2-1 continued:

Ref	Authors	Title	Year	Aluminum Alloy	Key Findings
				T651 with AA-1100 and AA-4043	
[16]	P. Praveen, et al.	Meeting challenges in welding of aluminum alloys through pulse gas metal arc welding	2005	Review	Review of dissimilar aluminum to aluminum joining, management of joint thermal conductivity and interfacial reaction.
[17]	P. Praveen, et al.	Advancements in pulse gas metal arc welding	2005	Review	Review of control methods for mean current during the weld process.
[18]	Celina Leal Mendes Da Silva, et al.	The influence of double pulse on porosity formation in aluminum GMAW	2006	AA-5052-F AA-4043	Comparison of pulsed vs double pulsed GMAW welding to explore consistent heat input vs unstable arc dimensions.
[19]	P. K. Ghosh, et al.	Arc characteristics and behavior of metal transfer in pulsed current GMA welding of aluminum alloy	2007	AA-5754	Arc stability at a given voltage through mean current and dimensionless factor of base current, peak current and frequency of pulse modification.
[20]	V. Balasubramanian, et al.	Effect of pulsed current and post weld aging treatment on tensile properties of argon arc welded high strength aluminium alloy	2007	AA-7075 AA5356	Enhancement of 8–10% in strength obtained due to simple post weld aging treatment irrespective of welding techniques.

Table 2-1 continued:

Ref	Authors	Title	Year	Aluminum Alloy	Key Findings
[21]	V. Balasubramanian, et al.	Effect of postweld aging treatment on fatigue behavior of pulsed current welded AA7075 aluminum alloy joints	2008	AA-7075 AA5356	A fatigue life increases of 20-25% is observed in artificially aged samples irrespective of welding techniques.
[22]	V. Balasubramanian, et al.	Effect of pulsed current welding on fatigue behaviour of high strength aluminium alloy joints	2008	AA-7075 AA5356	Pulsed current welding is beneficial to Improve the fatigue resistance of GMA and GTA welds
[23]	V. Balasubramanian, et al.	Effect of pulsed current welding on mechanical properties of high strength aluminum alloy	2008	AA-7075 AA5356	Comparison of GTAW with pulsed and constant current GMAW for WM grain size.
[24]	V. Balasubramanian, et al.	Influences of pulsed current welding and post weld aging treatment on fatigue crack growth behaviour of AA7075 aluminium alloy joints	2008	AA-7075 AA5356	Comparison of GTAW with pulsed and constant current GMAW for fatigue performance, with GTAW smaller grains and larger compressive residual stresses being favorable.
[25]	A. K. Lakshminarayanan, et al.	Effect of welding processes on tensile properties of AA6061 aluminium alloy joints	2009	AA-6061 AA-4043	Intergranular fracture features in GMAW joints from coarse grains in WM and FZ grain boundary segregation.
[26]	H. Guo, et al.	Formation of weld crater in GMAW of aluminum alloys	2009	AA-6005-T4 AA-4043	Rapid solidification of weld pool before arc pressure release results in unfilled crater and solidification

Table 2-1 continued:

Ref	Authors	Title	Year	Aluminum Alloy	Key Findings
					cracking. Crater is filled when current is gradually decreased, and weld direction is reversed.
[27]	V. K. Goyal, et al.	Analytical studies on thermal behaviour and geometry of weld pool in pulsed current gas metal arc welding	2009	Review	analytical model for estimation of temperature distribution in weld pool of pulsed current GMAW process operating at different pulse parameter found to be 10% accurate up to 2 mm away from heat source.
[28]	Rakesh Kumar, et al.	Thin sheet welding of Al 6082 alloy by AC pulse-GMA and AC wave pulse-GMA welding	2009	AA-6082 AA-4047	established electrode negativity ratio effect on penetration depth, with secondary findings of good porosity control from ac cleaning.
[29]	Yao Liu, et al.	Microstructure and mechanical properties of aluminum 5083 weldments by gas tungsten arc and gas metal arc welding	2012	AA-5083	Comparison of porosity in GMAW and GTAW joints, with ac cleaning action resulting in minimal voids and improved mechanical properties.
[30]	P. Kah, et al.	Advanced gas metal arc welding processes	2013	Review	Review of advancements in GMAW welding for thin sheet aluminum structures to avoid

Table 2-1 continued:

Ref	Authors	Title	Year	Aluminum Alloy	Key Findings
					burn through. Strong summary of low heat input welding processes for steel and aluminum.
[31]	Javier A. Vargas, et al.	Analysis of heat input effect on the mechanical properties of Al-6061-T6 alloy weld joints	2013	AA-6061-T6 AA-4043	Transient FEM and experimental correlation on the relationship of between the temperatures reached and resulting Vickers microhardness, yield strength and microstructural changes in the heat-affected zone to within 8%.
[32]	Alan Keith Hellier, et al.	Hardness-Tensile Property Relationships for HAZ in 6061-T651 Aluminum	2014	AA-6061-T651 AA-4043	Vickers microhardness is used to mathematically predict the yield strength of the HAZ and WM areas.
[33]	Yi Lu, et al.	Double-electrode arc welding process: Principle, variants, control and developments	2014	Review	Review of recent double pulse GMAW processes to optimize for an increased deposition rate for the same heat input during the weld process
[34]	Wen Liu, et al.	Investigation on effects of process parameters on porosity in dissimilar Al alloy lap fillet welds	2015	AA-356-T6 AA-7003 AA-5554	Study of welding torch angle and shielding gas composition on porosity, with vertically biased torch positions and He and CO ₂

Table 2-1 continued:

Ref	Authors	Title	Year	Aluminum Alloy	Key Findings
					compositions minimized weld porosity.
[13]	Tapas Bajpei, et al.	Mitigation of residual stresses and distortions in thin aluminium alloy GMAW plates using different heat sink models	2016	AA-5052-H32 AA-5356	Exploration of clamped steel backing plate, compressed air, and argon gas and water mixture as separate heat sink models analytically and experimentally, with the water gas mixture offering the lowest temperatures and least amounts of distortion.
[35]	Zhao Jiang, et al.	Effect of multiple thermal cycles on metallurgical and mechanical properties during multi-pass gas metal arc welding of Al 5083 alloy	2017	AA-5083 AA-5183	Mechanical properties of a non-heat treated aluminum alloy were seen to improve when columnar grains were partially transformed to refined equiaxed grains.
[36]	Belinga Mvola, et al.	Effects of shielding gas control: welded joint properties in GMAW process optimization	2017	Review	Shielding gas mixtures are found to reduce the porosity of aluminum and have an effect on the welding pool behavior.
[37]	Belinga Mvola, et al.	Review of current waveform control effects on weld geometry in gas metal arc welding process	2018	Review	Improving thermal transfer with reduced contact distance and waveform parameters enables stability and high cooling gradients to ensure penetration at higher travel speeds.

Table 2-1 continued:

Ref	Authors	Title	Year	Aluminum Alloy	Key Findings
[38]	Chenxiao Zhu, et al.	Effect of preheating on the defects and microstructure in NG-GMA welding of 5083 Al-alloy	2018	AA-5083 AA-5183	Thick plate welding defects can be reduced by preheating the base plates.
[39]	Isidro Guzman, et al.	Tensile and fracture behavior in 6061-T6 and 6061-T4 aluminum alloys welded by pulsed metal transfer GMAW	2019	AA-6061-T4 AA-6061-T6 AA-4043	Solubilization of base metal alloys instead of aging led to reduced porosity and favorable welding. Minimum hardness values are within 5% so no conclusion can be drawn.
[40]	Isidro Guzman, et al.	Comparative in mechanical behavior of 6061 aluminum alloy welded by pulsed GMAW with different filler metals and heat treatments	2019	AA-6061 AA-4043 AA-5356	Solution strengthened AA-4043 joints presented the strongest joint, with T4 and T6 tempers delivering similar stress when welded with optimized current.
[41]	Addanki Ramaswamy, et al.	Effect of variants of gas metal arc welding process on tensile properties of AA6061-T6 aluminium alloy joints	2020	AA-6061-T6 AA-4043	Comparison of 4 metal transfer modes including cold metal transfer, with a 2% difference in stress compared to a pulse transfer joint.

2.2. Aluminum Gas Metal Arc Welding Fatigue

Aluminum GMAW welds are tested in multiple joint configurations, including butt joints, lap joints, and T-joints. Sample geometry will dictate the type of loading and stress concentrations observed during fatigue testing. Butt joints are formed by welding two plates edge-to-edge in the same plane, commonly used to extract the mechanical properties of a weld metal. Tee joints involve welding a plate perpendicular to another, forming a T-shaped configuration. This type of joint is prevalent in frames and hollow rectangular structures, where the joint must resist bending and shear forces. Single lap joint joints consist of overlapping two plates and welding them along the edge of the overlap. Two plates can be welded to form a double lap configuration, which removes the out of plane bending effect. Single lap joint coupons are useful for studying the fatigue performance under shear loading, and as a mixture of axial and bending loads. Each joint configuration provides unique fatigue characteristics of aluminum GMAW samples, with separate crack initiation locations and stress states.

The fatigue performance of aluminum GMAW welds is influenced by the type of loading applied. Axial loading involves tensile or compressive forces along the axis of the welded joint. Shear loading involves forces acting parallel to the plane of the welded joint. Bending loading occurs when a welded joint is subjected to bending moments, causing tensile and compressive stresses across the weld section. Torsional loading involves twisting forces around the longitudinal axis of the weld. Variable amplitude loading provides similar loading events to real-world service conditions where the load magnitude vary over time. Complex multiaxial stress states also require a separate test configuration for combined loading [42].

Mechanical testing of aluminum GMAW welds for fatigue involves using specialized equipment to apply controlled cyclic loads and measure the response of the welds. Commonly used equipment includes Universal Testing Machines (UTMs) or Electromagnetic Resonance High-Frequency Fatigue Testing Machines for conducting the test. Digital Image Correlation (DIC) Systems measure strain and deformation across the weld surface in real-time, as well as capturing reference images to track the crack initiation cycle.

2.2.1. Microstructure Characterization

Most aluminum alloys are considered weldable with a fusion process, except for 2XXX, 7XXX and 8XXX series that are limited by hot cracking [11]. The welding process involves rapid thermal cycling, which leads to the formation of distinct microstructural zones: the weld metal (WM), the partially melted zone (PMZ), the heat-affected zone (HAZ), and the base metal (BM). The microstructure of aluminum welds influences defect and stress concentration locations and resulting crack initiation, so it is important to consider when defining the weld process parameters.

An overview of the weld area including the WM, PMZ, HAZ, and BM is shown in Figure 2-3 with a focus on the columnar grain structure of the WM. The separate areas in Figure 2-4 offer higher magnification for observation of the WM. The weld metal forms primary dendrite arms that grow from the fusion boundary toward the center of the weld pool, guided by the thermal gradient. Variations in cooling rates or the addition of specific alloying elements influence the development of secondary and tertiary dendrite arms, which alters the solidification morphology. However, achieving a microstructure with equiaxed grains typically requires controlled nucleation conditions, as opposed to adjustments in cooling rates alone.

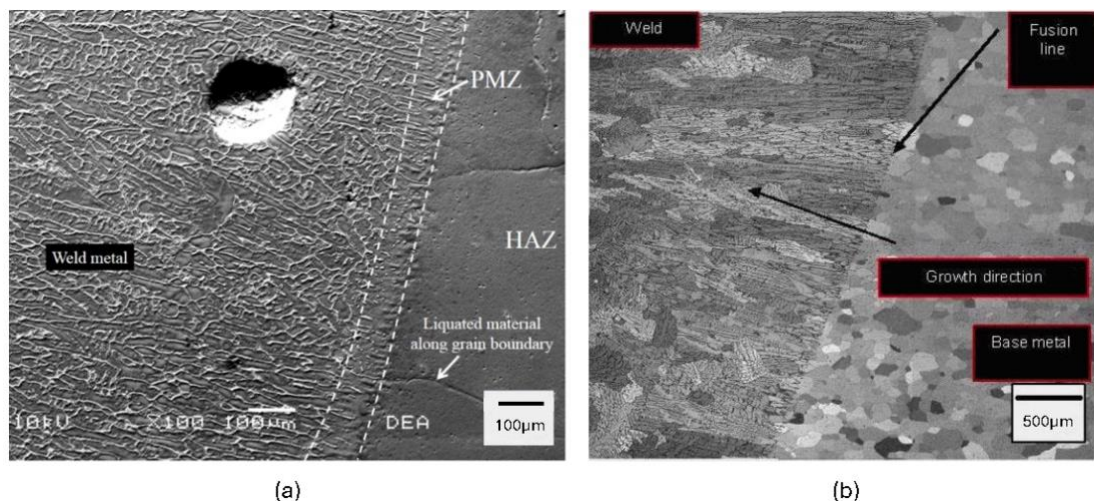


Figure 2-3: a) 100X mag fusion zone overview showing the partially melted zone transition, moving from columnar grains to equiaxed grains. Obtained from [43] b) 500X mag fusion zone overview showing the columnar grains in the weld metal.

Obtained from [44].

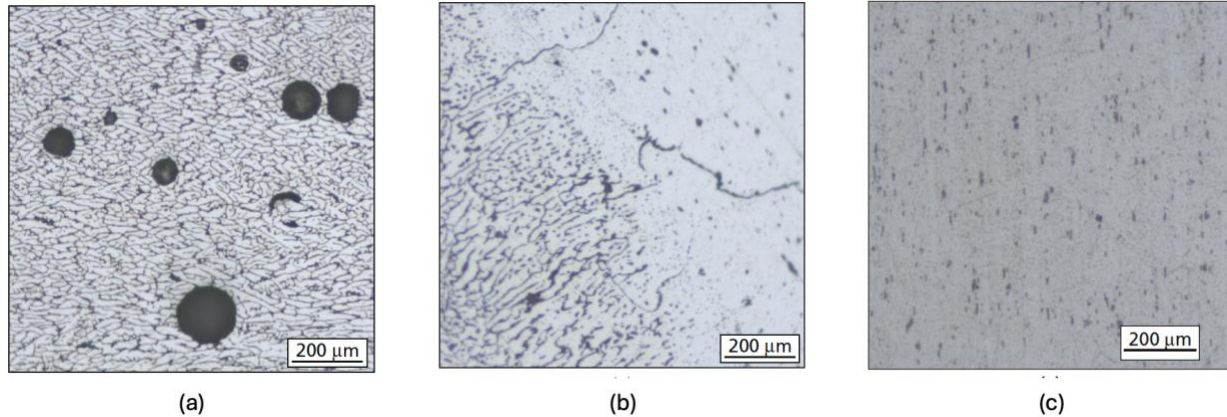


Figure 2-4: Optical micrographs of AA6061 showing the following: (a) Microstructure of the weld pool showing the weld metal column grains with pores interspersed (b) Microstructure of the fusion zone showing the grain boundaries of the partially melted zone, as well as possible segregation of alloying elements. (c) Microstructure of the mating plate with visible precipitates for fusion zone benchmarking. Obtained from [45]

Porosity within the weld metal occurs from evaporating alloying elements, oxide inclusions or trapped hydrogen as shown in Figure 2-5, while gaps form from a lack of fusion or mechanical fit up. The HAZ undergoes microstructural changes as heat is distributed to the base metal. Inclusions and alloying elements with a lower melting temperature migrating to the weld pool boundary at the PMZ as shown in Figure 2-6 can also lead to microcracks when subject to thermal stresses. The HAZ will transition to an elongated grain structure, typical of the rolled base metal. The presence of intermetallic compounds, porosity, and other weld defects further affects the fatigue performance of the welded joints.

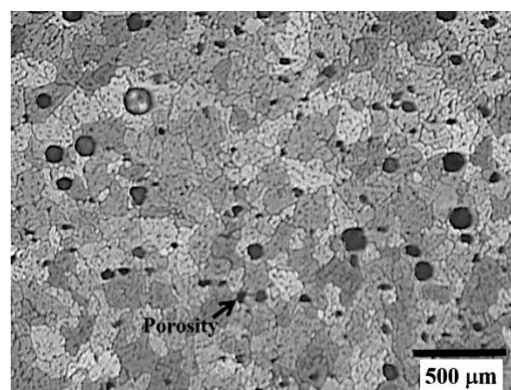


Figure 2-5: Round vapor pores within the weld metal, with no observable gaps. Obtained from [43].

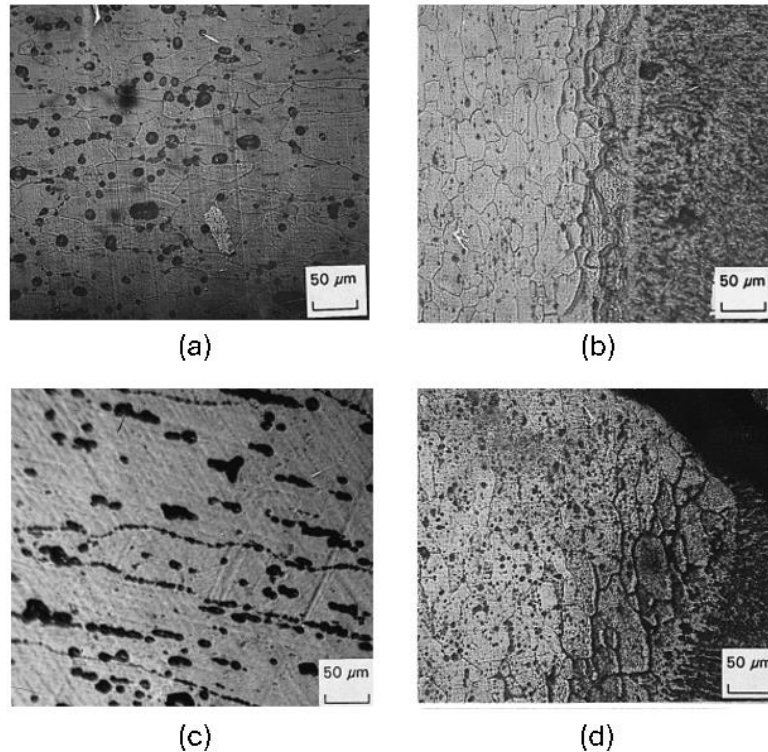


Figure 2-6: a) base metal 5083-H321 showing magnesium intermetallic as a baseline. b) weld metal and mating plate 5083-H321 transition, with segregation at the partially melted zone. c) base metal 6061-T6 showing Mg₂Si precipitates as a baseline. d) welded 6061-T6 showing the alloy element rich grain boundaries of the partially melted zone and overaged precipitates in the HAZ. Obtained from [46]

While grain growth and segregation are common in fusion welding, 2XXX and 6XXX series aluminum base metal face unique challenges with over aging of precipitates in the HAZ near the PMZ. 2XXX series Guinier-Preston zones and 6xxx series Mg₂Si phases are the primary strengthening mechanism, and can dissolve, coarsen, or transform under thermal cycling leading to decreased HAZ hardness. The precipitate condition across the weld and HAZ for 2XXX is shown in Figure 2-7, with 6XXX following a similar trend.

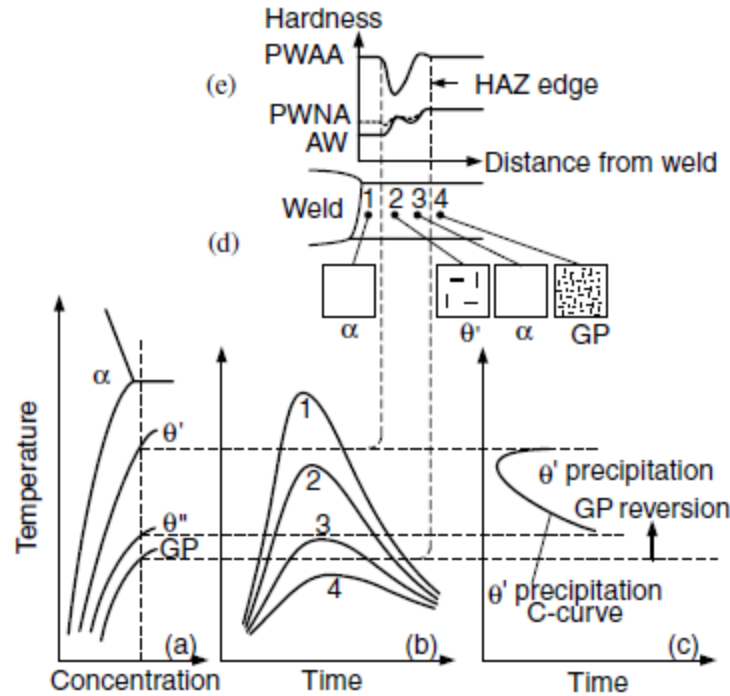


Figure 2-7: Overview of the effects of welding heat input on the FZ and HAZ of precipitation hardened aluminum joints for as welded (AW) and artificially aged (AA) conditions. The reduction of hardness is associated with the transition from solid solution strengthened weld metal to the dissolution of precipitates in the mating plate. Obtained from [47].

2.2.2. GMAW Fatigue Failure

Fracture mechanics is used to characterize the crack growth of aluminum GMAW. The crack initiation phase of aluminum welds is influenced by the non-uniform microstructure and the presence of porosity, root inclusions and other welding defects. Once a crack is initiated, its propagation is governed by the applied cyclic stress and the fracture toughness of the material. Paris' law is often used to describe the fatigue crack growth rate as a function of the stress intensity factor range [48].

Duan et al. [49] focused on the fatigue damage mechanisms of 6082 aluminum alloy T-joints welded using Metal Inert Gas (MIG) welding. The research revealed that fatigue cracks predominantly initiated at pores or root inclusions near the HAZ. Microcracks form along the dendritic grain structure, before branching into a main crack. The study also offered unique insight into hydrogen entrapment and release by the oxide inside the insipient crack.

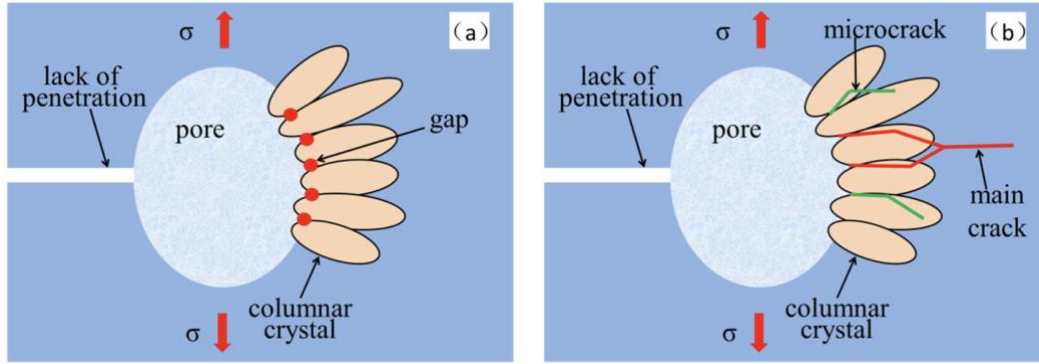


Figure 2-8: Crack initiation mechanism at the root inclusion: (a) fatigue-crack incubation at the HAZ, showing dendrite structure and location of gaps that are prone to crack initiation, (b) intergranular crack initiation from the weld root inclusion. Obtained from [49]

Yang et al. [50] examined the microstructure and fatigue properties of MIG-welded 6005 aluminum alloy lap joints. Cracks initiated both the weld toe and root, points *a* and *b* in Figure 2-9. Single lap joint specimens loaded axially develop an out of plane bending load, which causes the angle between the two plates to increase. The author identified that shear loads acting at point *a* along the *c* to *d* direction increase with increasing angle, which matches the tendency of samples to fail at point *a* or the weld toe for higher applied loads.

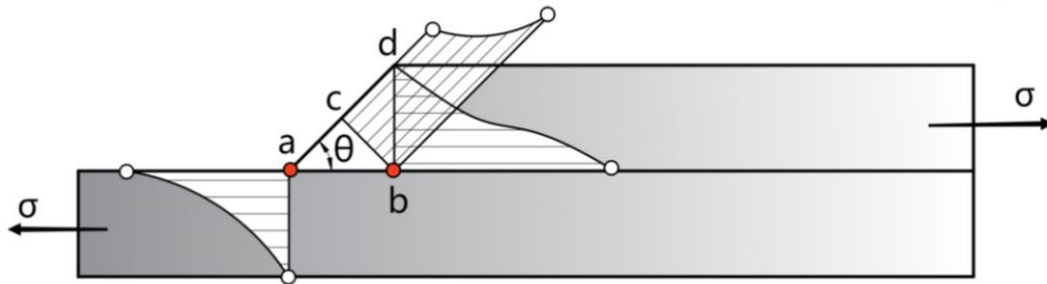


Figure 2-9: Stress distribution field of 6005 lap welded joint during loading, showing predicted stress distributions at weld toe and root stress concentrations. The shear stress along CD increases with applied load and dictates the failure location of lap welded joints. Obtained from [51]

2.3. Aluminum Gas Metal Arc Welding Fatigue Modeling

The International Institute of Welding (IIW) offers validated methods, recommendations, and guidelines for the fatigue evaluation of welded structures [52]. The IIW recommendations encompass S-N curves, modeling techniques, and fatigue assessment methods that range from general statistical validation to parametric consideration of local effects. These methods require varying degrees of geometric detail, and the approaches to stress extraction differ.

The nominal stress approach, known as a global approach, assesses the service life of welded joints by comparing nominal stress amplitudes to experimentally correlated S-N curves [52]. This approach applies material properties, bulk geometrical factors, and weld quality to each S-N curve, allowing for statistical validation of similar designs.

The structural stress or strain approach [52] focuses on evaluating the fatigue strength based on structural stresses or strains at the 'hot spot' near the weld toe. This method does not explicitly consider the notch stress effect of the weld toe. Variants include the structural strain approach proposed by Haibach [52], hot spot structural stress approaches for tubular and non-tubular joints [52], the structural stress approaches proposed by Dong [53], and the Volvo method, named for the partnership between Chalmers university of technology and Volvo Cars and proposed by Fermer [54]. This method is the simplest local approach that assesses a structural member with significantly different parameters than the base SN curve.

The notch stress approach [52] assesses fatigue strength based on fatigue-effective notch stress amplitudes derived from elastic notch stress analysis. It includes variants like the critical distance approach [55] and fictitious notch rounding approach [56]. The notch stress intensity approach assesses fatigue strength based on the notch stress intensity factor amplitudes at the weld toe, considered a corner notch [57]. This approach links to the structural stress and crack propagation approaches, extending assessments from crack initiation to total fracture. It introduces concepts like the J-integral and strain energy density for evaluating fatigue limits.

The crack propagation approach evaluates fatigue life through macrocrack propagation analysis, starting from assumed microcracks and extending to through-thickness cracks [52]. Stress intensity factors derived from notch and structural stresses are used in the analysis. This approach is unique in its detailed examination of crack initiation and growth, providing insights into fatigue life from initial crack presence to ultimate fracture. The method includes numerical integration techniques and considers residual stress effects on crack growth.

2.3.1. Nominal Stress Method

The nominal stress method is a global approach that excludes local stress-raising effects. Stress is extracted at a distance of 2 to 3 times the plate thickness from the stress concentration using linear elastic structural mechanics.

Material testing establishes SN curves for a given material with constant geometry. Additional testing is used to create separate SN curves for each geometry or loading condition, where the local effects are implicitly considered. The resultant SN curves are labeled by the stress value at their endurance limit. A certain degree of misalignment is included in the FAT class, but for non-parallel or offset joints, an additional stress magnification factor must be considered. The nominal stress method is limited by plate thickness and joint angle. Endurance limit classes in the IIW recommendations cover common joints in construction, marine, and shipbuilding industries, which determine the SN curves at 97.7% probability of survival.

2.3.2. Effective Notch Method

The notch stress approach models the total stress at the weld toe and root by including a fictitious notch. IIW recommends a notch radius of 1 mm for steel and aluminum joints. Thin sheets less than 5 mm are recommended to have a radius of 0.05 mm [58]. This radius is originally based on Neuber's micro-structural support theory to account for weld irregularities and non-linear behavior [59]. The notch stress approach idealizes weld geometry, and the evaluated stresses are not directly measurable. SN curves are used in this method based on the reference radius and material.

2.3.3. Structural Stress Methods for Automotive

Destructive testing for variable specific statistical validation is time-consuming, costly, and limits the number of possible design iterations. Numerical methods have been increasingly used alongside physical testing since the 1990s to support an iterative design process with reduced cost and increased durability. Both linear and non-linear FE models have grown in complexity, paralleling advances in computational power.

Fatigue life prediction in the automotive industry began using linear static FE models and load histories from measured test events. Initially, most fatigue failures originated in welded areas, but tools for weld fatigue life predictions were not able to capture the effects in detail. Structural stress approaches were introduced for fatigue life prediction of GMAW for thin steel structures [54]. The approach uses structural mechanics theory to derive stress states from nodal forces and moments at the weld toe.

This method does not require detailed modeling and provides accurate results efficiently, making it popular in the automotive industry. Dong's approach, also known as the Verity method [53], applies a single master S-N curve for various loading and joint configurations. Verity uses a stress correction based on Paris' law from fracture mechanics to combine loading conditions [53]. Commercial fatigue software implements multiple structural stress methods, with Fe-safe offering the Verity method as a solver. nCode and hyperlife utilize the Volvo method.

2.3.3.1. Volvo Method

Structural stresses calculate the normal stress along the weld line to correlate loads with the anticipated fatigue life [54]. The Volvo method was developed to overcome the challenges of determining the stress state at the weld toe and root without being dependent on the mesh configuration. This method extracts nodal forces and moments to calculate the structural stress in elements adjacent to the weld, calculated in Equation 1.

$$\sigma_{\perp}(y) = \sigma_b(y) + \sigma_n(y) \quad (1)$$

Where σ_b is the bending stress along the weld line, calculated from nodal moments, and σ_n is the normal or membrane stress calculated from nodal forces. Nonlinear stresses arising from local weld geometries are not included in this calculation.

Bending and membrane stresses normal to the weld line correlated well with the crack locations observed during experimental testing [60]. A visualization of the effect of each stress is shown in Figure 2-10.

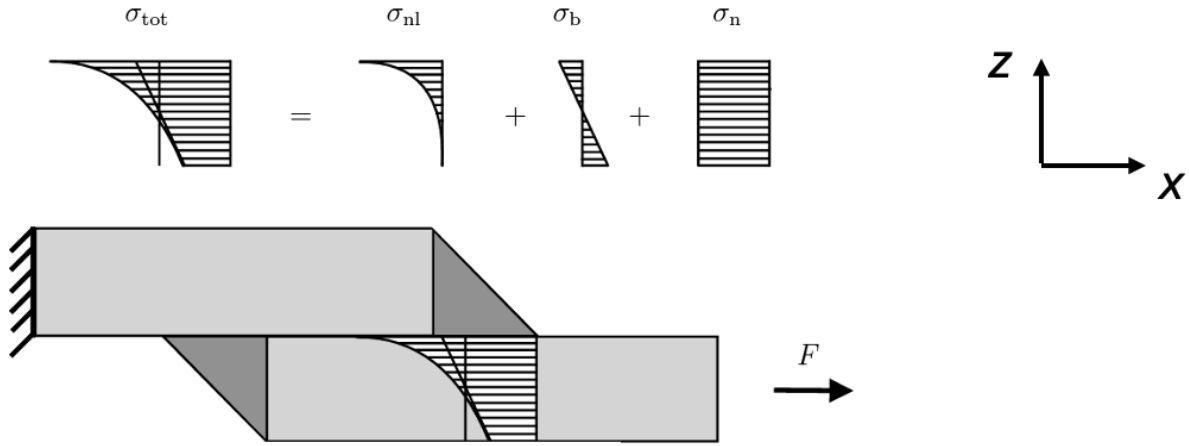


Figure 2-10: Weld toe through thickness stress distribution. Structural stress does not include nonlinear local effect. Adapted from [60].

The complete derivation is available from Fermer et al. [54], where the nodal forces N_x and nodal moments M_y are taken from FEM for any node along the weld root or weld toe. The line moments and line forces are calculated below. Figure 2-11 shows the intended extraction of structural stresses from an FEA model at the elements and nodes of interest, where $E(i)$ marks each element. Figure 2-12 offers an in depth look at the direction of calculated structural stresses and identification of nodal forces and moments along the weld root or toe for a given element. The nodal moments are calculated in Equation 2, and the nodal forces are calculated in Equation 3.

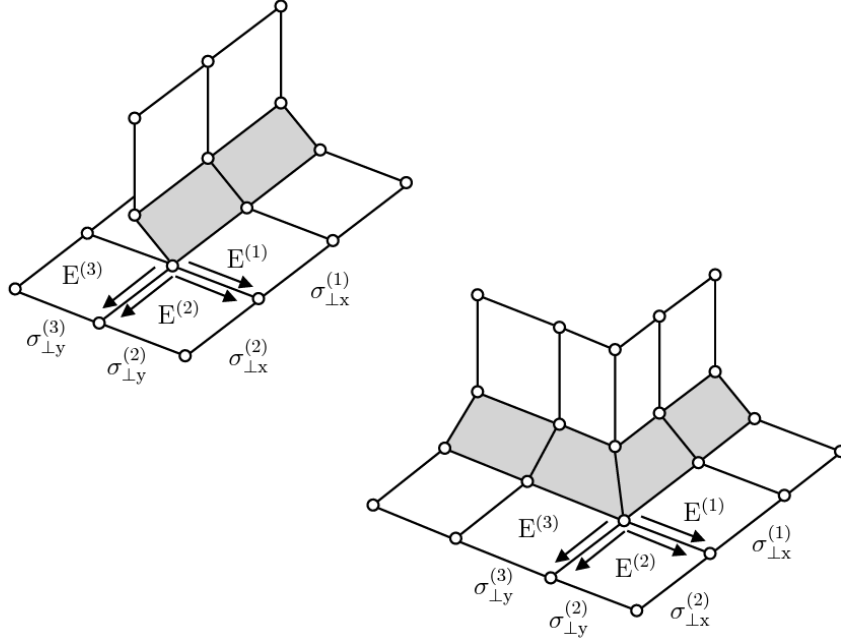


Figure 2-11: Overview of element selection for stress extraction, showing nodal force and moment directions based on weld line direction. Nodal forces and moments are extracted from nodes directly adjacent to grey weld elements. Adapted from [54].

$$m_y^{(i)}(y) = \frac{2}{l_y^{(i)}} \left[M_{y1}^{(i)} \left(1 - \frac{y}{l_y^{(i)}} \right) + M_{y2}^{(i)} \frac{y}{l_y^{(i)}} \right] \quad (2)$$

$$n_y^{(i)}(y) = \frac{2}{l_y^{(i)}} \left[N_{y1}^{(i)} \left(1 - \frac{y}{l_y^{(i)}} \right) + N_{y2}^{(i)} \frac{y}{l_y^{(i)}} \right] \quad (3)$$

Where $l_y(i)$ is the length of the element for a first order element, or the distance between nodes for a 2nd order element, and y is the position along the weld line. i identifies the element and y_1 and y_2 represent the node increment. The bending stress and normal stress calculations based on line forces and moments are shown in Equation 4 and Equation 5 respectively.

$$\sigma_b(y) = \frac{-12m_y(y)z}{t^3} \quad (4)$$

$$\sigma_n(y) = \frac{-n_x(y)}{t} \quad (5)$$

z is the distance through the sheet thickness, t is the total sheet thickness, m_y and n_x are calculated weld line moment and weld line force.

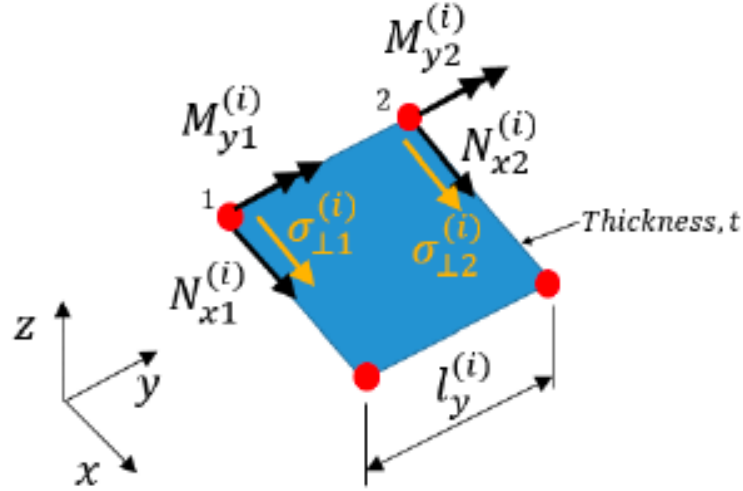


Figure 2-12: Element length, l , thickness, t , and nodal forces and moments in weld toe elements used in stress calculations [61]

The structural stress of the top surface is used to calculate stresses for the weld line nodes of one weld element, where y is the distance along the weld line. The distance along the weld line is used to differentiate the node at $y = 0$ and $y = y$ for a given element, since each node will have 2 stress values, with corresponding stresses calculated in Equation 6 and Equation 7 respectively. The maximum calculated value for each element is used with a maintained sign.

$$\sigma_{\perp}(0) = \frac{-12M_{y1}^{(i)}}{l_y^{(i)}t^2} - \frac{2N_{x1}^{(i)}}{l_y^{(i)}t} \quad (6)$$

$$\sigma_{\perp}(y) = \frac{-12M_{y2}^{(i)}}{l_y^{(i)}t^2} - \frac{2N_{x2}^{(i)}}{l_y^{(i)}t} \quad (7)$$

Load life curves are related to the structural stress to create stress life curves. The Volvo method segments curves into bending dominated S-N curves and normal force dominated S-N curves where the normal force is normal to the weld line.

The Volvo method uses two master S-N curves, one for loading dominated by bending and the other for membrane stress. Experimental testing showed joints loaded in bending generally exhibit higher fatigue resistance compared to those under tensile loading [54][62]. These curves are differentiated by a bending ratio r , calculated as the proportion of bending stress to the total structural stress in Equation 8. The reference curve changes from the stiff membrane stress curve to the flexible bending stress curve at $r > 0.5$.

$$r = \frac{|\sigma_b|}{|\sigma_b| + |\sigma_n|} \quad 0 \leq r \leq 1 \quad (8)$$

It is desirable to present permissible design stress ranges as a combination of test configurations with multiple R ratios. Haigh diagram and mean stress corrections are used describe the combined effects of residual and mean stresses. Traditional approaches often assume tensile residual stresses at the yield limit, leading to the neglect of mean stress corrections[63], [64], [65]. However, stress-relieved or post-weld treated joints show significant mean stress effects, warranting corrections. The IIW recommends a conservative mean stress correction factor, but this does not fully account for beneficial compressive residual stresses, which can enhance fatigue life, especially in post-weld heat treated aluminum welds [60]. The Volvo method makes use of Haigh mean stress corrections, which further collapsed structural stress curves [54].

Thickness effects are studied extensively by Li et al. [66] to tie welding process defects, size effect fatigue theories and loading contributions to the observed thickness effect across fatigue data. Common standards are to apply a thickness correction factor for samples thicker than a reference thickness. The available literature using structural stress methods discussed later in

Table 2-2 show acceptable prediction of 1.5 mm thin sheets, up to 12.7 mm and 20 mm, with the limitation that loading and thickness effects on crack propagation are not independent variables.

2.3.3.2. Applications of Structural Stress Methods

Kang et al. [67], [68], [69] generated the fatigue lives of single and double lap joint, start-stop, butt and perch welded samples to further verify and validate the Volvo and Verity methods for modern AHSS materials. The study found sheet thickness as the most significant factor for fatigue life of single lap samples, with minimal effects from start stop conditions and mean stress. Both stress extraction methods were found to correlate well, with an added emphasis on the importance of capturing manufacturing variability within the scatter of an updated material SN curve.

Lin et al. [70] calculated the fatigue life of a light duty truck frame to find areas with infinite predicted life. Further margin is established by using lower stress life values and increasing the applied loads beyond expected values, to estimate areas that would be jeopardized with a higher stress concentration. Material is removed from areas that maintain infinite life with inflated loads. The original model is solved again with optimized holes once target weight and warranty life are achieved for validation. Song [71] expanded on this method, with proving ground loads from acceleration time history of a test vehicle applied to a baseline truck chassis. The unmodified fatigue life was solved for using the Verity method, with unchanged areas receiving lightweighting holes and another verification of the new predicted life. Wu et al. [72] further explored mesh insensitivity and weighting functions to extract consistent stress values for the Volvo and Verity methods across multiple commercial applications.

Costa et al. [73], [74] correlated proving ground measured component life with a bench test, with further FEA correlation using nCode's built in Seam-Steel SN curve. Acceleration amplitude history is input into a modal transient analysis using time domain, leading to modal stresses and coordinates. Processing with nCode yields an estimated fatigue life comparable with bench and proving ground testing, with initiation in areas with the highest FE reported structural stress.

Wei et al. [75] predicted the fatigue life of single lap joint samples as a comparison between the Volvo and Verity structural stress methods. Both methods were adequate for statistical validation of fatigue life, with the Verity method showing promise for complex loading and multiaxial fatigue parameter fitting.

These studies show widespread adoption of the Volvo method in industry, with comparable performance between the Volvo and Verity methods. Limitations are exposed for averaging the results for each element and considering the start and end effect of the welds. The existing literature summarized in sheets.

Table 2-2 is focused on reporting and validating steel alloys, with a special focus on thin AHSS samples. Therefore, there is a general lack of knowledge on experimental verification and validation of Al GMAW weld Volvo fatigue curves, particularly, for thin sheets.

Table 2-2: Applications of structural stress methods in literature

Ref.	Authors	Title	Year	Method Thickness	Base Material Filler Material Geometry and Load
[54]	Fermer et al.	Fatigue Life Prediction of MAG-Welded Thin-Sheet Structures	1998	Volvo $1.5 < t < 3.0$	Steel Cruciform Joint H Joint
[53]	Dong, P	A structural stress definition and numerical implementation for fatigue analysis of welded joints	2001	Verity Unknown thickness	Steel Butt joint Tee joint Lap joint
[76]	Yoshida	Fatigue life prediction for welded steel sheet structures	2003	Volvo $2.3 < t < 3.2$	Steel Lap Joint
[77]	Potukutchi	Fatigue Analysis of Steel MIG Welds in Automotive Structures	2004	Verity $12.7 < t < 20$	Steel Lap Joint

Table 2-2 continued:

Ref.	Authors	Title	Year	Method Thickness	Base Material Filler Material Geometry and Load
					Tee Joint
[78]	Shiozaki	FE-based Fatigue Life Prediction Techniques for Welded Automotive Structures	2006	Volvo $2.3 < t < 7.9$	Steel Lap Joint Tee Joint H Joint
[79]	Yang	Application of Verity Method to Predict Bushing Fatigue Life and Load Limit	2009	Verity Unknown thickness	Steel Component
[69]	Kang	Application of Fatigue Life Prediction Methods for GMAW Joints in Vehicle Structures and Frames	2011	Volvo and Verity $1.6 < t < 3.4$	Steel Lap Joint Tee Joint
[80]	Wei	Fatigue Life Assessment of Welded Structures with the Linear Traction Stress Analysis Approach	2012	Verity Unknown thickness	Steel Component
[81]	Wei	Comparison of Verity and Volvo Methods for Fatigue Life Assessment of Welded Structures	2013	Volvo and Verity $1.6 < t < 3.4$	Steel Lap joint
[72]	Xiao	A Structural Stress Recovery Procedure for Fatigue Life Assessment of Welded Structures	2017	Volvo and Verity $1.6 < t < 3.4$	Steel Lap joint
[82]	Hong	Application of Weld Fatigue Evaluation Procedure for Considering Multi-Axial Stress States Using the Battelle Structural Stress Method	2017	Verity $t = 8$	Steel Component
[73]	Costa	Frequency FE-Based Weld Fatigue Life Prediction of Dynamic Systems	2017	Volvo Unknown thickness	Steel Component

Table 2-2 continued:

Ref.	Authors	Title	Year	Method Thickness	Base Material Filler Material Geometry and Load
[83]	Lin	A New Weight Reduction Lightening Holes Development Approach Based on Frame Durability Fatigue Performance	2017	Volvo Unknown thickness	Steel Component
[84]	Yang	A Probabilistic Approach in Virtual CAE Fatigue Life Prediction for Components of Exhaust System	2018	Verity Unknown thickness	Steel Component
[85]	Hong	Incorporating Weld Residual Stress Effects into Fatigue Life Predictions using the Battelle Structural Stress Method	2018	Verity t = 4	Steel Weld Material
[86]	Munson	A Finite Element Based Methodology for Combined Crack Initiation and Crack Growth Prediction in Welded Structures	2019	Verity Unknown thickness	Steel Tee joint
[87]	Song	Chassis Lightweight Hole Placement with Weldline Evaluation	2020	Verity Unknown thickness	Steel Component
[88]	Pendse	Fatigue Assessment and Test Correlation of Seam Welded Joints Using Force Based Equivalent Structural Stress Solid Weld Approach	2024	Verity Unknown thickness	Steel Component

3. Methodology

This chapter will outline all weld process optimization and sample creation, fatigue testing, and fatigue modeling setups and methods used to complete the study.

3.1. Material and Sample prep

2.3 mm thickness Al 6061-T6 commercially available sheets are used for base metal. All aluminum sheets were cleaned with acetol and grinded with 80 grit flap disks on the welded edges and surfaces immediately before welding to remove contamination and root inclusions. 1.2 mm diameter ER 4043 filler wire is used for all parameter optimization and sample fabrication. 99.999% Argon shielding gas is used at a standard flow rate of 20 LPM.

3.2. GMAW production

A FANUC Robot ARC Mate 120[®] controls an Electric PowerWave[®] R500 DC electric positive power supply to perform consistent welds for the lap joint and tee joint samples, shown in Figure 3-3. The Precision Pulse mode for 4043 filler wire is used to minimize the required heat input for adequate fusion. Two sets of welded samples were fabricated: lap joint shown in Figure 3-1 and tee in Figure 3-2. Through holes are precut into the tee joint to allow for through sample clamping, which allows for mechanical testing boundary conditions that approximate 6 DOF fixed conditions further discussed in Chapter 5. The lap joint fixture schematic is shown in Figure 3-4, where C clamps are used to prevent large distortion during welding. The tee joint fixture method is shown in Figure 3-5. A total of 56 lap joint and 114 tee joint individual samples were produced and cut out from 43 attempted larger welds with identical parameters. Samples with melt through or an inconsistent root area were kept separate and were not used for fatigue testing. Tee joint samples were doubled due to an adjustment in fixturing during testing.

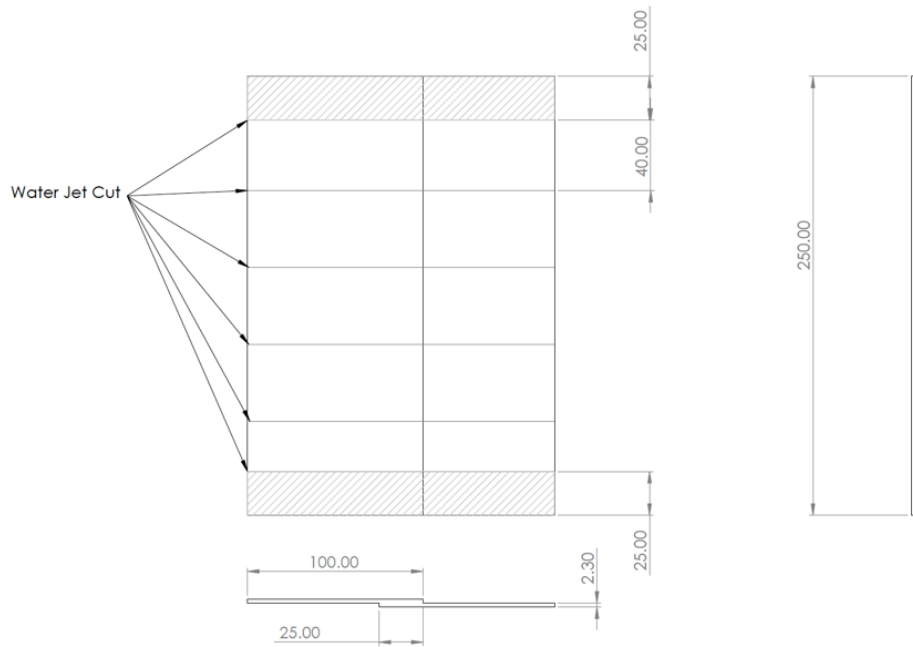


Figure 3-1: larger lap joint and individually cut samples

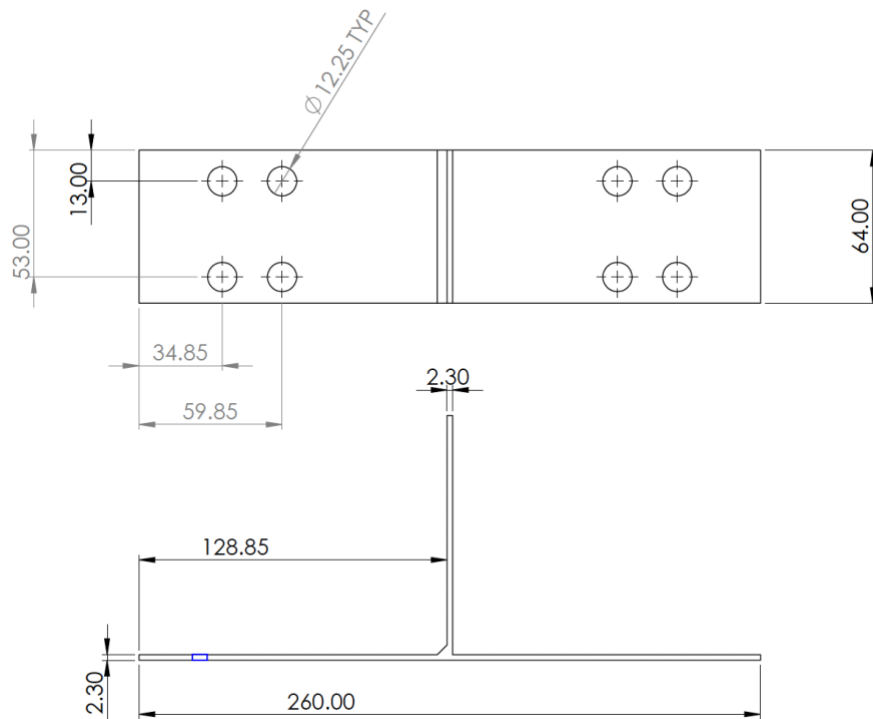


Figure 3-2: larger tee joint and individually cut samples. Clamping holes are precut to avoid tee joint distortion. Slots are used between samples to allow for smooth surface waterjet cutting

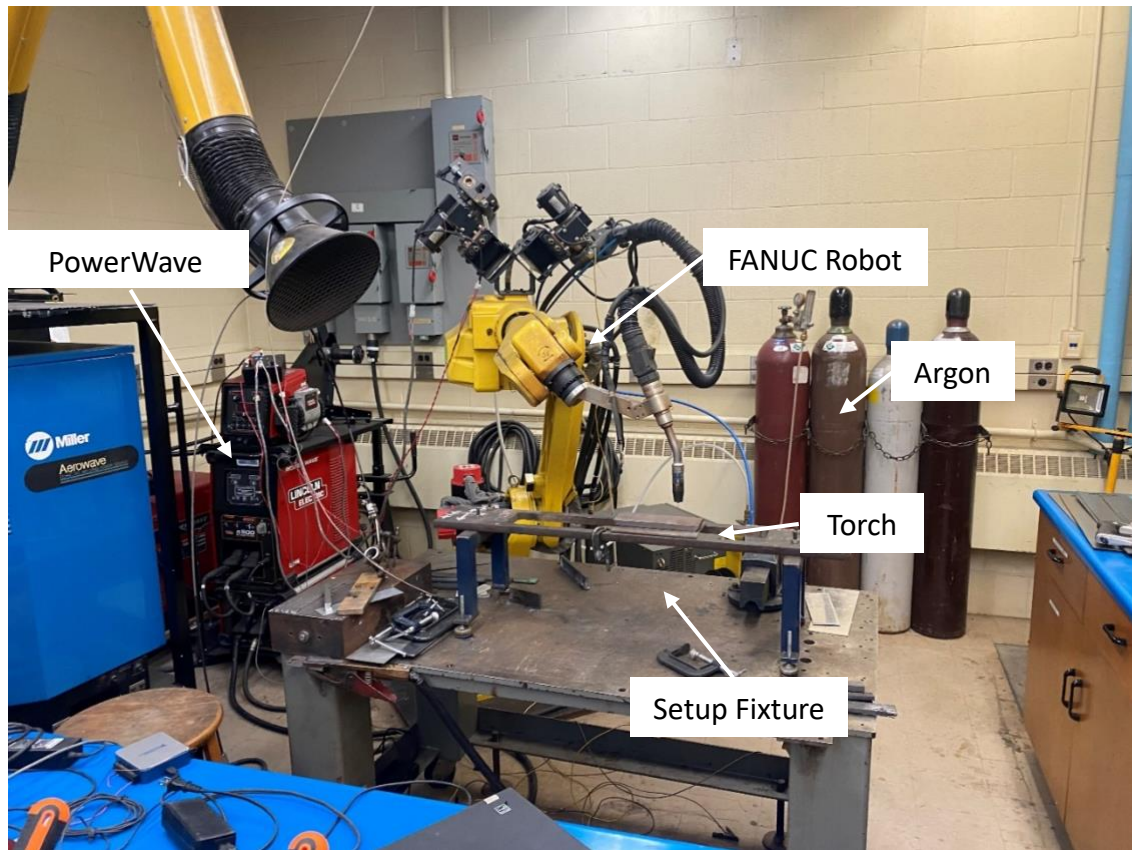


Figure 3-3: GMAW experiment setup showing the 6 degrees of freedom FANUC robot carrying the welding torch and wire feeder set up for 1.2 mm 4043 ER electrode and PowerWave 500 power supply. The grounding cable is attached to the setup fixture as close to the sample as possible during welding. The setup fixture is aligned with the X and Y linear motion axis of the robot. Gas flow is adjusted with a regulator at the tank.



Figure 3-4: Lap joint fixture setup showing the two mating plates clamped rigidly with an overlap. The exposed edge of the top sheet is the location where the linear weld will be applied. Samples with dimensions shown in Figure 3-1 will then be waterjet cut from parent weld.

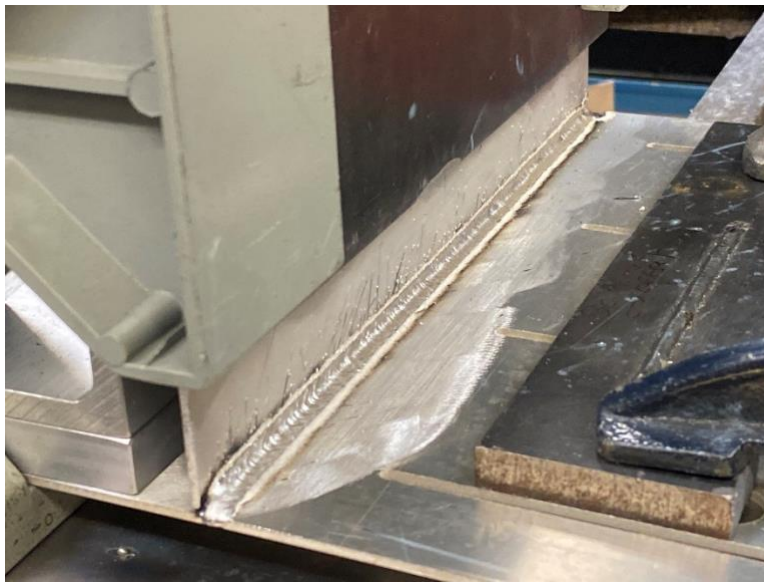


Figure 3-5: Tee joint fixture setup showing the corner clamps and backplate datuming fixture positioning the top mating plate in the center of the bottom mating plate. The top member is rigidly clamped with the corner clamps and stiffened with a front steel plate and aluminum back plate to prevent bowing. The bottom plate is clamped rigidly except for the location where the linear weld will be applied. Samples with dimensions shown in Figure 3-2 will then be waterjet cut from parent weld.

3.3. High-speed imaging and recording data

A Photron Fastcam Mini UX50 highspeed camera is paired with RICOH F2.8/50 mm lenses to focus on the GMAW torch tip for recordings at 3200 fps. This is performed on several tests with optimized parameters to ensure minimal shorting and that consistent penetration had been achieved. A National Instruments Data acquisition system recorded current and voltage data through a multimeter reported through LabVIEW.



Figure 3-6: Welding high speed video setup. Camera is attached to the torch to maintain focus and lighting on the electrode.

3.4. Weld cross section sample preparation and optical microscopy setup

Durofast and Durolast resin is mixed to hold the optical microscopy (OM) cross section samples of tee joint and lap joints during production and weld process optimization. The samples are ground and polished per the aluminum metallurgy guide shown in Table 3-1. Images are captured on a Keyence VHX-7000 series to automatically stitch the images and control sample lighting. Samples are etched with Keller's reagent at 50 ml of water, 10 ml HF, 15 ml HCl and 25 ml of HNO₃ ratios for 20 to 25 seconds.

Table 3-1: Aluminum polishing and grinding guidelines

	Stage 1	Stage 2	Stage 3	Stage 4
Disc	MD- Molto	MD- Largo	MD-Mol	MD-Chem
Suspension	Water	DiaPro Largo 9	DiaPro Mol R3	OP-U
RPM	300	150	150	150
Time (min)	4	4	3	1

3.5. Experimental methodology

3.5.1. Hardness measurement

Hardness measurements start and end over 8 mm into the parent material of both mating plates, traversing through the BM, HAZ, and FZ. Tests are performed with the Clemex CMT using a 200 g indenter load with indent spacing of 300 microns.

3.5.2. Lap joint and tee joint test fixture

A tee joint test fixture was fabricated to perform quasistatic and fatigue testing with boundary conditions as rigid as possible. The fixture shown in Figure 3-7 has the sample resting flat against the fixture when unloaded. The final geometry has a support distance of 49.5 mm from the top base member to the fastened support. Each end is fixed with 4 M12 bolts that pass through the welded sample. The lap shear is inserted with 2.3 mm thick 40 mm by 40 mm shims directly into the load frame grips as shown in Figure 3-8. Misalignment in the samples and the test fixture were minimized by utilizing lap shear shims and a datuming fixture for tee joint top plate placement with a tolerance band of ± 0.2 mm.

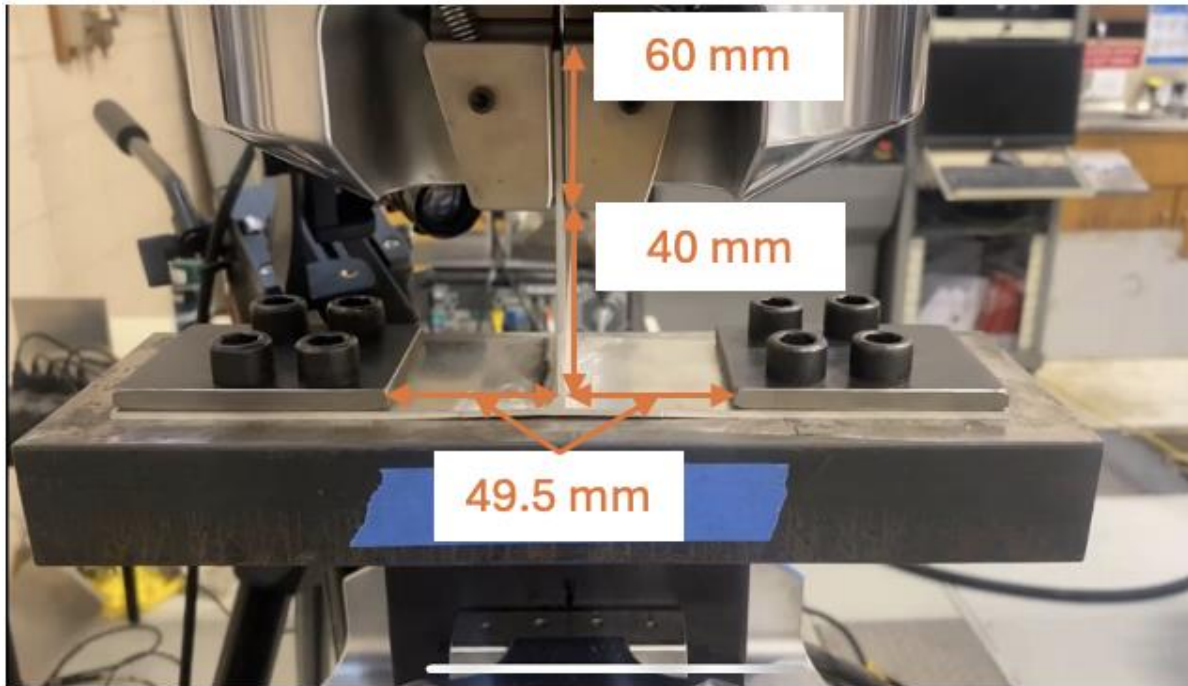


Figure 3-7: Tee joint 2.3 mm Fz test configuration, where the sample is first gripped and centered with the upper grip before the bottom clamps are applied.

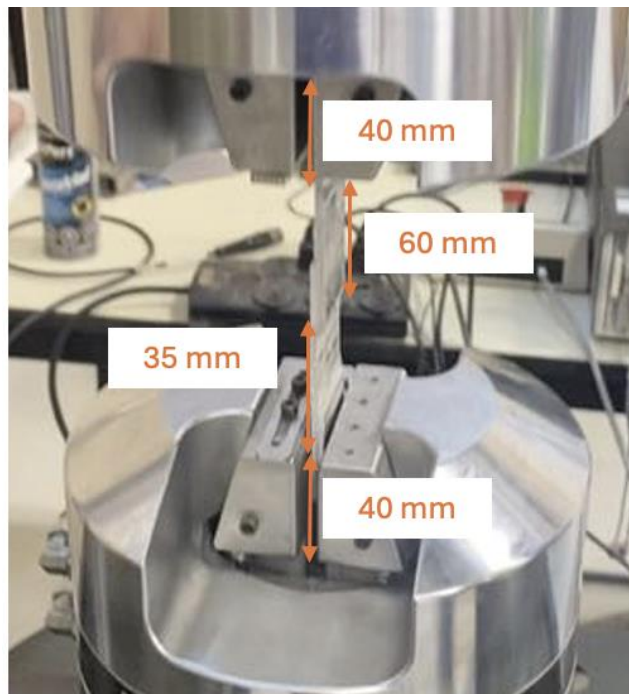


Figure 3-8: Lap joint 2.3 mm Fx loading configuration, where 2.3 mm thick 40 mm by 40 mm shims are applied to sample ends and fully covered by load frame grips. The Dimensions shown measure the distance to the weld root, with the top mating plate root to support distance of 60 mm.

3.5.3. Quasistatic test procedure

An MTS Landmark servo hydraulic model 370.10 test system with 100kN load capacity is used for both lap joint and tee joint specimens. Quasistatic tests are used to verify fixturing and estimate fatigue load levels. Tests were performed in displacement control at a rate of 2 mm/min with a final target displacement of 5 mm for lap joint and 20 mm for tee joint.

3.5.4. Fatigue test procedure

The MTS Landmark 370.10 is used for fatigue testing under load control. Test frequencies ranged from 5 Hz to 20Hz depending on load level and geometry. Cycles to failure were reported by observing with correlated systems cameras to capture crack initiation and propagation of 1 mm. Tests were run until sample fracture or runout of 2,000,000 cycles.



Figure 3-9: Camera setup for lap joint start and end recording during fatigue testing for crack initiation and propagation recording.



Figure 3-10: Camera setup for tee joint start and end recording during fatigue testing for crack initiation and propagation recording. Cameras are mounted on tripods for further stability during recording.

3.6. Fatigue Model

The material and GMA welding process is characterized by predicting the stress life of a loading history. The damage accrued for one cycle is given by stress-based approaches, with modifying factors. The Volvo method described in detail in Chapter 2 provides structural stresses for thin sheets that correspond well to observed failure modes, where cracking along the normal direction of the weld dominates. Utilizing existing correction factors provides an improved fit of tested load life data into discrete structural stress vs life curves.

4. Aluminum GMAW weld process development and optimization

This chapter outlines the material preparation, process window development and fabrication of test samples.

4.1. Coupon geometries and configurations

Lap shear and tee joint samples are produced with 2.3 mm extruded Al 6061-T6 flat bar. A minimum of 50 samples are produced for quasistatic and fatigue testing, as well as reserve samples for duplicate tests as a contingency for weld quality inconsistencies. The geometries and layout of the specimens cut from the welds are shown in Figure 4-1 and Figure 4-2.

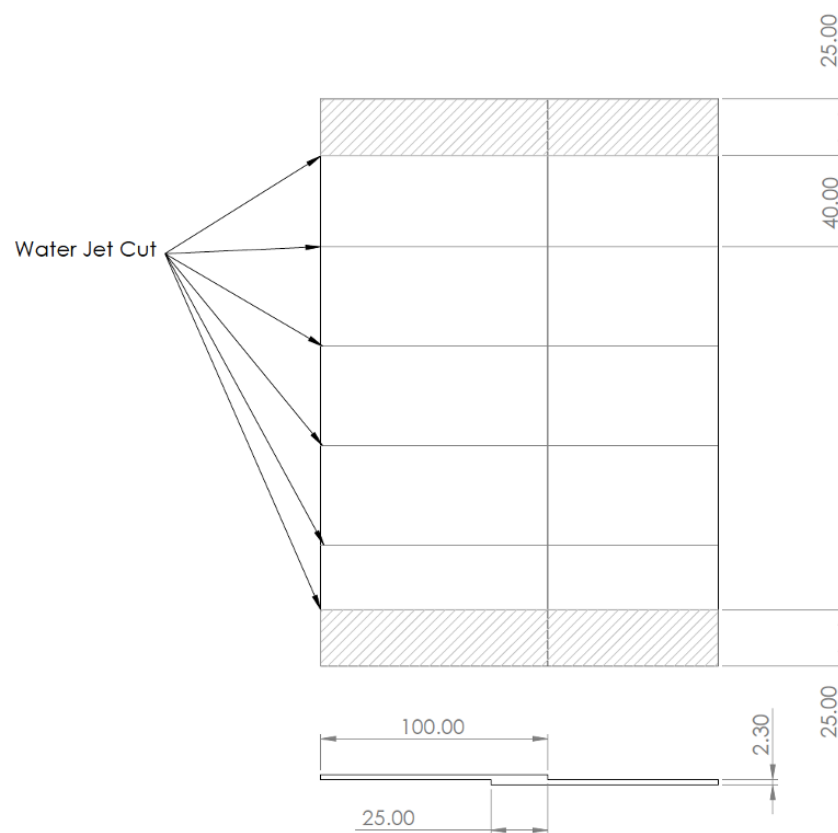


Figure 4-1: 2.3 mm thick lap joint sample geometry for University of Waterloo testing

[illegible]

4.2. Design of Experiment for Optimization and Process Window

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4.2.1. Melt Through

Melt-through, also known as burn-through, occurs when excessive heat input causes the weld pool to penetrate through the entire thickness of the material, creating holes in the base material above the weld. To address this defect, the following parameters were varied. The electrode position is established by ensuring consistent fit up of the base metal to avoid warping or significant thermal expansion. A steel front plate and aluminum backing plate are used to stiffen the top plate and datum the top and bottom base metal in the fixture. The electrode position is kept at a consistent distance to avoid dragging or flexing during movement.

Initial variation of parameters resulted in insignificant reduction of burn through with reduced voltage and current values for heat input. Increasing work and travel angles decreased observed burn through, resulting in a planned DOE with 5-degree angle increments.

4.2.2. Inconsistent Penetration

WM penetration is used in industry as a weld process target to ensure maximum reinforcement. Penetration is given as a percentage of weld metal fusion into the mating plate as a percentage of thickness, which modifies the fracture location and root effects as shown in Figure 4-3. This thesis is using a penetration target range given by the industry partner.

Consistent penetration across the width of individual samples is crucial to characterize the mechanical performance of minimum and target penetrations in Chapter 5. Consistent penetration is controlled by adjusting contact distance and Ultimarc parameters to ensure a consistent arc and metal transfer.

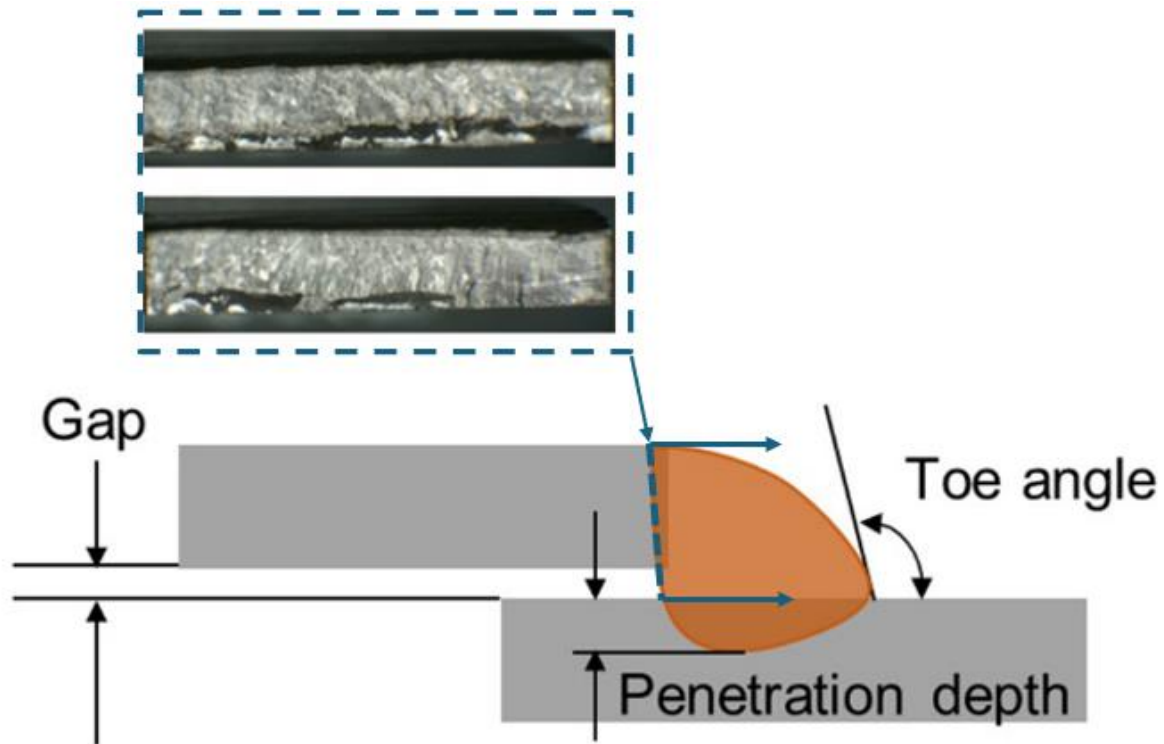


Figure 4-3: Diagram for joint penetration as a percentage of WM penetration distance to mating plate thickness. Obtained from [89].

A short contact distance in pulsed spray transfer can result in short circuits, where the bead & electrode are in constant contact. Further contact distance leads to excess deposited weld material with low arc heat, as the current required to melt the wire decreases. This parameter can be directly tuned, moving the electrode closer with multimeter monitoring until consistent shorting is observed as shown in Figure 4-4, alongside a linked high-speed video of droplet transfer. The Ultimarc parameter for ac aluminum pulse adjusts the frequency of the waveform, with noticeable effects on the heat reducing negative background phase. This parameter is optimized in tandem between maintaining arc stability with higher values and reducing melt through with negative values. As the melt through problem is optimized with a separate set of parameters, waveform frequency is primary used for arc stability.

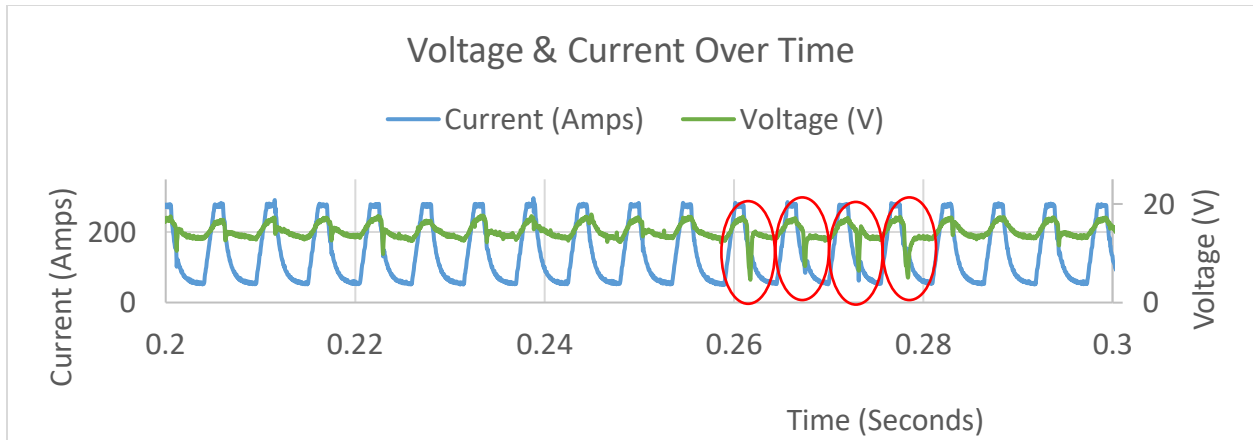


Figure 4-4: Current and voltage during pulsed spray transfer at 13 mm contact distance, with observed short circuits highlighted in red. The number of acceptable short circuits was established by cross section examination of welded joints across the sample width. High speed video of pulsed spray transfer welding of Al6061-T6 with 4043ER filler wire, to show complete pulse without shorting. Also available <https://youtu.be/p9dycoSpuBY>

4.2.3. Porosity and root inclusions

Porosity is observed as voids distributed throughout the weld metal. Oxide inclusions are a separate mechanism where base metal oxide contributes to larger vacancies, usually observed at the root of the weld. The base metal is originally cleaned with a steel wire brush followed by an acetone wipe. After detection of root inclusions, a flap disk & angle grinder are used to remove the oxide from the base metal surfaces & edges in contact with the weld pass.

Gas coverage levels are optimized after work & travel angle parameters are set by adjusting the flow rate of the tank regulator. A fractional factorial guided by the influence of parameters on the defects listed in Table 4-1.

Table 4-1: List of weld process parameters modified during design of experiment.

Sample #	trim	WFS (IPM)	TS (IPM)	WA (deg)	TA (deg)	UA	CTWD (mm)
1	0.8	280	40	45	10	-1	17
2	0.85	280	40	45	10	-1	17
3	0.9	280	40	45	10	-1	17
4	0.9	240	35	45	10	-1	17
5	0.92	240	30	60	15	-1	17

Table 4-1 continued:

Sample #	trim	WFS (IPM)	TS (IPM)	WA (deg)	TA (deg)	UA	CTWD (mm)
6	0.92	240	30	60	15	-1	17
7	0.92	240	30	60	20	-1	17
8	0.85	240	30	60	20	-1	17
9	0.8	240	30	60	20	-1	17
10	0.8	210	30	60	20	-1	17
13	0.83	225	30	60	20	-1	17
12	0.83	225	30	55	20	-1	17
14	0.83	225	30	60	25	-1	17
11	0.83	225	30	50	20	-1	17
15	0.83	225	30	60	25	-1	17
16	0.83	225	30	60	25	-1	17
17	0.83	225	30	60	25	-1	17
18	0.9	210	30	60	25	-1	17
19	0.9	210	30	60	25	-1	17
20	0.9	210	30	60	25	0	14
23	0.9	210	30	60	25	1	14
24	0.9	210	30	60	25	1	14
25	0.9	225	35	60	25	1	14
26	0.9	225	35	60	25	0	14
27	0.9	240	40	60	25	0	14
29	0.9	240	35	60	25	0	14
30	0.9	240	37	60	25	0	14
31	0.9	240	37	60	25	0	14
32	0.9	240	37	60	25	0	14
33	0.9	240	37	60	25	0	14
28	0.9	210	30	60	25	0	14
21	0.9	210	30	60	25	2	14

Table 4-1 continued:

Sample #	trim	WFS (IPM)	TS (IPM)	WA (deg)	TA (deg)	UA	CTWD (mm)
22	0.9	210	30	60	25	4	14
34	0.9	240	37	60	25	0	14
35	0.9	240	37	60	25	0	14
36	0.9	240	37	60	25	0	13
37	0.9	240	37	60	25	0	12
38	0.9	240	37	60	25	0	10
39	0.9	240	37	60	25	0	13
40	0.9	240	37	60	25	0	13
41	0.9	240	37	60	25	0	13
42	0.95	270	37	60	25	0	13
43	0.88	234	37	60	25	0	13
44	0.88	234	37	60	25	0	13
45	0.88	234	37	60	25	0	13
46	0.9	235	37	55	25	0	13
47	0.9	235	37	55	25	0	13
48	0.9	235	37	55	25	0	13

Table 4-2: Weld parameters from weld process DOE for lap joint and tee joint to optimize for consistent penetration levels of 50%, representing a characteristic weld in line with industry acceptance criteria.

Parameter	Value
Material	2.5mm Al 6061-T6 -> 2.5mm Al 6061-T6
Electrode	1.2mm 4043
Mode	Lincoln Pulse 4XXX "72"
Contact Tip to Work Distance	13 mm
Work Angle	55 degrees (from vertical plate)
Travel Angle	25 degrees
Wire Feed Speed	235 in/min
Trim	0.90
Travel Speed	37 in/min

4.3. Microstructure characteristics of welds

Cross section samples for the lap joint shown in Figure 4-5 and the tee joint shown in Figure 4-6 are used to establish points of interest within the microstructure. The root of the weld is of particular interest as the source of crack initiation, as discussed in chapter 2. Further, precipitate over aging and grain growth within the HAZ is predicted, as well as a columnar grain structure within the weld metal. Low magnification overviews of etched samples for the lap joint in Figure 4-7 and the tee joint Figure 4-8 show a clear demarcation of the FZ, alongside inclusions or root porosity at the weld root for both the lap joint and tee joint.

The WM exhibits a dendritic grain structure consistent with Al GMA welds in both the lap joint in Figure 4-10 and the tee joint in Figure 4-9. The HAZ shows a gradient of microstructural changes, transitioning from the coarse dendritic structure of the weld metal to the finer, more equiaxed grains typical of the base metal. Peripheral coarse grain layers were not observed.

The presence of porosity and inclusions within the weld metal, particularly at the weld root, highlights potential issues with gas shielding and oxide or environmental contamination during the welding process. The Inherent gap that exists between two plates joined in the GMAW process results in transient and heterogeneous heat transfer between the material that further affects dendrite solidification and the resulting grain structure in this area.

Comparing the microstructures of the lap shear and tee joints, distinct differences at the weld root are observed. The lap shear joint displays a more pronounced dendritic structure with a higher density of porosity and inclusions, which could be attributed to the overlapping configuration that complicates gas flow and heat distribution. In contrast, the tee joint exhibits a finer dendritic structure at the root, with fewer but larger pores, suggesting a different solidification dynamic and path of gas flow. The phase distribution in both joint types is dominated by aluminum dendrites with inter-dendritic regions occupied by lower melting point alloying elements.

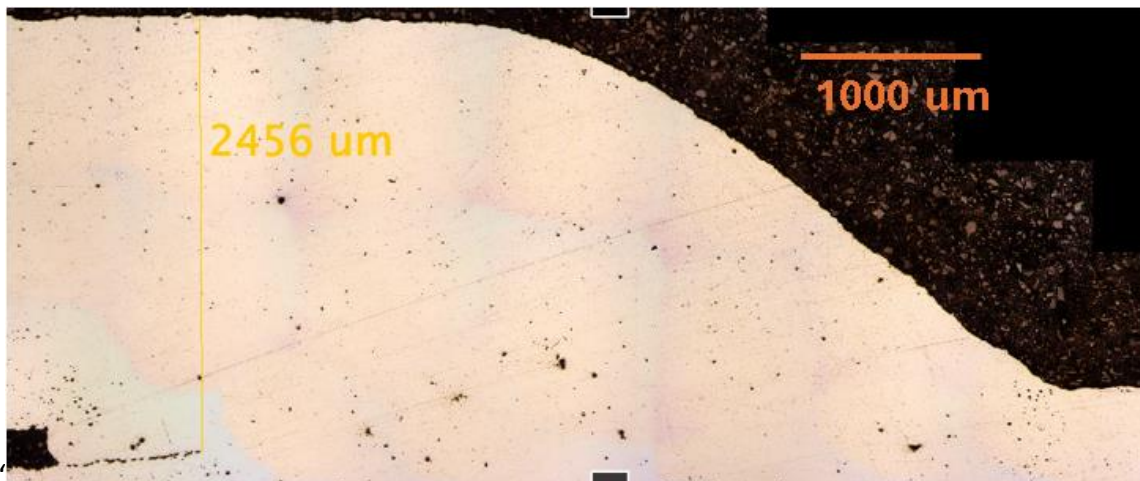


Figure 4-5: Lap joint cross section providing geometry and site locations for further inspection.

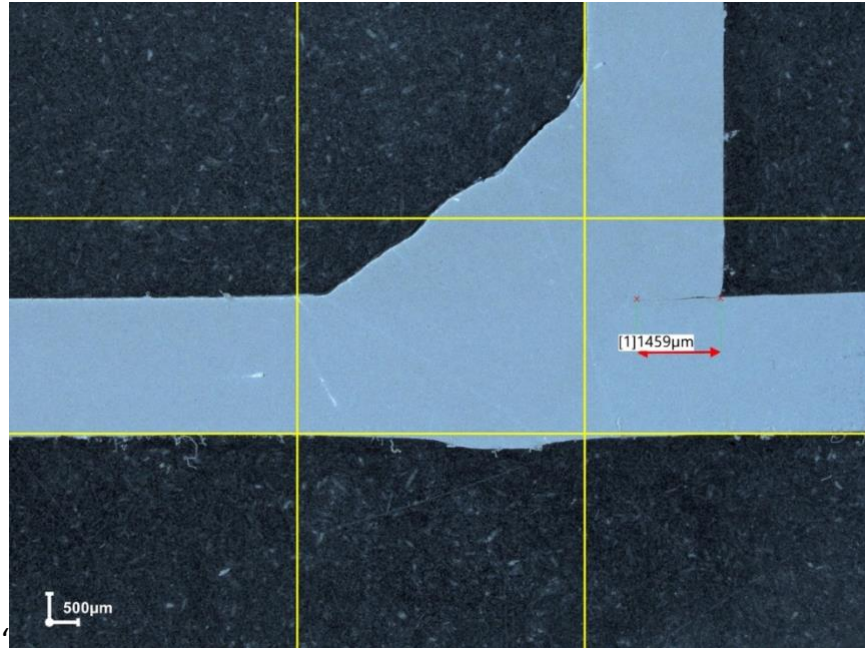


Figure 4-6: Tee joint cross section providing geometry and site locations for further inspection.

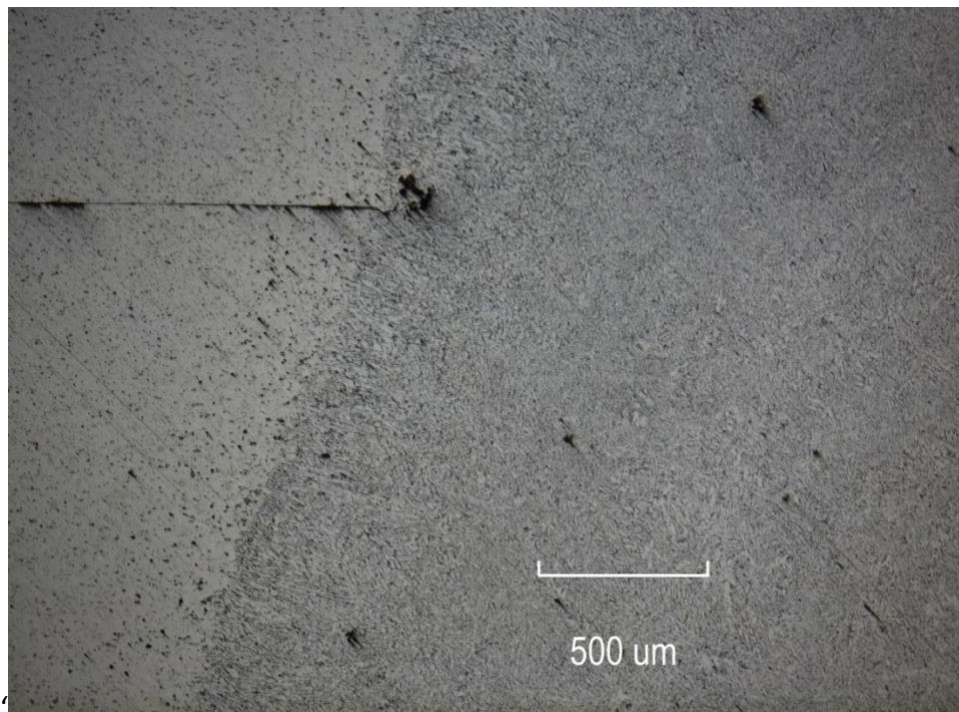


Figure 4-7: 5X magnification of lap joint centered on the weld root using polarized light with Keller's etchant for 20 seconds. Overview shows distinct fusion zone, with precipitate size increasing from the BM towards the FZ. Columnar grains within the WM are observed.

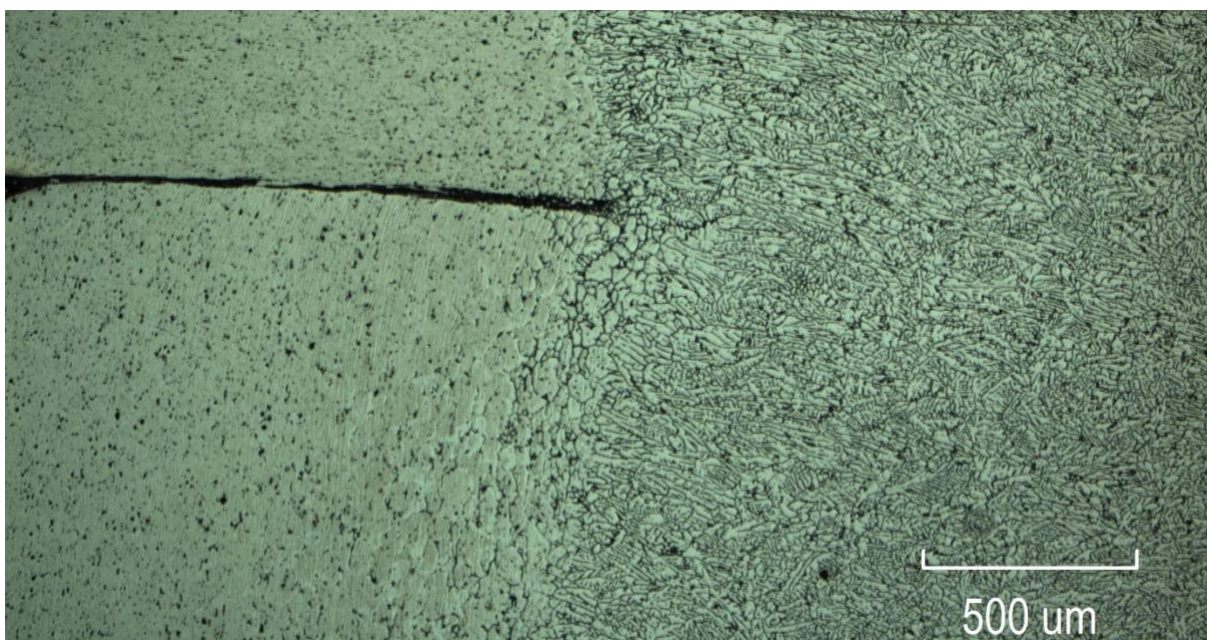


Figure 4-8: 5X magnification of tee joint centered on the weld root using polarized light with Keller's etchant for 25 seconds. Overview shows distinct fusion zone, with precipitate size increasing from the BM towards the FZ. Columnar grains within the WM are observed. Tee joint bottom plate fusion zone grain boundaries are darkened compared to the vertical plate. This suggests the biased heat input towards the bottom plate to avoid melt through adversely changes the cooling rate.

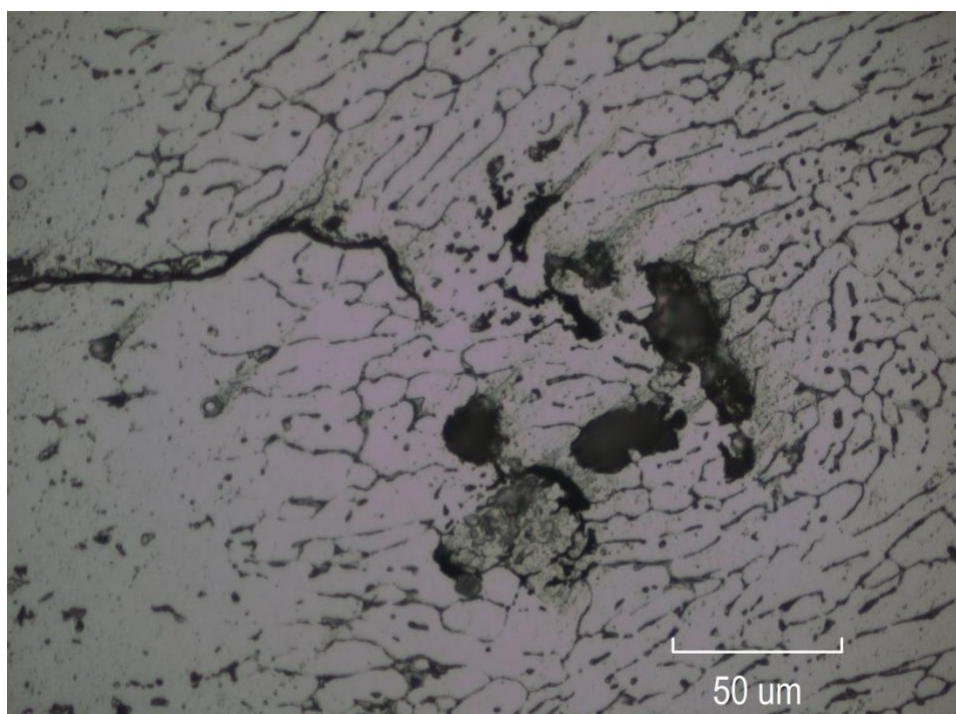


Figure 4-9: 50X magnification of lap joint centered on the weld root using polarized light with Keller's etchant for 20 seconds revealing dispersed inclusions at the weld root, with the preexisting gap between mating plates extending into the fusion zone.

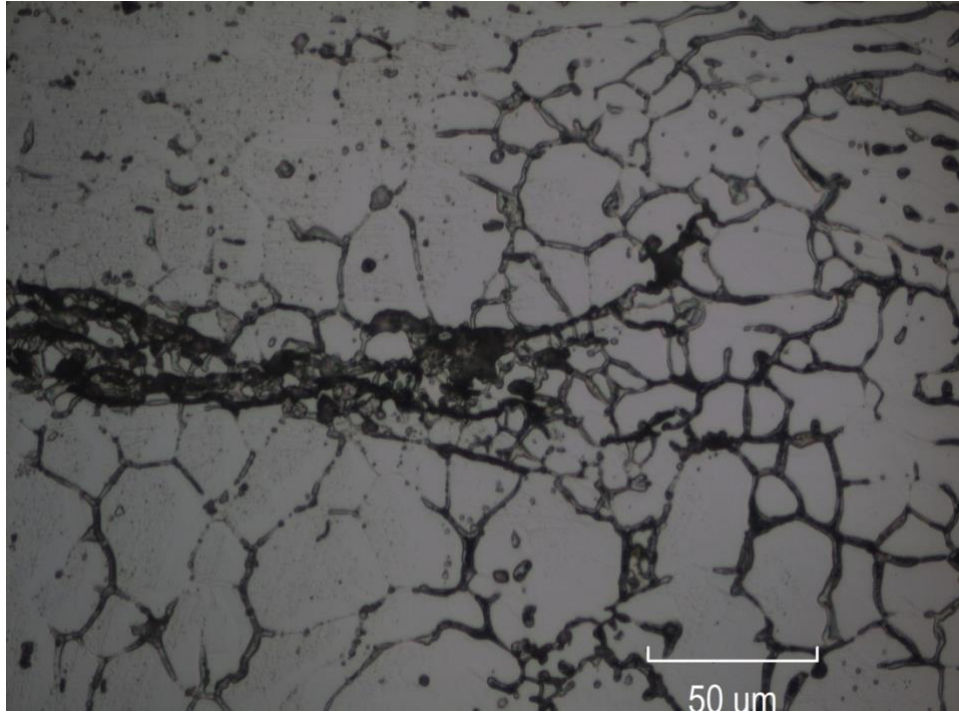


Figure 4-10: 50X magnification of tee joint centered on the weld root using polarized light with Keller's etchant for 25 seconds, with a more pronounced fusion zone on the bottom plate running parallel to the existing grain direction of the BM.

4.4. Mechanical (hardness) properties of welds

Hardness measurements of the lap joint traverse in Figure 4-12 and tee joint traverse in Figure 4-13 show a reduction of hardness within the weld metal summarized in Table 4-3, predicted by the non-heat treated strength of the filler wire. The weld metal, heat affect zone and base metal areas are averaged from the hardness traverses shown in Figure 4-14 and Figure 4-15. Hardness values in the heat affected zone are not compared to the welding parameters as the influence of parameters on the HAZ has been reported by Malin et al. [12] and the purpose of the current welding is to produce components for fatigue testing. The coarsening of grain size is observed in the HAZ within 8 mm of the fusion zone. The reported values are in line with recent literature for Al 6061-T6 extruded flat plate and ER 4043 filler wire [90], [91]. The lap joint hardness traverse is taken on either end of the root, as data provided from the company sponsor and literature [89] suggests root-initiated failures for the given geometry and loading type. Samples were naturally aged in the laboratory for seven or more days before mechanical testing or hardness measurements were taken.

Table 4-3: Average hardness across the WM, HAZ, and BM 8 mm away from the FZ.

Location	Lap Joint Hardness (HV)	Tee Joint Hardness (HV)
Weld metal	77	75
Heat affected zone	73	72
Base metal	101	101

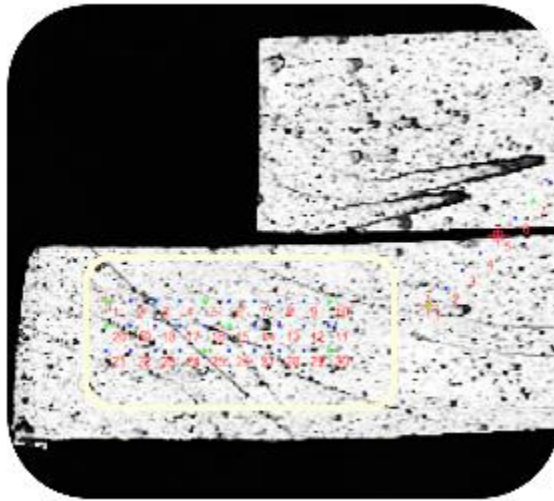


Figure 4-11: Base metal hardness traverse, taken on the same sample shown in Figure 4-12

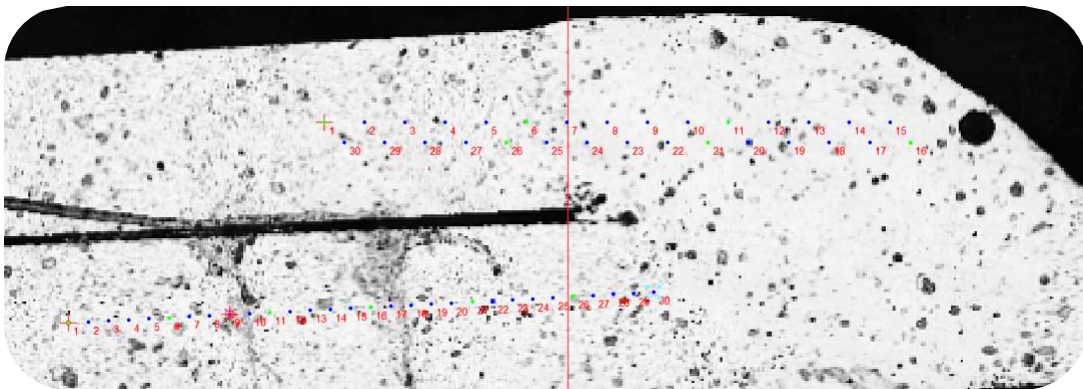


Figure 4-12: Hardness traverse of lap joint to capture WM, FZ, HAZ, and BM values. Base metal hardness is measured on the lap joint traverse for direct comparison as the sample is long enough to avoid the effects of the HAZ

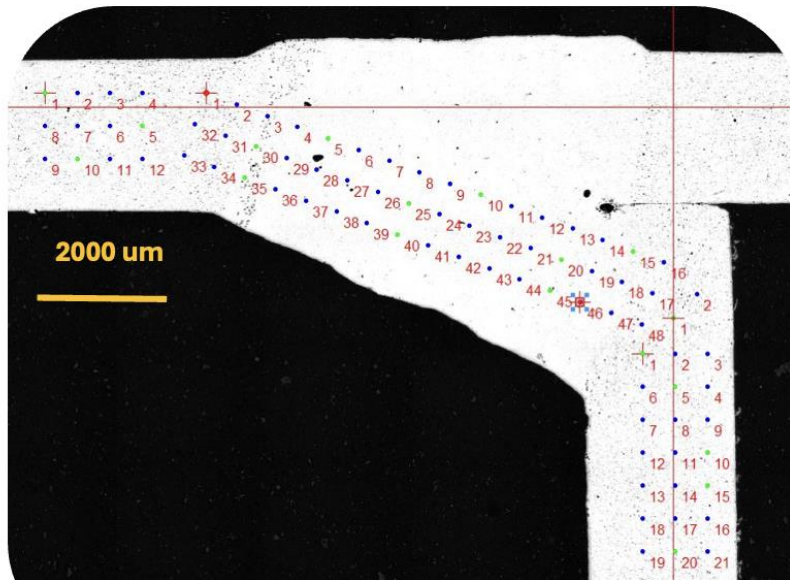


Figure 4-13: Hardness traverse of tee joint to capture WM, FZ, HAZ, and BM values for both mating plates. Additional points are used to supplement FZ data collection.

The traverse shown in Figure 4-14 reveals consistent hardness across the base metal, towards the end of the lap joint sample. Measurement locations around 8 mm from the observable fusion zone report HAZ hardness within 5% of the measured BM hardness, within the error of ASTM E384 standard accuracy. The lap joint HAZ sees a linear averaged reduction in hardness before stabilizing near the partially melted zone and fusion zone areas, with a small increase within the weld metal.

The tee joint hardness traverse shown in Figure 4-15 displays points within the HAZ, as the geometry of the joint within the sample resin was less than the 8 mm required to see BM values. As such it provides an averaged HAZ value with a consistent hardness between the WM and HAZ within 2 mm of the FZ.

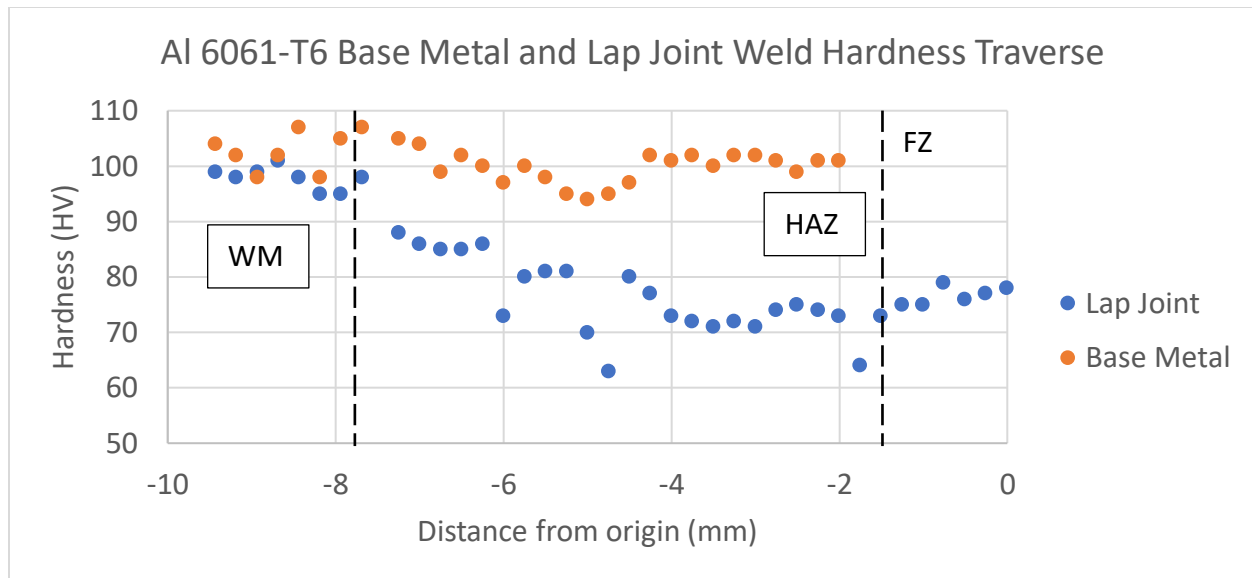


Figure 4-14: BM, and lap joint HAZ and WM hardness traverse, with the distance from origin zeroed on the observable fusion zone for the lap joint WM and on the right points in Figure 4-11 for the BM.

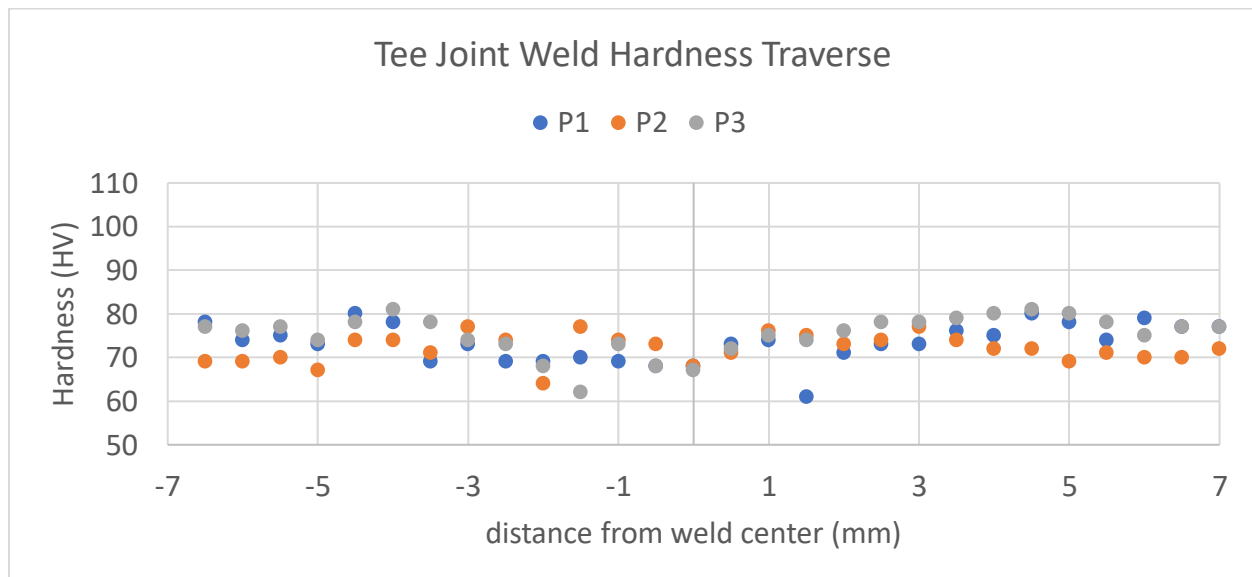


Figure 4-15: Tee joint WM and HAZ traverse, with the X axis focused on the geometric center of the weld.

5. Quasistatic and cyclic behavior of aluminum GMAW

This chapter reports the quasi static and fatigue testing of 2.3 mm to 2.3 mm Al6061-T6 lap joint, and tee joint samples joined with 4043ER filler wire. All lap joint samples were shimmed to reduce misalignment, using 40 mm by 40 mm shims 2.3 mm thick. The mechanical response of the samples is detailed, and crack initiation is monitored during fatigue testing. Fractography is conducted for low and high life cycles to detect the crack initiation site and observe the mechanisms of propagation and fracture.

5.1. Quasistatic experimental results

Quasistatic testing is performed to measure the strength of the welds. Strength values were employed to calculate the fatigue loading levels. Fracture surfaces of the failed sample were analyzed to understand failure modes and mechanisms. The load displacement response of each joint is reported.

5.1.1. Qs lap joint

Five lap shear specimens welded with the same optimized weld parameters outlined in Chapter 4 are tested with quasistatic loading condition in displacement control at 2 mm per minute to validate the variation in maximum load before failure & elongation in Figure 5-1. All samples failed consistently along the top plate, from the root and through the HAZ of the base metal illustrated in Figure 5-2 . Lap shear samples show a similar elastic response before plastic strain starts to accumulate in the root and preexisting gap between the plates. Further quasistatic testing of varied weld parameters was not performed for lap shear samples, as the optimized samples exceeded the 165 MPa minimum strength requirement referenced in AWS D1.2 for Al6061-T6 with 4043ER filler wire [92].

As discussed in Chapter 2, single weld lap shear samples have axial loads along the base plate and a shear load along the hypotenuse of the weld, which develops an out of plane bending moment. The resultant peel angle from the imposed bending moment is shown in Figure 5-3, where the overlap angle increases until rupture. Peel angles are recorded during testing as they can be used for FEA correlation but are not used in this thesis, as the structural stress methods discussed in Chapter 6 will not consider local effects to the strain field in the weld root. The strength of the welded joint is not a function of weld geometry or penetration for failure modes initiating in the root, but lack of fusion defects reduces the failure cross section and reduce the joint strength.

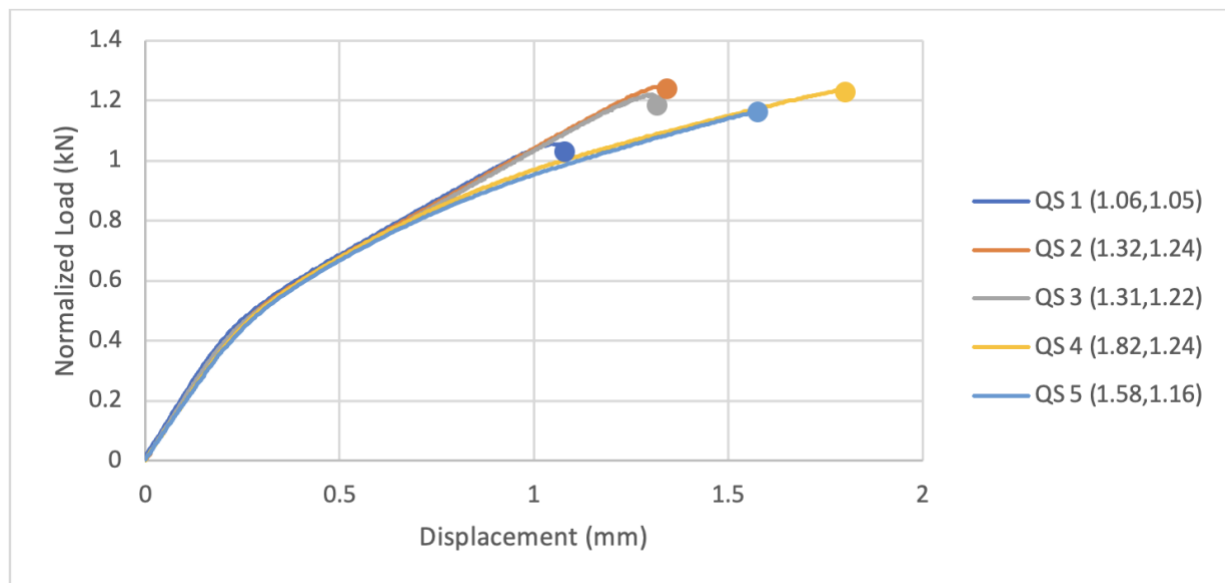


Figure 5-1: Normalized load displacement curve for 2.3 mm lap joint samples.

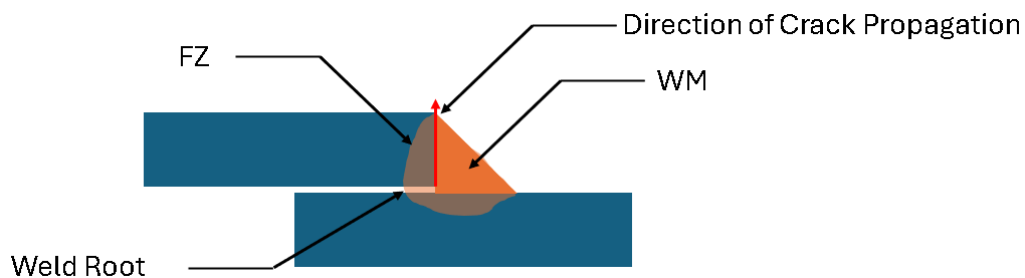


Figure 5-2: Lap joint point of failure for axial loading.



Figure 5-3: Lap joint eccentricity, with peel angle increasing with increasing applied load.

The quasistatic fracture surfaces in Figure 5-4 show minimal porosity and an even location of the root. Samples 1 and 5 had the highest porosity at 8 and 7 percent respectively. Samples 2, 3, and 4 had 4, 4, and 5 percent porosity respectively. The min and max normalized loads recorded were 1.05 kN/kN and 1.24 kN/kN, a 16.6% difference for samples 1 and 2 respectively, so as shown in Figure 5-1 there is no observable trend in ductility but samples with worse root fusion observed a lower max load.

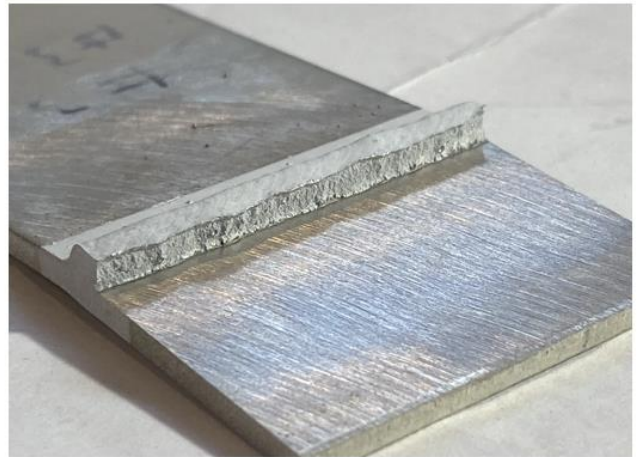


Figure 5-4: QS fracture surface of sample 1 (left) and sample 2 (right)

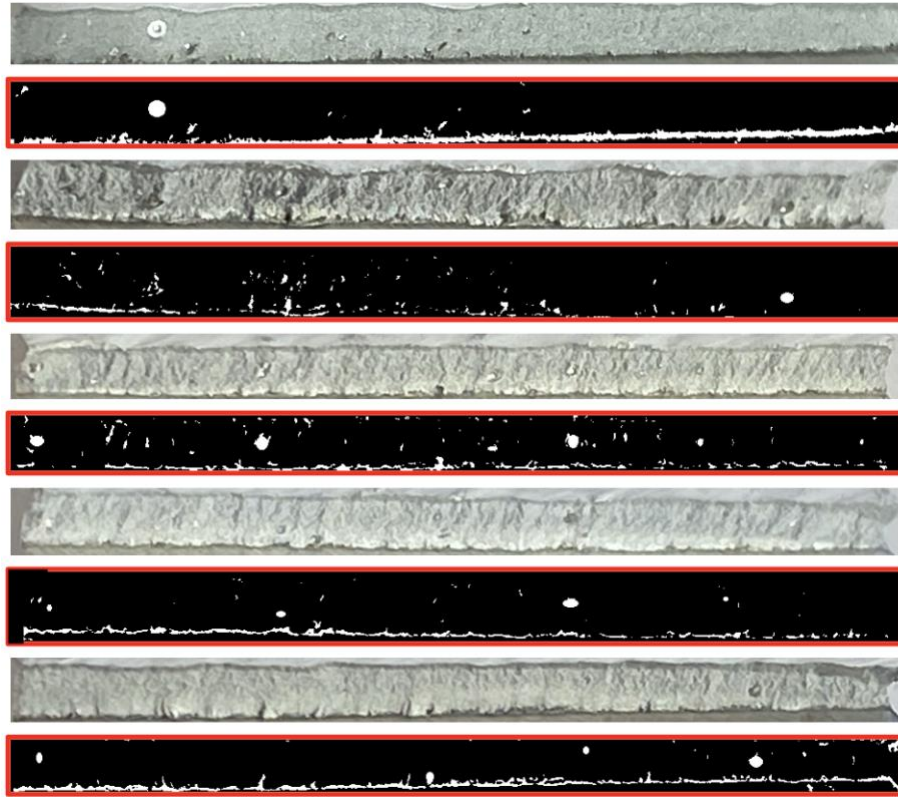


Figure 5-5: Fracture surface and ImageJ threshold adjustment below each fracture surface for measurement of total porosity % of QS fracture surface. Sample 1 at the top and 5 at the bottom. Root inclusions at the bottom of each fracture surface represent most of the porosity volume within the sample, with 0.5 mm being the largest pore diameter in sample 1.

5.1.2. QS Tee Joint

Industry partner specified weld penetration of 50% is targeted as the model weld, with a minimum accepted penetration of 15%. Quasistatic tests consisting of 2 weld penetration populations are included to confirm the failure mode remains unchanged between this level. A further 3 samples using the optimized weld parameters are included to predict load levels. The mechanical response of all tests shown in Figure 5-6 demonstrates a similar compliance profile, with large compliance observed up to 10 mm, and a nonlinear change in stiffness until rupture at 15 to 16.5 mm. All samples observed the same failure mode, with rupture originating through the root of the weld through the bottom plate as shown in Figure 5-7. Additional weld material in the throat does not seem to influence this failure. The bottom plate develops a permanent set as shown in Figure 5-8. Root defects causing a reduced cross section are observed in lap shear and tee joint configurations.

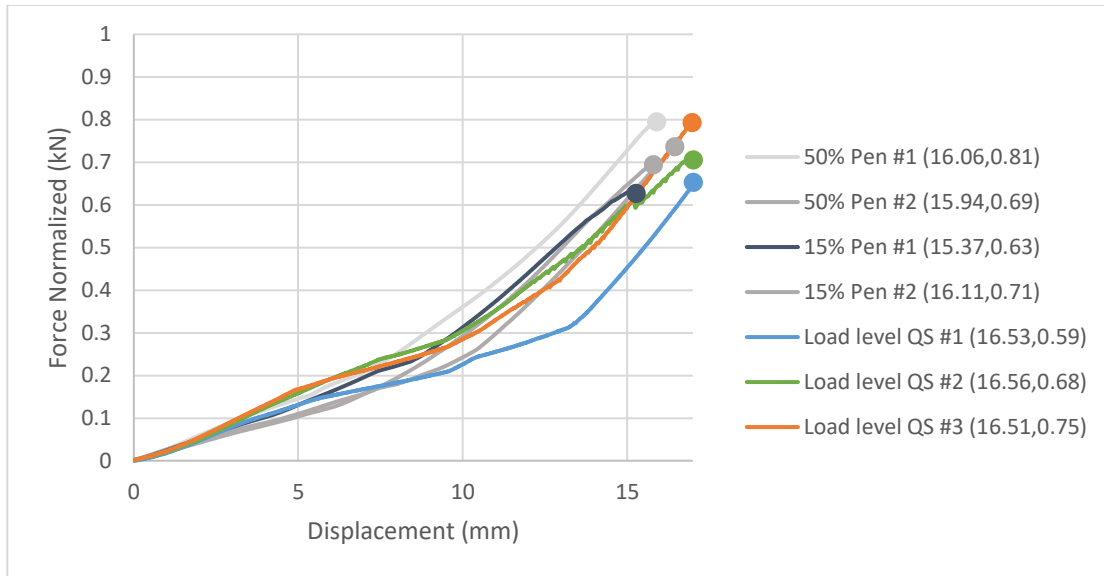


Figure 5-6: Normalized load displacement curve for 2.3 mm tee joint samples

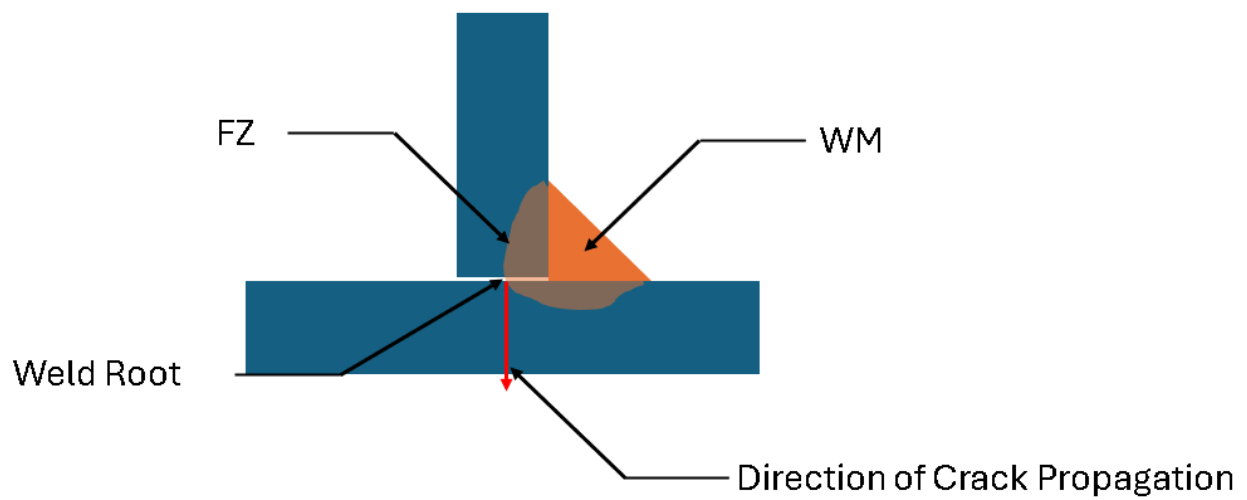


Figure 5-7: Tee joint point of failure for vertical member applied axial load

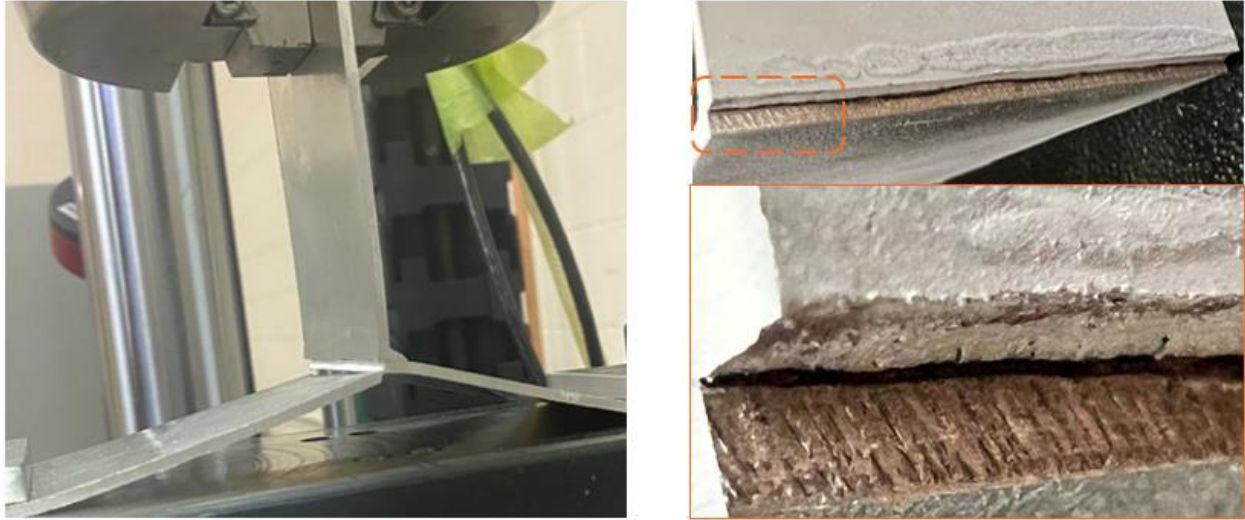


Figure 5-8: Tee joint fracture location during quasi-static testing.

Tee joint porosity is not directly measured from the fracture surface, as the root shown in Figure 5-8 is recessed and cannot be processed with ImageJ. Samples with poor root fusion were observable from the burn through at the back of the sample, and samples with consistent fusion were binned for testing.

5.1.3. Discussion on QS behavior and comparison with literature

In comparing the quasi-static (QS) behavior of the lap joint samples from this study to those documented in the literature, the results highlight some key differences in load-bearing capacity and failure modes. The lap joint samples in this research exhibited a higher initial peak load capacity than similar samples reported in other studies. This can be attributed to the optimized welding parameters that ensured consistent penetration and reduced porosity. Microstructural analysis showed a narrow partially melted zone, with a rapid transition from the annealed equiaxial grains of the HAZ to the columnar grains of the WM with minimal softening, which likely delayed crack initiation and propagation during QS loading.

The cracks were observed to initiate at the root stress concentration with a preexisting plate gap and propagated near or at the fusion zone of the weld, the softest region at the HAZ/weld metal (WM) interface. These findings are consistent with literature that emphasizes the impact of weld quality on QS performance, particularly concerning load capacity and the point of failure onset.

QS behavior of tee joint samples closely mirrors existing literature, with crack initiation consistently occurring at the root and propagating near or at the fusion zone of the weld down through the bottom plate. This region, identified as the softest part of the HAZ/WM interface, is prone to failure due to its reduced hardness and strength measured in Chapter 4. The weld toe has similar microstructure at the HAZ/WM interface, but the stress distributions in the chosen geometries and loading conditions did not lead to observed failures or cracks in the toe region so the weld root will be discussed in more detail.

As discussed in Chapter 2, the preexisting gap between mating plates acts as a stress concentration. This area is especially vulnerable to crack initiation when combined with the thermal gradients formed from the lack of plate contact. Despite the optimized welding conditions, the tee joints still exhibited failure in this vulnerable area, suggesting that even with refined welding parameters, the inherent microstructural characteristics of the fusion zone play a critical role in determining failure modes. Studies exploring local stress effects are beginning to analyze thresholds for shifting tee joint failure modes but have so far made no conclusions.

5.2. Fatigue experimental results

Load life plots, stiffness degradation by cycle, failure modes and damage accumulation are discussed. Tests are conducted under load control cyclic test using 38 lap-shear with positive R-ratio of 0.25 and 53 Tee weld samples with positive R-ratio of 0.25. Optimized weld parameters outlined in Chapter 4 are used for all fatigue testing samples. 10 lap joint load levels and 11 tee joint load levels were selected to obtain lives between 1000-1000000. These results will be used in Chapter 6 to establish the S-N curves of the welds.

5.2.1. Fatigue lap joint

Load levels are selected as a percentage of the average load before fracture from quasi static testing. Lap joint samples start with 50 percent of the fracture load, with 2 million cycle runout observed around 15 percent. 5 repetitions are used to for 10 thousand and 1 million cycle load levels. The remainder of tests are used to record low cycle failure, and to generate log steps between the load level range. Test scatter range is observed to be inversely proportional to the load level, while staying within an order or magnitude of the mean life. Observable crack initiation to rupture occurs within 25,000 cycles, with no recorded loss in stiffness from low to high cycle fatigue.

Table 5-1: Completed test matrix for lap joint samples at R = 0.1

Max. load (kN)	Min. load (kN)	Load range (kN)	Loading Freq (Hz)	Test 1	Test 2	Test 3	Test 4	Test 5
0.62	0.06	0.55	1	2,151	2,210	2,818	4,291	-
0.49	0.05	0.44	3	3,559	5,119	5,287	7,292	7,347
0.37	0.04	0.33	10	13,167	21,313	24,091	26,975	34,546
0.32	0.03	0.29	10	40,014	45,191	50,563	60,559	61,950
0.25	0.02	0.22	15	129,586	137,353	199,864	316,904	320,250
0.21	0.02	0.19	20	534,163	561,294	579,924	-	-
0.20	0.02	0.18	20	649,903	-	-	-	-
0.19	0.02	0.17	20	655,286	-	-	-	-
0.19	0.02	0.17	20	1,072,752	1,086,127	1,290,809	1,586,662	-
0.19	0.02	0.17	20	Runout	-	-	-	-

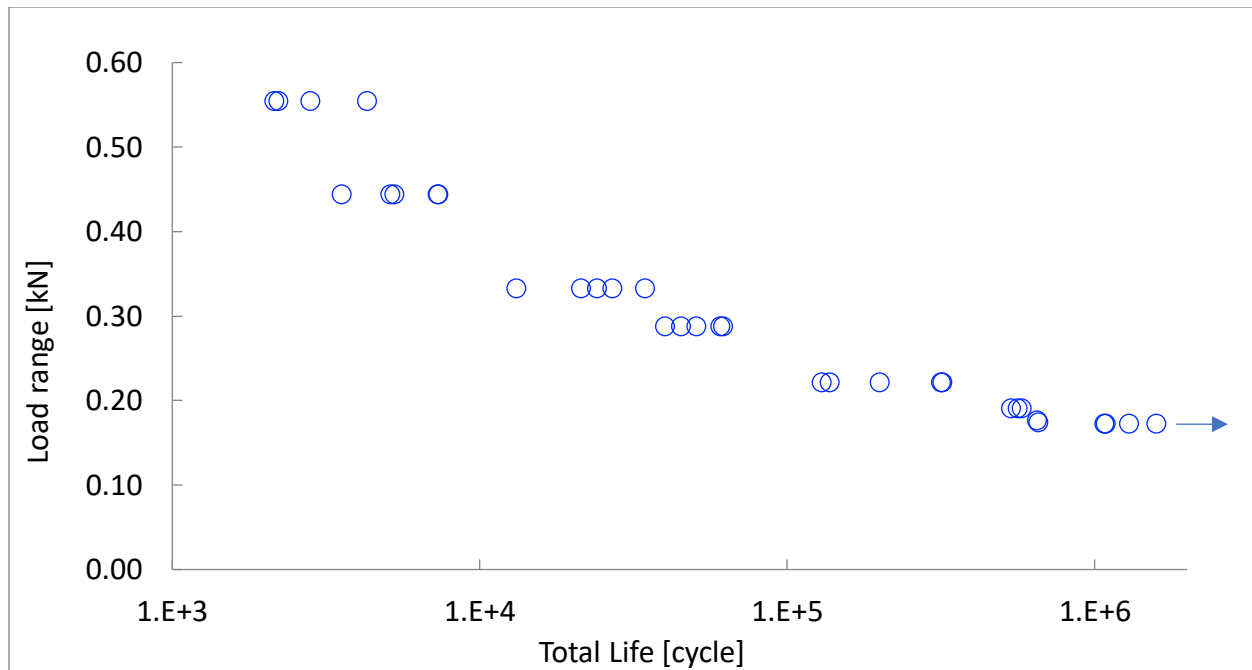


Figure 5-9: Load life curve for lap joint samples

The Digital Image Correlation technique was used to capture high-resolution images of crack propagation at regular intervals. The number of cycles to failure is reported when a 1 mm crack is visible through either side of the weld. All lap joint samples ruptured during testing. The root gap angle begins to increase just before a crack is visible. Crack initiation across the sample population is distributed between the observed start and end of the weld, without an apparent bias for either side. Crack initiation is unchanged from quasistatic testing shown in Figure 5-2, where a visible crack initiates from the root within 1,000 cycles at the 3 kN load level and at 7,000 cycles at the 2.4 kN maximum load level. The approximate initiation and rupture cycles are visible in Figure 5-10, Figure 5-11, and Figure 5-12 respectively, with videos available in the captions. Sample stiffness is recorded in Figure 5-13 and Figure 5-14 in case the load level could not be maintained until final rupture of the sample. Lap joints maintained consistent test parameters until final rupture.

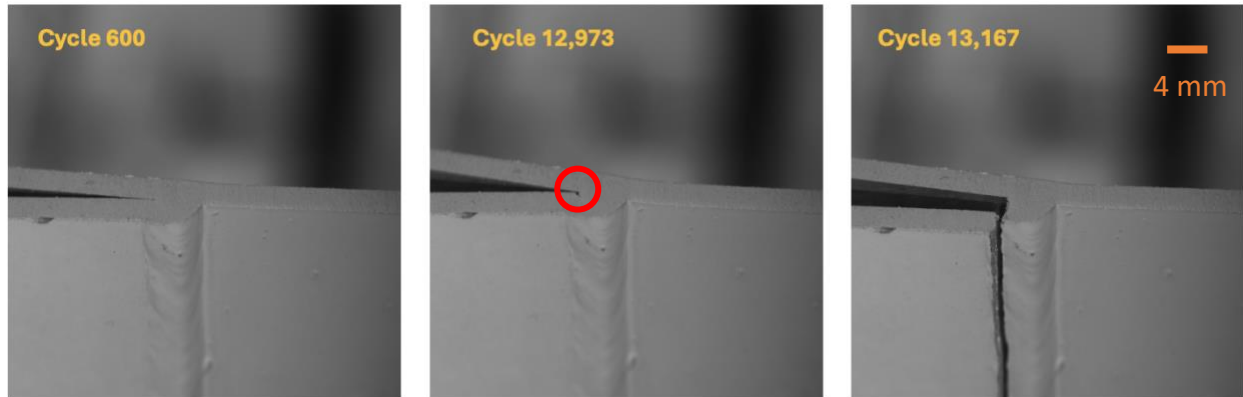


Figure 5-10: Crack initiation at 10,000 Cycles. The recording for a similar sample captures the length of time between initiation, propagation, and final rupture at 39,000 cycles. Available <https://youtu.be/ZEWQWrz9E3o>

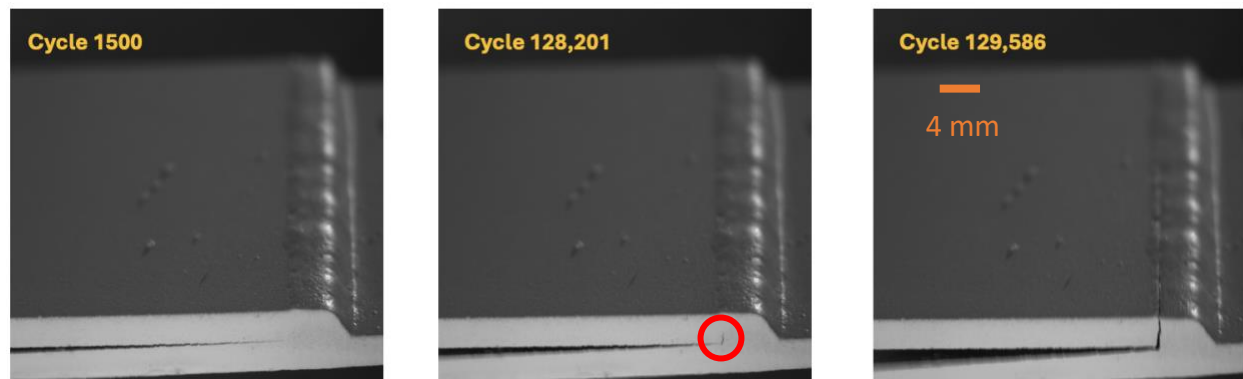


Figure 5-11: Crack initiation at 100,000 Cycles. The recording for a similar sample captures the length of time between initiation, propagation, and final rupture at 500,000 cycles. Available <https://youtu.be/en69to1M3aE>

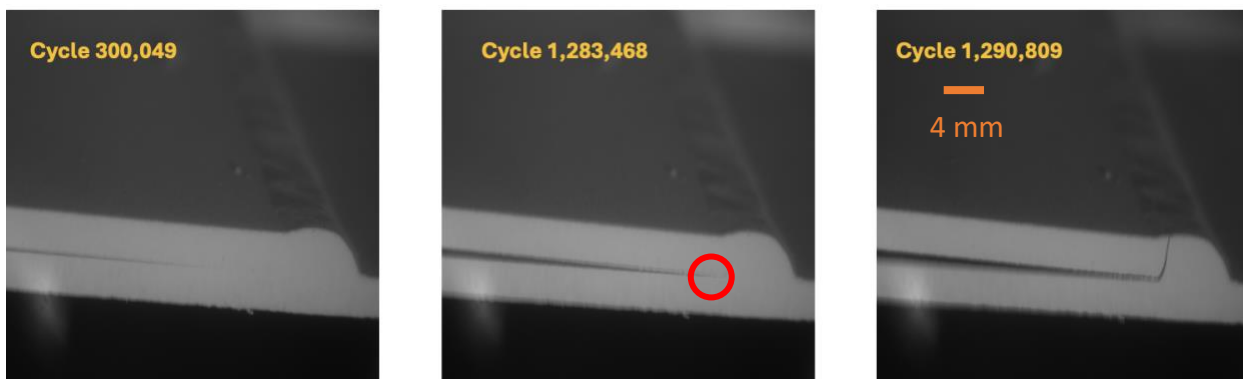


Figure 5-12: Crack initiation at 1,000,000 Cycles. The recording captures the length of time between initiation, propagation, and final rupture at 1,000,000 cycles. Available https://youtu.be/Ep_WUSHQ88

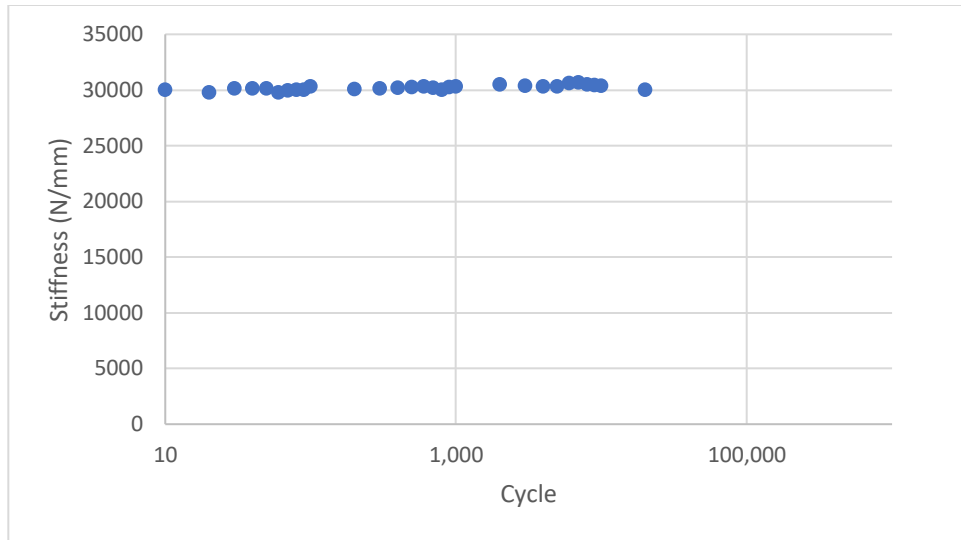


Figure 5-13: Lap joint stiffness plot for 10,000 cycle failure at 4.6 kN max load

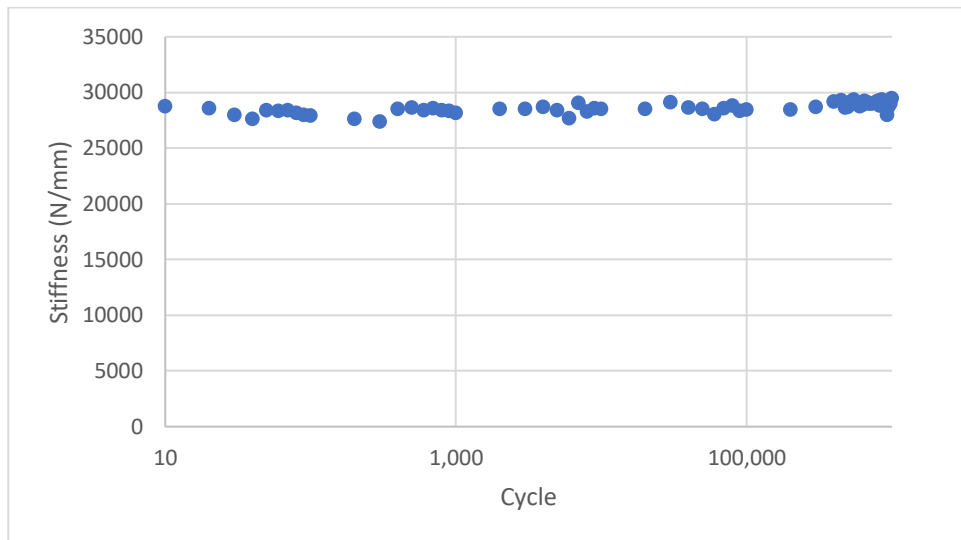


Figure 5-14: Lap joint stiffness plot for 1,000,000 cycle failure at 2.4 kN max load

Fatigue testing of welded joints uncovers unique microstructures and existing defects that contribute to crack initiation. SEM fractography is employed In order to build the relationship between the fatigue tested samples and their failure modes and existing defects of the fracture surfaces.

Analysis of samples with a life of 10,000 cycle failure found several cracks along the root area of the fracture surface, suggesting initiation from a lack of fusion or inclusions. This is consistent with the macroscopic porosity analysis of the quasi-static fracture surfaces shown in Figure 5-5. Most of the sample life is spent initiating the crack from the root shown in the microstructure of Figure 4-9 and possibly the extended preexisting crack appearing in Figure 5-16 of the root fracture surface. Striations are not readily visible in the suspected fatigue region, but an abrupt change has been noted in Figure 5-17 where a smooth area rapidly transitions to an area populated with deep equiaxed dimples. DIC imaging recorded rapid rupture within 200 cycles of an observable crack in Figure 5-10, leading to the area observed in Figure 5-18 where ductile rupture rapidly occurred at the higher load amplitude.

Examining the 1,000,000 cycle failure found inclusions and porosity along the root edge of the fracture surface. A large smooth surface is observed with dense river like patterns, suggesting periods of stable crack growth with intermittent rapid propagation. Tightly packed striations in Figure 5-20 follow the propagation direction shown in Figure 5-2. A few thousand cycles pass between visible crack initiation and rupture in Figure 5-12, with the suspected ductile fracture area showing bottom visible parabolic dimples, where the width of the weld was progressively overloaded as shown by Figure 5-21.

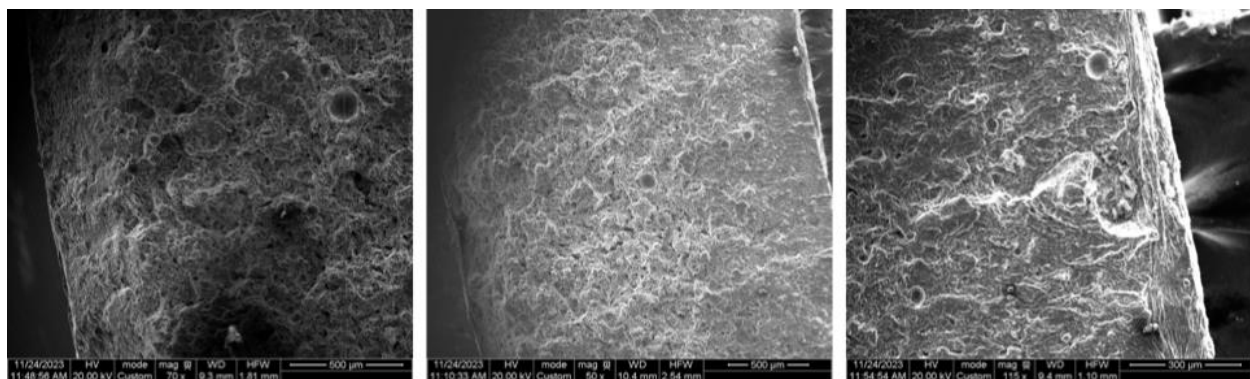


Figure 5-15: Lap joint SEM 10,000 cycle to failure overview, showing a possible ductile fracture surface, a smooth fatigue surface, and possible fatigue initiation site for further review.

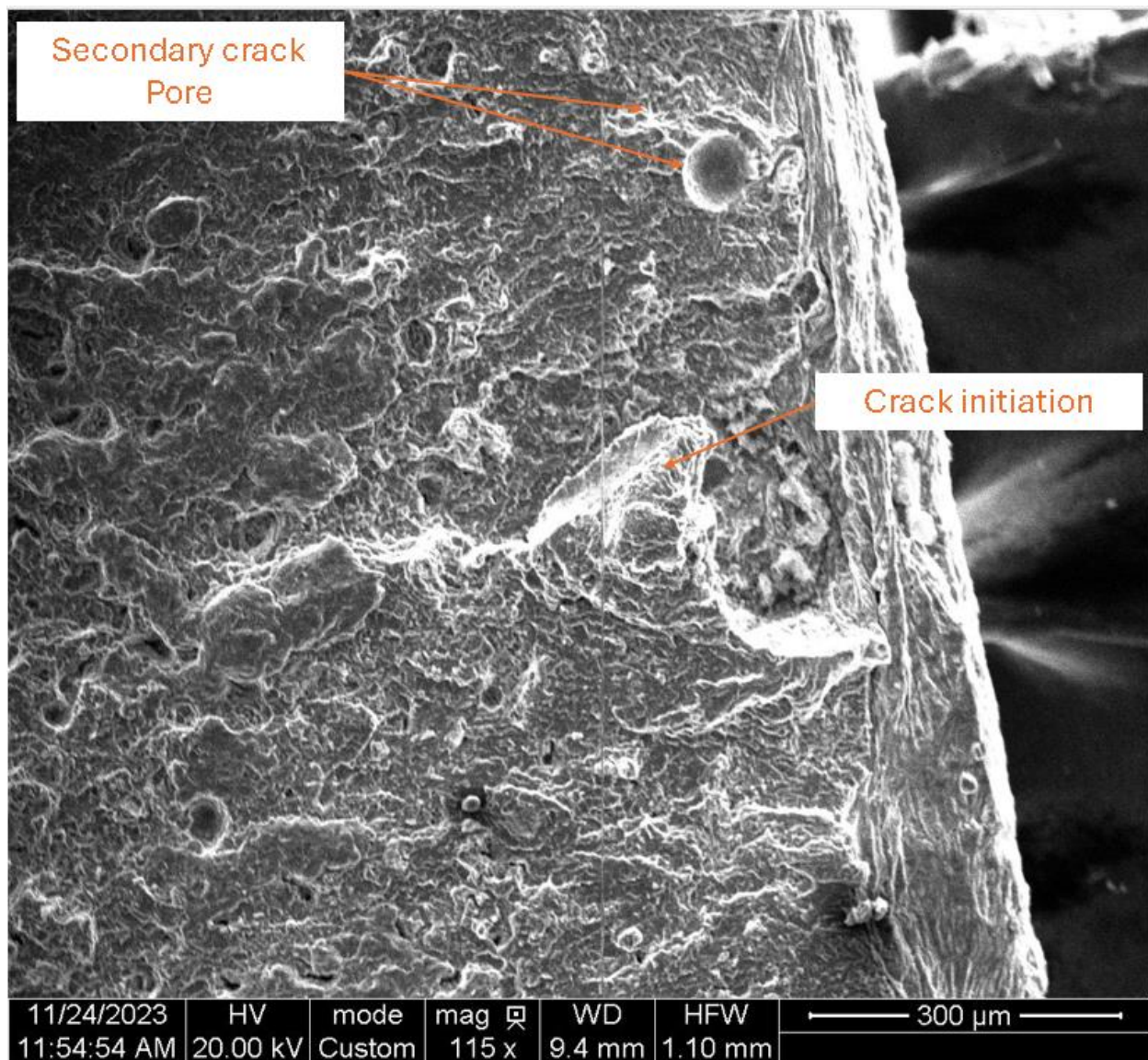


Figure 5-16: 115 X magnification of possible crack initiation or preexisting crack from weld solidification. Smaller pores show signs of secondary cracks from the surface.

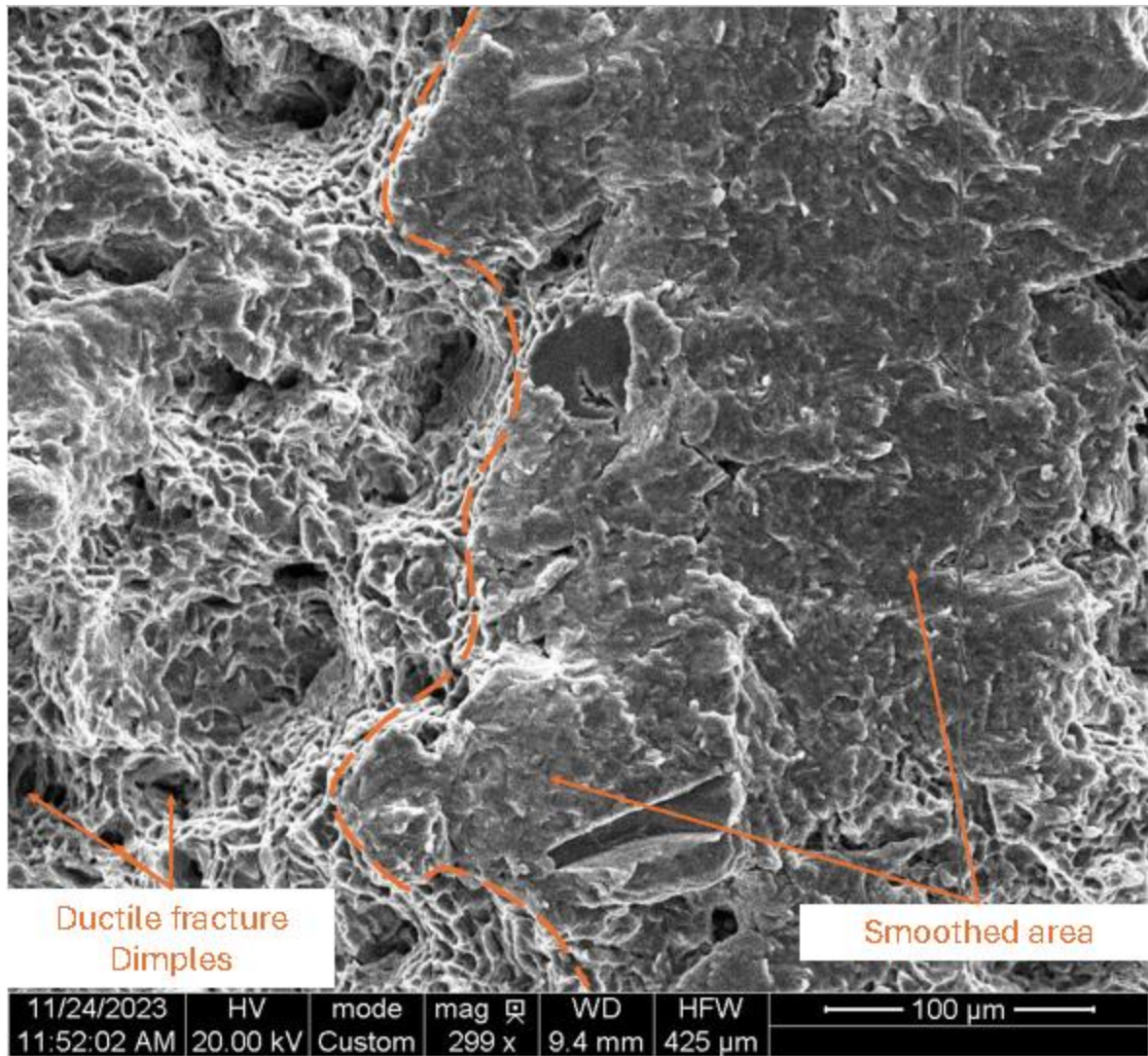


Figure 5-17: 299X magnification of transition between possible smoothed fatigue area from slip bands or micro void coalescence. Measured in the thickness depth similar visible crack initiation. Smooth area abruptly transitions to ductile fracture area with large visible dimples.

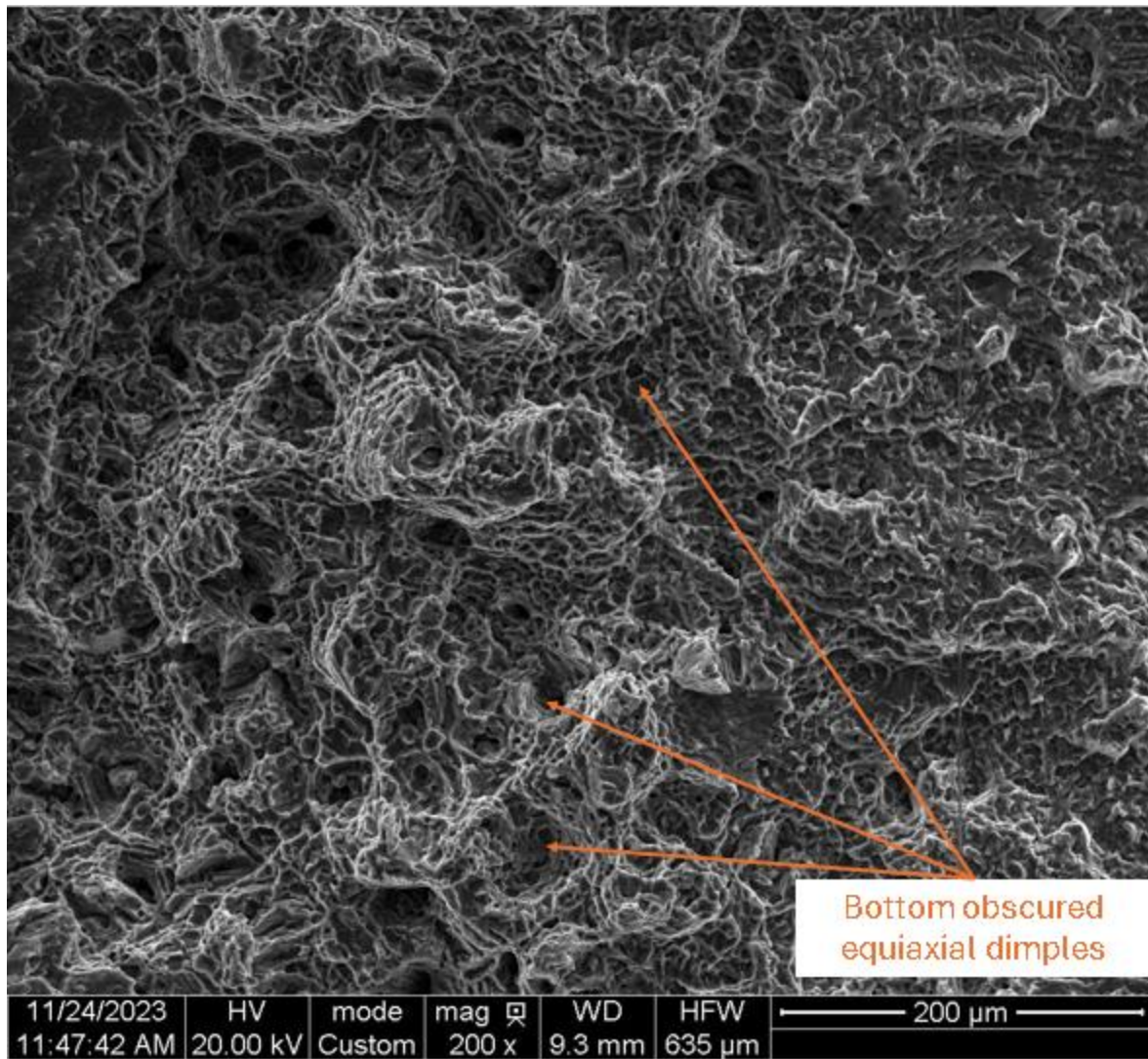


Figure 5-18: 200X mag of final rupture area with large dimples.

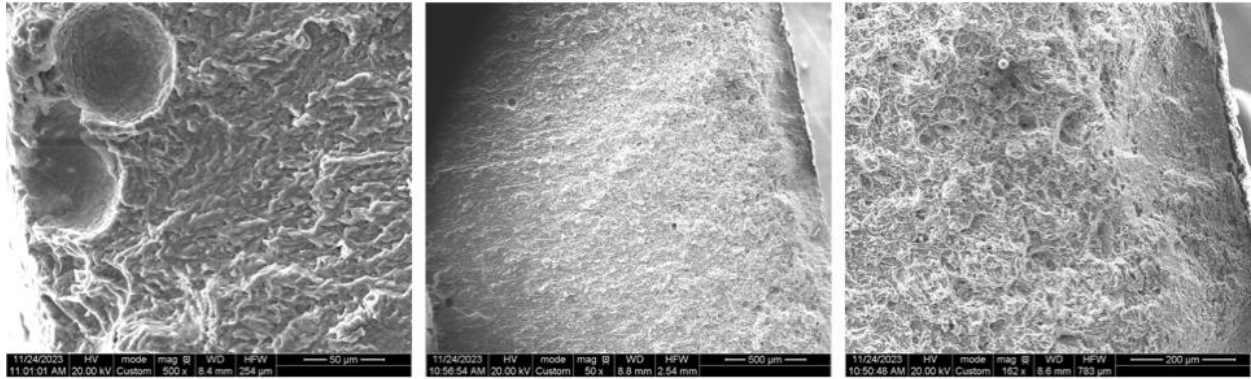


Figure 5-19: Lap joint SEM 1,000,000 cycle to failure overview, showing a possible crack initiation site, a significant smooth fatigue surface, ductile fracture surface for further review..

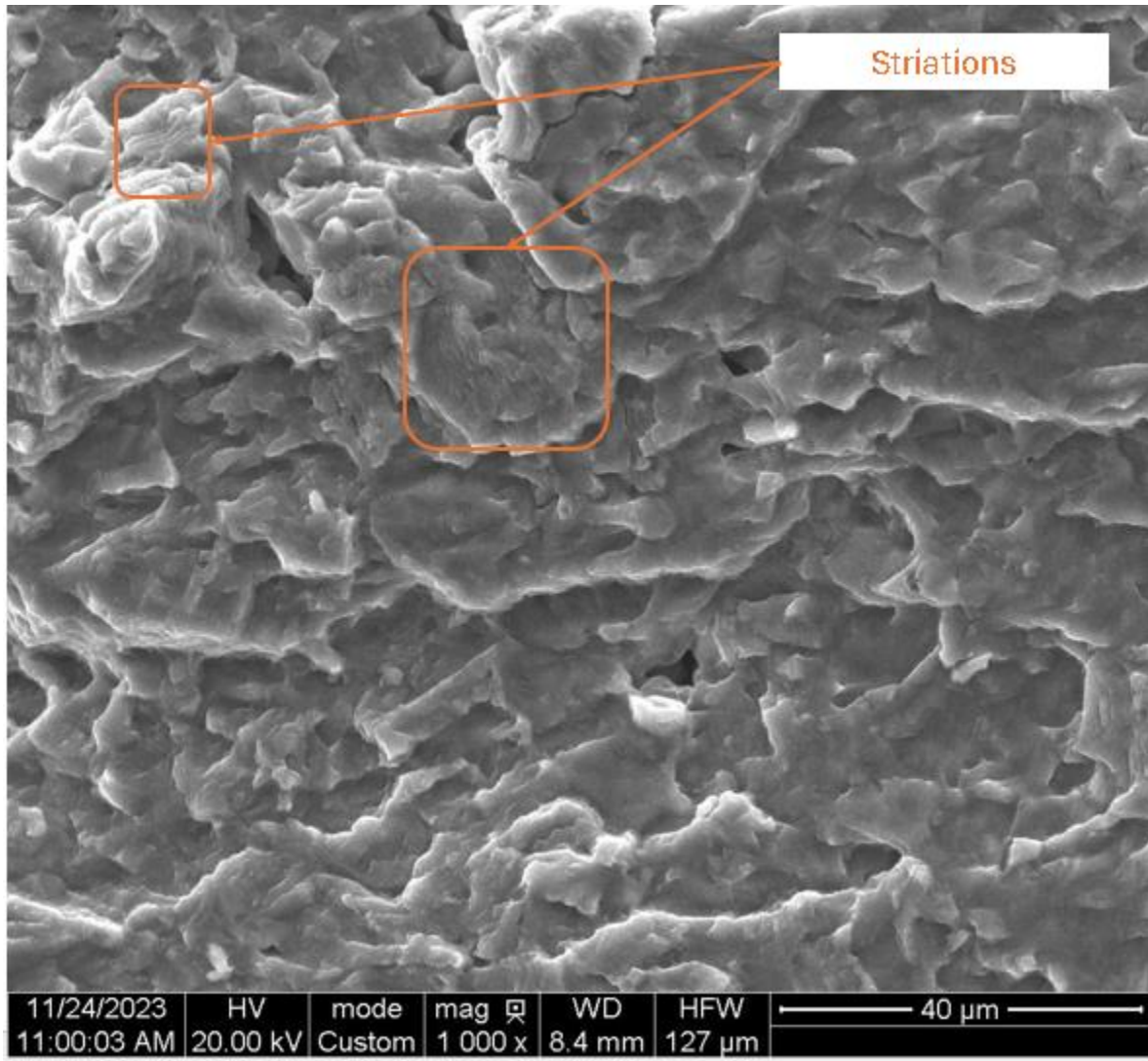


Figure 5-20: 1000X mag image of root area with tightly packed striations in focused areas.

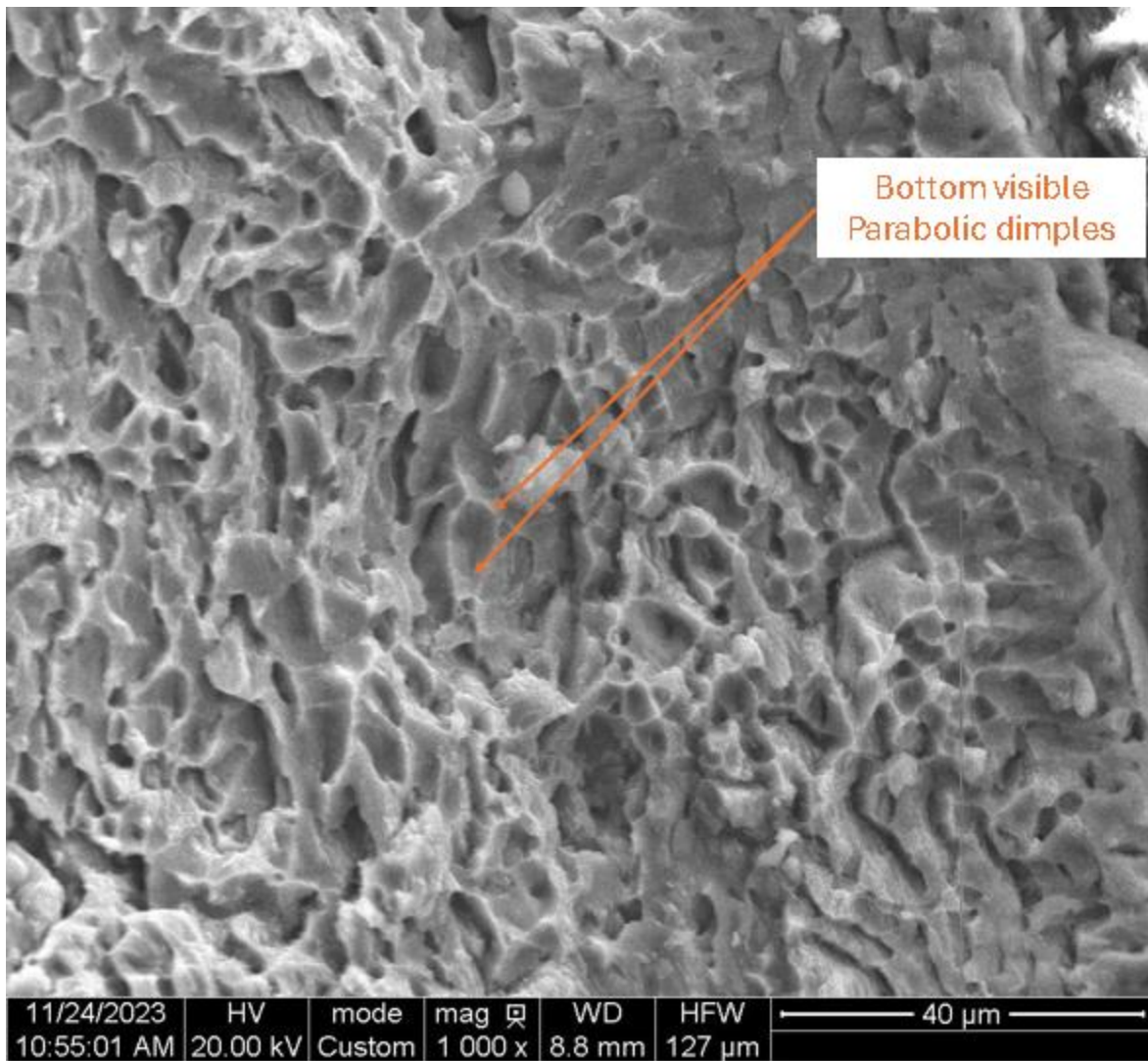


Figure 5-21: 1000X mag rupture area showing shallow parabolic dimples.

5.2.2. Fatigue tee

High bending moments from the sample geometry led to the selection of load ranges from 20 percent of the load before quasi static fracture for low cycle fatigue characterization of the tee welds. Loading increments decreased by 2 percent until runout of 2 million cycles is achieved. Five tests are conducted at the highest and lowest load levels, with the remainder of tests used to record low cycle failure and fill in the load range steps. Samples above 0.04 kN/kN load range fully ruptured within 25,000 cycles of crack initiation, with no measurable loss in stiffness. Higher life samples had increased compliance with observable crack initiation, with larger scatter observed between tests. Fatigue lives are extracted at the onset of an observable 1 mm crack through the HAZ on either side, monitored by the DIC, but tests were run until fully fractured or reached the 2 million cycle runout.

Initial fatigue testing necessitated additional clamping force to confirm rigid boundary conditions, with the diagram shown in Figure 5-22. The distance from the weld to the fixed supports is decreased to increase the range of load levels and to increase testing stability. Since a visual gap was confirmed at the boundary, 2 additional bolts were added to each support, where the displacement and moment at the edge were visually confirmed to be zero. It is imperative to ensure accurate boundary conditions for structural stress conversions, as the boundary value problems will give incorrect nodal forces and moments unless the FEA model matches the tested conditions. An approximation of fixed boundary conditions in all 6 degrees of freedom is assumed when there is zero displacement at maximum cyclic load.

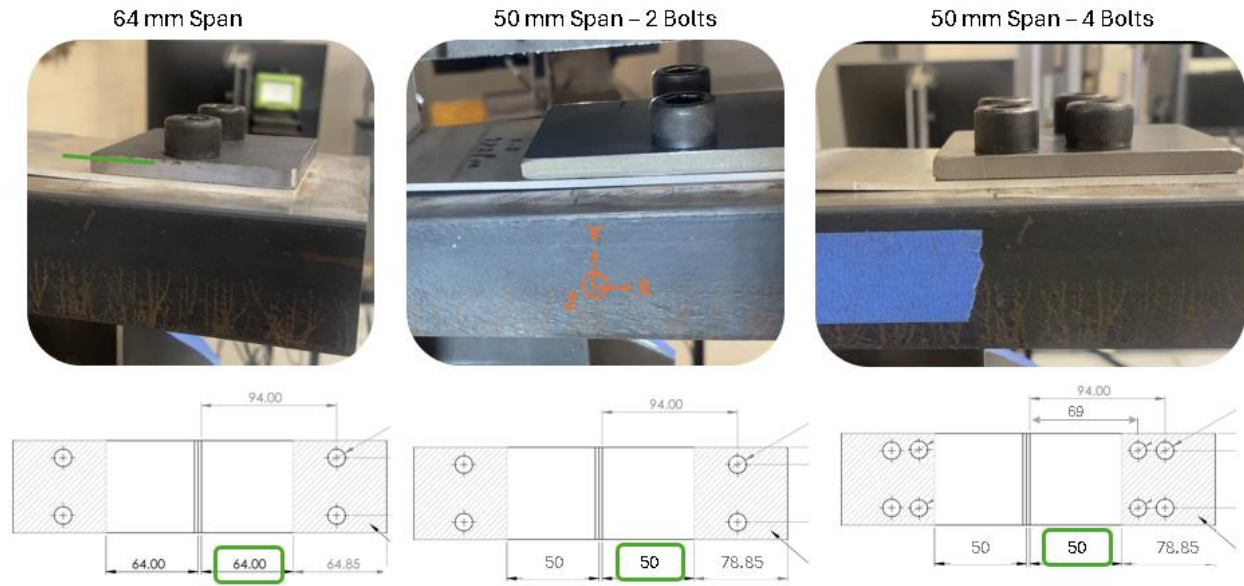


Figure 5-22: Changes to tee joint fatigue testing boundary conditions, where the distance from the weld to the fixed support is reduced for improved test stability and to widen the range of load levels. 2 additional bolts are added to ensure the displacement in the X axis and the moment along the Z axis is fixed.

Table 5-2: Completed test matrix tee joint samples at $R = 0.25$

Max. load (kN)	Min. load (kN)	Load range (kN)	Loading Freq (Hz)	Test 1	Test 2	Test 3	Test 4	Test 5
0.13	0.03	0.10	5	5,551	6,238	6,580	-	-
0.10	0.02	0.07	5	9,569	11,396	12,671	13,409	16,945
0.08	0.02	0.06	7	25,025	33,904	-	-	-
0.06	0.02	0.05	10	53,086	76,570	-	-	-
0.06	0.01	0.04	15	82,073	90,615	94,545	-	-
0.05	0.01	0.04	15	133,739	162,557	-	-	-
0.05	0.01	0.04	15	215,738	243,841	488,766	-	-
0.04	0.01	0.03	15	156,230	282,146	459,777	-	-
0.04	0.01	0.03	15	272,601	331,138	358,369	386,825	-
0.04	0.01	0.03	15	655,824	-	-	-	-
0.03	0.01	0.03	15	681,803	875,244	1,106,445	1,419,037	1,933,498

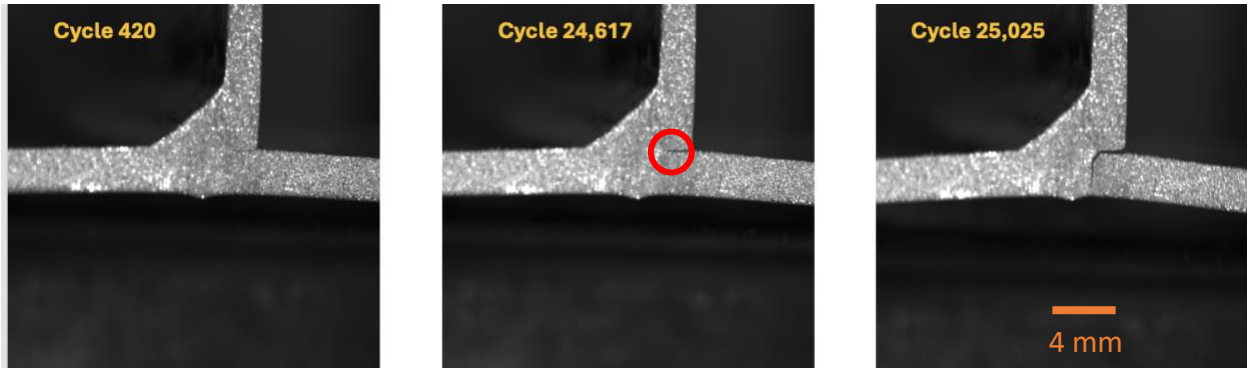


Figure 5-24: Crack initiation at 10,000 Cycles

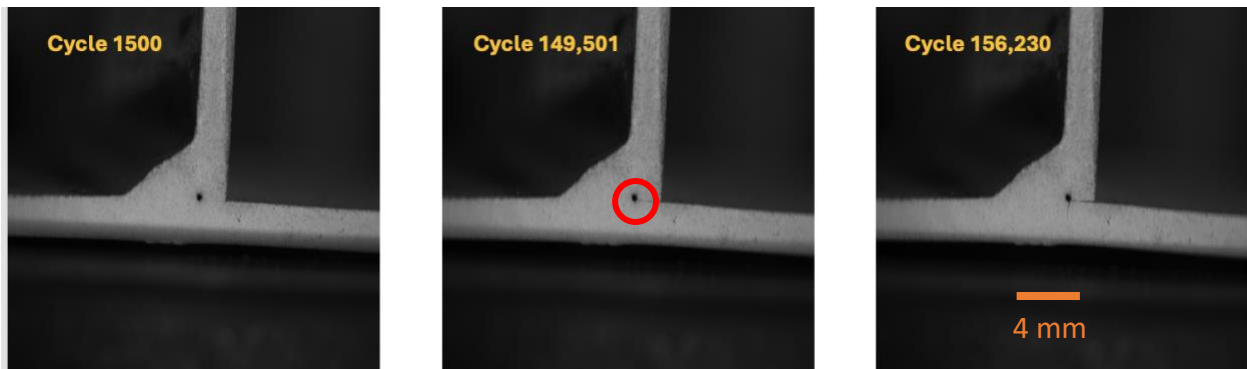


Figure 5-25: Crack initiation at 100,000 Cycles. The recording for a similar sample captures the length of time between initiation, propagation, and final rupture at 500,000 cycles. Available <https://youtu.be/zQ6Af64B1mw>

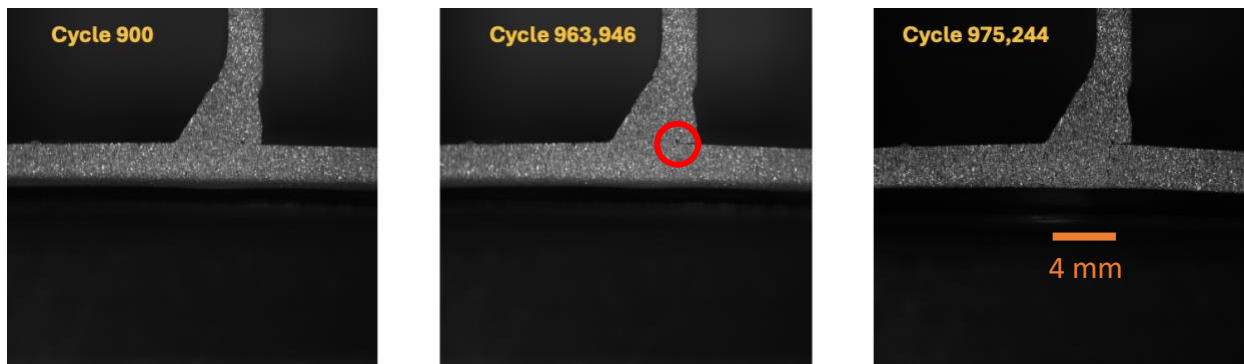


Figure 5-26: Crack initiation at 1,000,000 Cycles

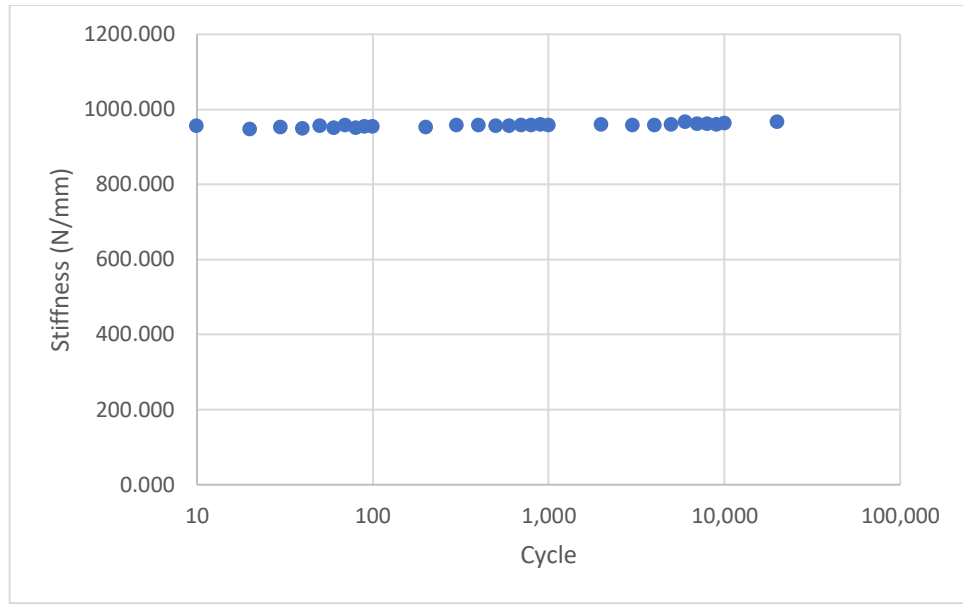
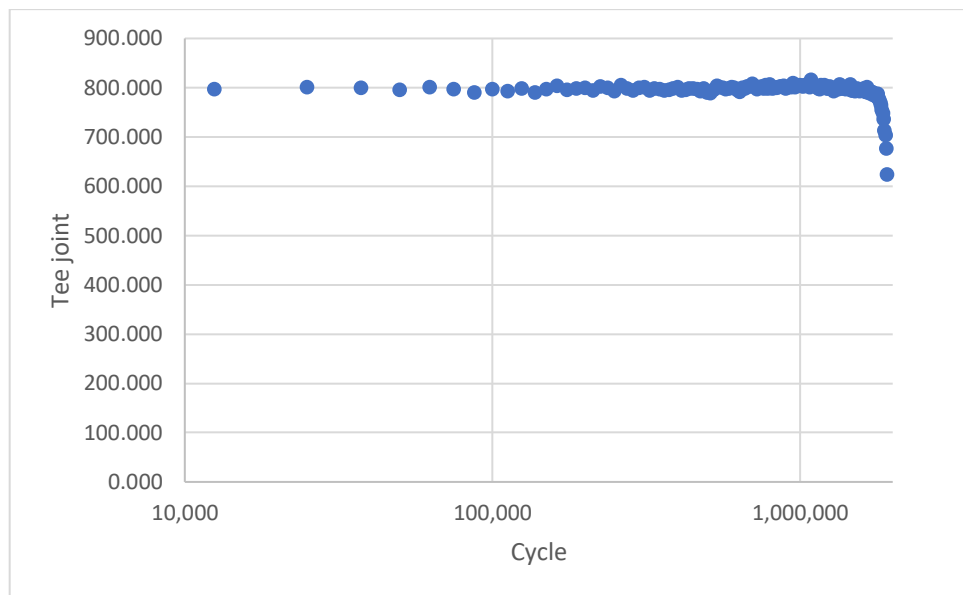


Figure 5-27: Stiffness plot for 10,000 cycle failure at 1.52 kN max load



Like the lap joint, fractography is conducted with macroscopic analysis and SEM imaging. Analysis of samples with a life of 10,000 cycle failure found a smooth region around the weld root, with large coarse dimples dominating most of the fracture surface as shown in the overview Figure 5-29. The smooth region is in line with the root area. The root area is shown in literature in Chapter 2 as well as the weld characterization in Chapter 4 to have porosity and root inclusion gaps that act as a stress concentration and nucleation site for initiation. The end of the smooth area likely coincides with the change in segregation from Figure 4-8. Visible cracks at the weld start and end from Figure 5-24 take up most of the applied cycles to initiate the crack, leading to the tightly spaced striations observed at a 1200 X magnification in Figure 5-30. The tee joint has more cycles between visible initiation and final rupture or test halting than the lap joint, which complicates the ductile failure surface at the bottom of the plate. The mix of loosely spaced striations and steeped planes suggest shear void coalescence. The crack front movement through the width of the sample is observed in Figure 5-24 is supported by the change in fusion zone microstructure in Figure 4-8.

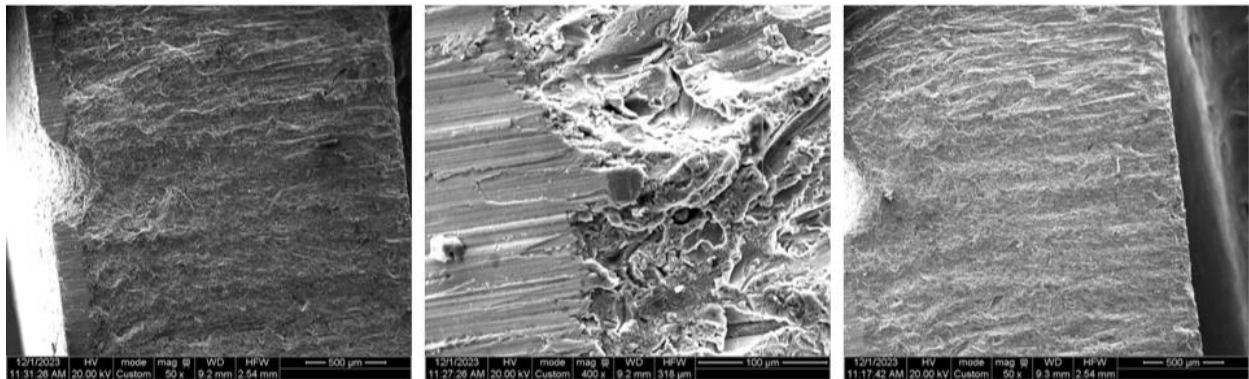


Figure 5-29: Tee joint SEM 10,000 cycle to failure overview, showing a smooth region at the weld root location with inclusions, the transition of smooth to secondary surface, and possible shear dimple coalescence or smooth fatigue surface for further review.



Figure 5-30: 1200X magnification of 10,000 cycle tee joint fractography showing possible striations emanating from the weld root area traveling across the thickness of the sample.

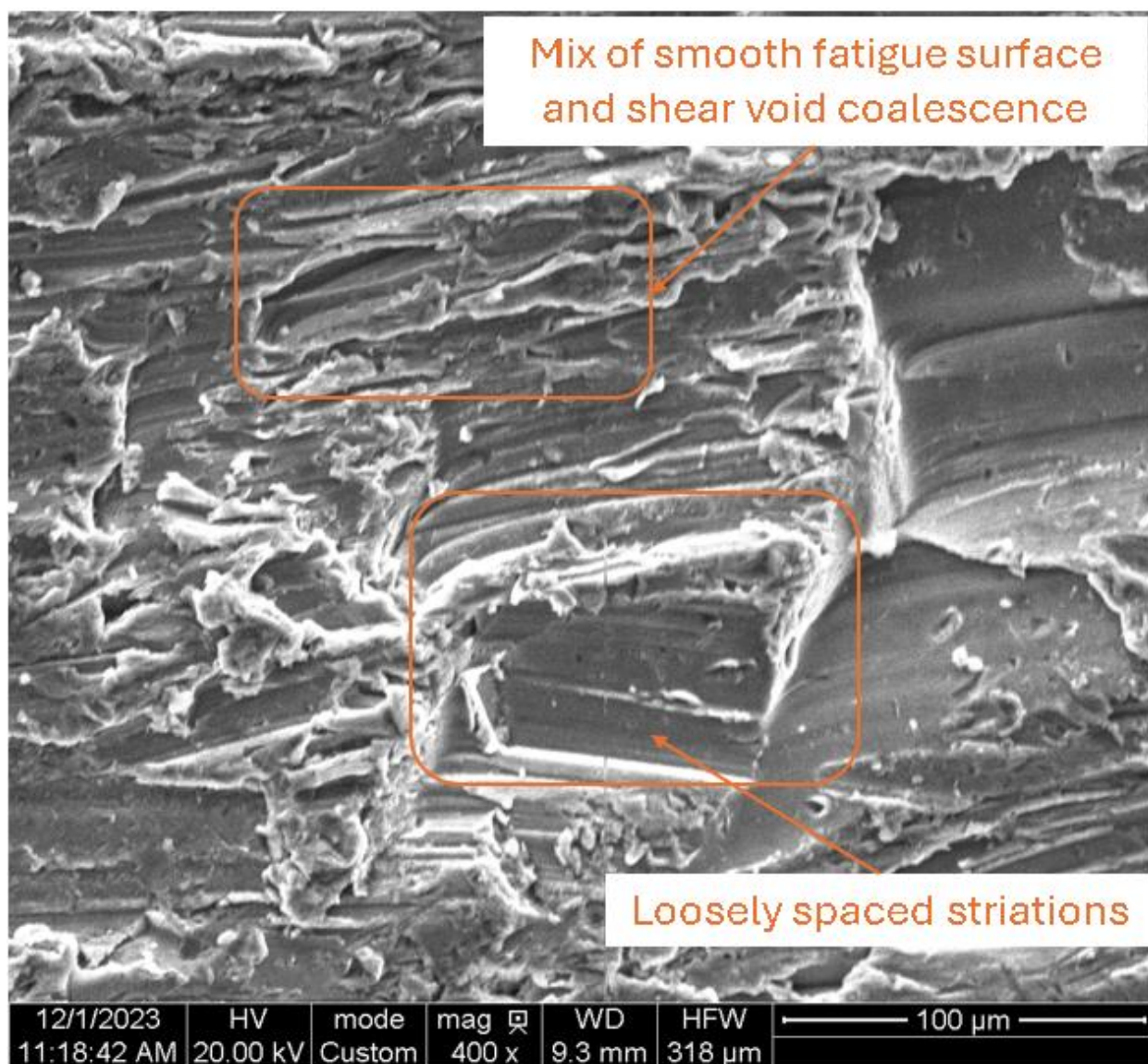


Figure 5-31: Larger possible striations or shear dimple coalescence observed at 400X magnification along the width of the joint.

6. Fatigue modelling of aluminum GMAW

Testing is completed at the University of Waterloo for 2.3 mm samples and at the partner company for 4 to 4.5 mm and 4 to 8 mm samples. All load life data is converted to structural stress life data using the Volvo method. The finite element methodology, analytical model for calculating structural stress, and correction factors are discussed. Two structural stress prediction curves are established, with select samples withheld from regression modeling for comparison between predicted and tested lives. The goal of this chapter is to unify the stress life data with statistical fitting and correction factors to present a design curve for al 6061-t6 GMA welded joints. The goal of this chapter is to present structural stress values for each tested geometry and loading condition, as well as industry modifying factors to further collapse the Volvo SN curves.

6.1. Purpose and Methodology of Volvo Method

A detailed overview of the finite element (FE) model used for predicting fatigue life of aluminum Gas Metal Arc Welded (GMAW) joints is provided. The necessity of FE modelling arises from the complexity of stress distribution in welded joints, which cannot be accurately captured using analytical methods alone. The model simulates the structural response of the welded joints under cyclic loading, allowing for the prediction of fatigue life based on stress analysis. Reported stress values have been normalized by the yield strength of AA 6061-T6 obtained by Vargas et al. [93] following ASTM: E8/E8 M-11.

6.1.1. Details of FEA modeling

Nodal forces and moments converge with a coarser mesh compared with element stress values. The use of an analytical model to calculate structural stresses gives rise to the label of a mesh independent approach as element sizes of five to ten mm could be used with sufficient accuracy. The standardization of the Volvo method relies on the following guidelines:

- First order quadrilateral shell elements should be used for all weld and base plate elements.
- The mid plane of each plate should be used.
- The assigned weld element thickness should equal the actual throat.
- Elements should be sized to 5 mm.
- Avoid modeling small radii and features.

The studied geometries were meshed with an element size of 5mm, and the element type used for the analysis was CQUAD4. To capture the stiffness of the weld, the lap joint was meshed with a one row element. Material properties utilized are listed in Table 6-1.

Table 6-1: Material parameters for FEM

Description	Parameter	Value	Unit
Youngs Modulus	E	70.0	GPa
Poisson Ratio	ν	0.3	GPa

The meshed geometry for the tee joint is shown in Figure 6-1 and the lap joint in Figure 6-2. All samples are meshed with a five mm element size. The tee joint top plate height varies based on the loading direction, and the width of the samples varies by plate thickness. The individual boundary conditions and applied loads will be discussed in a future section.

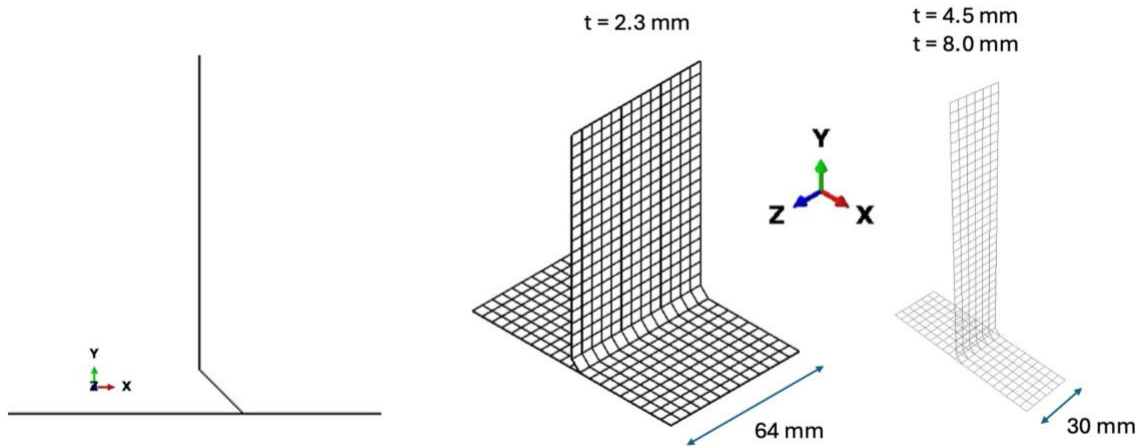


Figure 6-1: Tee joint meshing and FEA dimensions

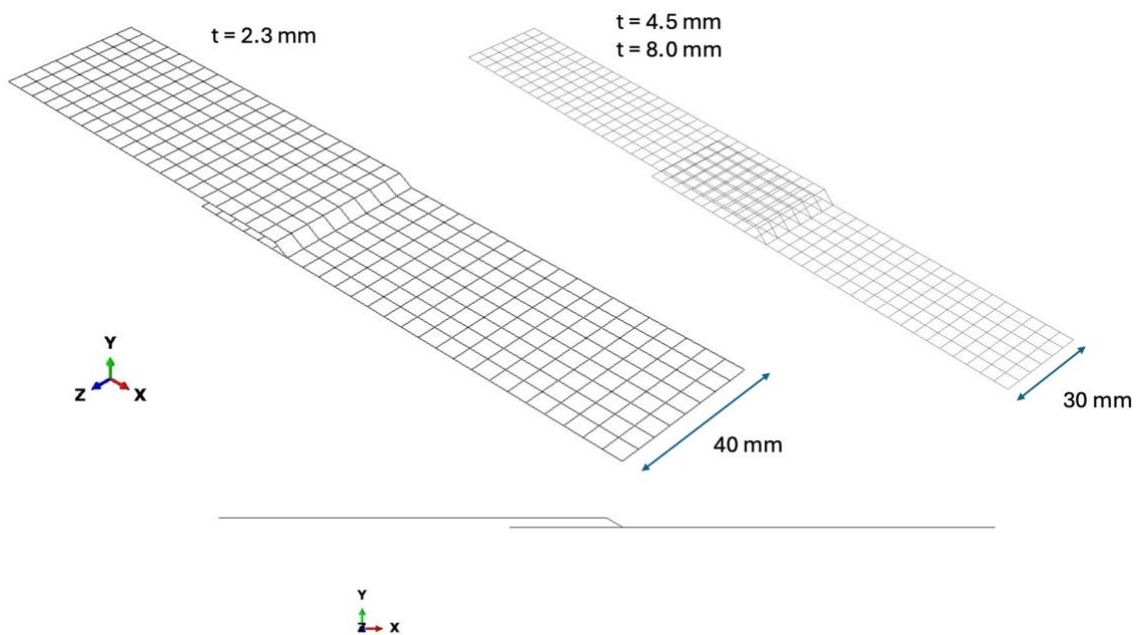


Figure 6-2: Lap joint meshing and FEA dimensions

Nodal forces and moments are the forces and moments that are applied directly to the nodes as either applied loads or reaction loads. Forces converge faster than FEA calculated stresses since they rely on continuous shape functions rather than discontinuous displacement gradients.

Nodes for calculation are selected based on the root and toe nodes of the weld, that share a border with the throat elements, with the top toe nodes shown in blue and the bottom toe nodes shown in orange in Figure 6-3. The bottom toe nodes will be used for all stress calculations to ensure consistency in reported values.

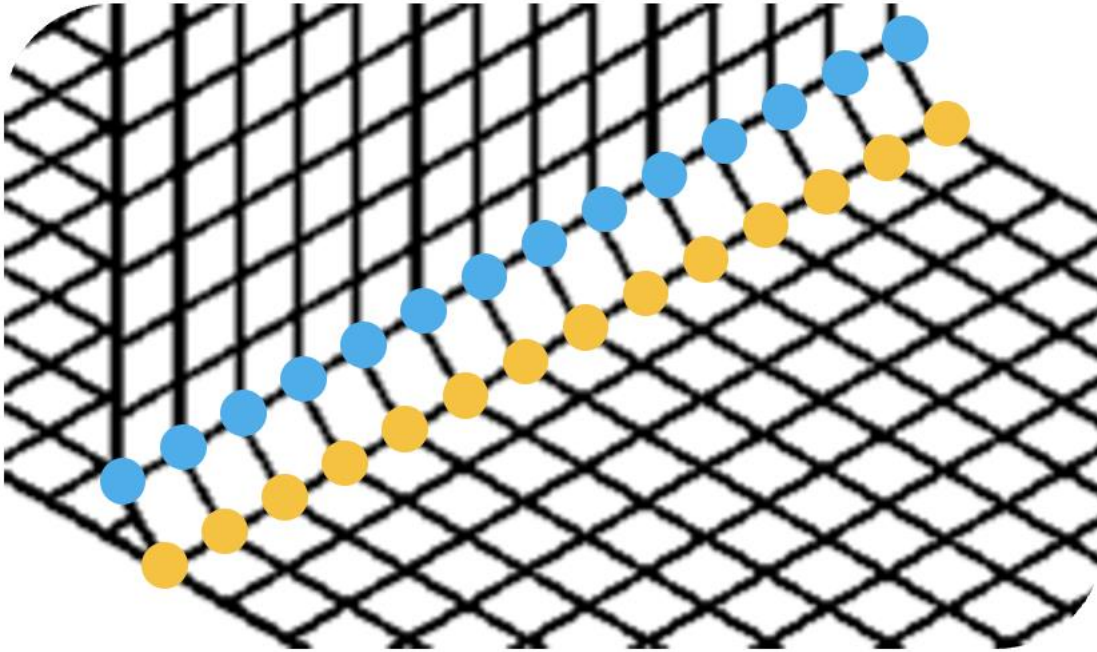


Figure 6-3:Volvo method nodes for stress calculation. All stresses are extracted from the orange bottom weld toe elements to ensure a consistent stress life curve.

As previously described in the literature review, structural stresses are calculated using the nodal forces and moments shown in Equation 9. Weld start and stop nodes will have one stress value as they are located at the edge of the model and interface with one element. The other nodes are shared between two elements and will have two structural stress values. maximum structural stress values are used to report life and construct the SN curve in this paper, as is recommended in the original method.

$$\sigma_{\perp} = \frac{-12M_y}{l_y t^2} - \frac{2N_x}{l_y t} \quad (9)$$

The prediction of fatigue life is outlined below in Figure 6-4, from the identification of the loading and construction of the joint to the modeling and calculation of structural stresses, and the eventual prediction of life for the untested joint. The prediction of life will depend on the resultant bending ratio.

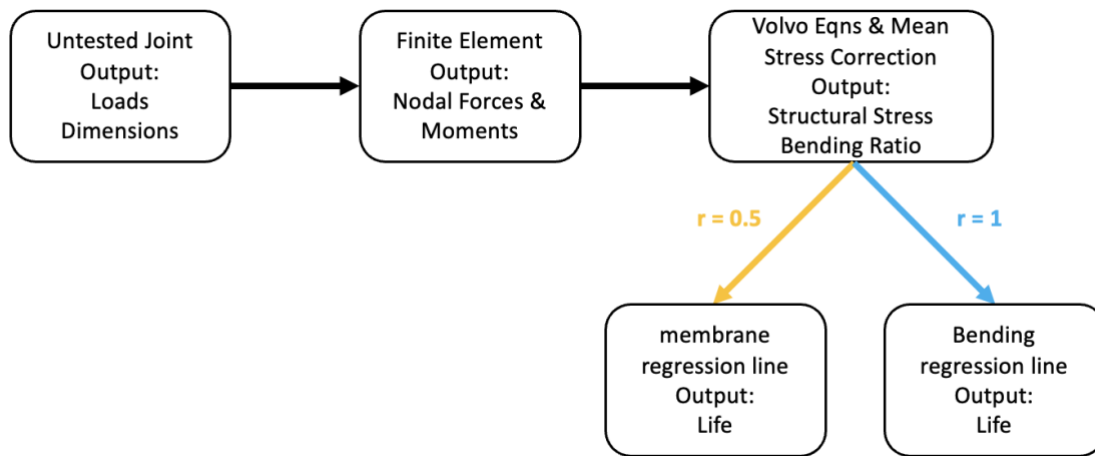


Figure 6-4: Fatigue life prediction flow chart for a sample without load life test data available

6.1.2. Detail results of modelling all different loading configurations

The UW experimental campaign consisted of 2.3 mm testing of lap joint Fx and tee joint Fz samples. Additional testing data from the industry partner is compared for 4 mm to 4.5mm and 4 mm to 8 mm lap joints and tee joints for Fx, Fy, and Fz loading directions for the purpose of validation and fatigue life prediction. The directions referenced for loading are shown in Figure 6-5 and used for describing sample configurations. Abaqus coordinate systems are referenced separately in FEA figures and boundary conditions (BC), where the Y and Z coordinates are switched. This additional data also enables the use of bending ratios around 0.5 for the construction of a membrane-based SN curve. A sensitivity study is performed based on known boundary conditions from the UW test and observed boundary conditions from the industry partner. Sample edges with fixture support are approximated as fixed, with the results shown in Table 6-2.

Table 6-2: Applied boundary conditions

Sample	Load Direction	Fx	Fy	Fz	Mx	My	Mz
Tee	Fx			Fixed	Fixed	Fixed	
Tee	Fy	Fixed				Fixed	Fixed
Tee	Fz	Fixed	Fixed		Fixed	Fixed	Fixed
Lap	Fx		Fixed	Fixed	Fixed	Fixed	Fixed
Lap	Fy	Fixed	Fixed		Fixed		Fixed
Lap	Fz		Fixed	Fixed	Fixed	Fixed	

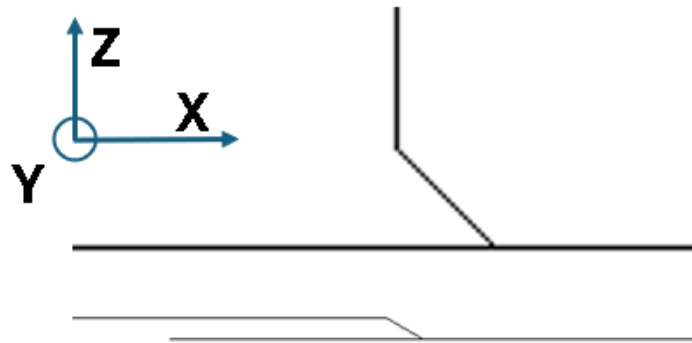


Figure 6-5: Coordinate system for applied loads, where X is along the length of the horizontal mating plates, Y is through the width of the weld, and Z is applied to the vertical tee member and as a 4 point bending load for the lap joint. ABAQUS coordinate systems are displayed in each FEA figure and used separately for BC and FEA figures, with Y and Z switching.

The lap joint applied load, boundary conditions and boundary dimensions are shown for loads in Fx, Fy, and Fz in Figure 6-6, Figure 6-7, and Figure 6-8. The tee joint applied load, boundary conditions and boundary dimensions are shown for loads in Fx, Fy, and Fz in Figure 6-9, Figure 6-10, and Figure 6-11. Support distances were measured from the fixture to the bottom toe of the weld. This ensured the maximum nodal moment was located at the bottom weld toe, which increased the consistency of structural stress conversion for tested samples.

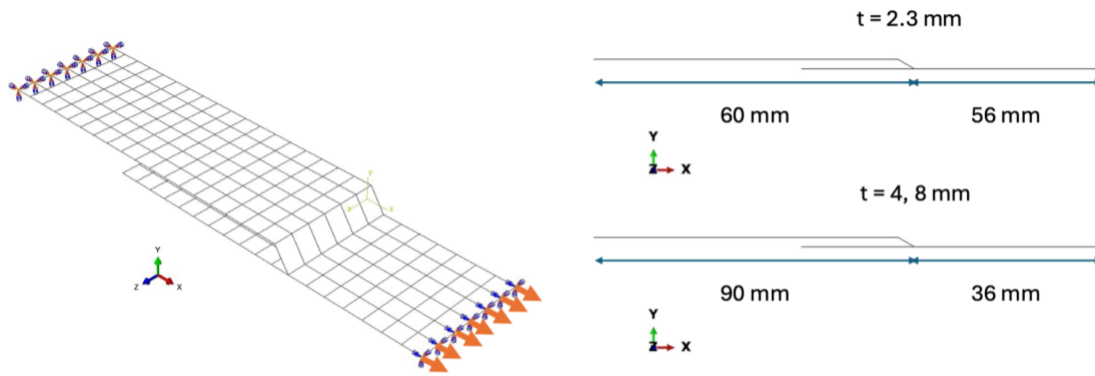


Figure 6-6: Lap joint Fx loading and boundary conditions. Loads distributed over nodes with loaded end boundary conditions

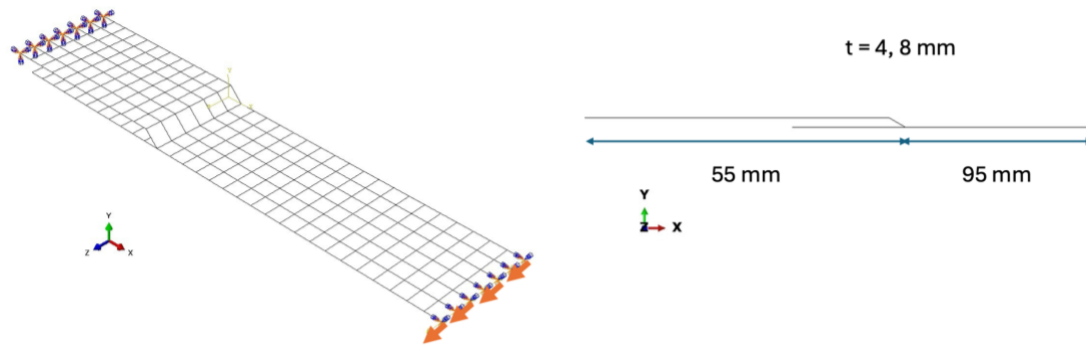


Figure 6-7: Lap joint Fy loading and boundary conditions. Loads distributed over nodes with loaded end boundary conditions

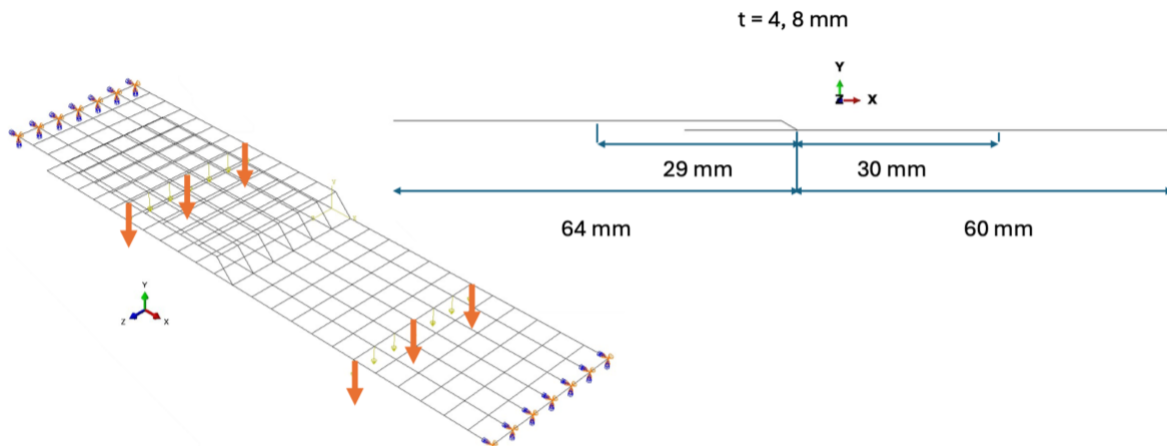


Figure 6-8: Lap joint Fz loading and boundary conditions. Loads distributed over nodes 30 mm from the lower weld toe

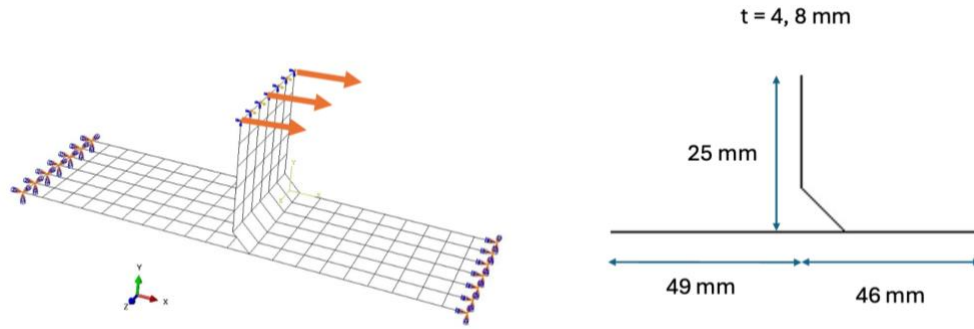


Figure 6-9: Tee joint Fx loading and boundary conditions. Loads distributed over nodes with loaded end boundary conditions

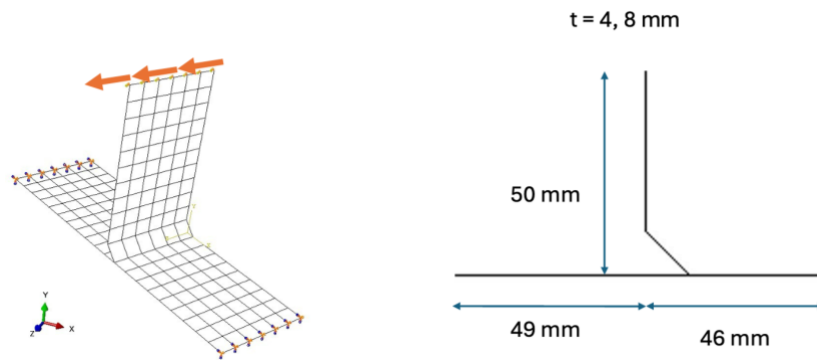


Figure 6-10: Tee joint Fy loading and boundary conditions. Loads distributed over nodes with loaded end boundary conditions

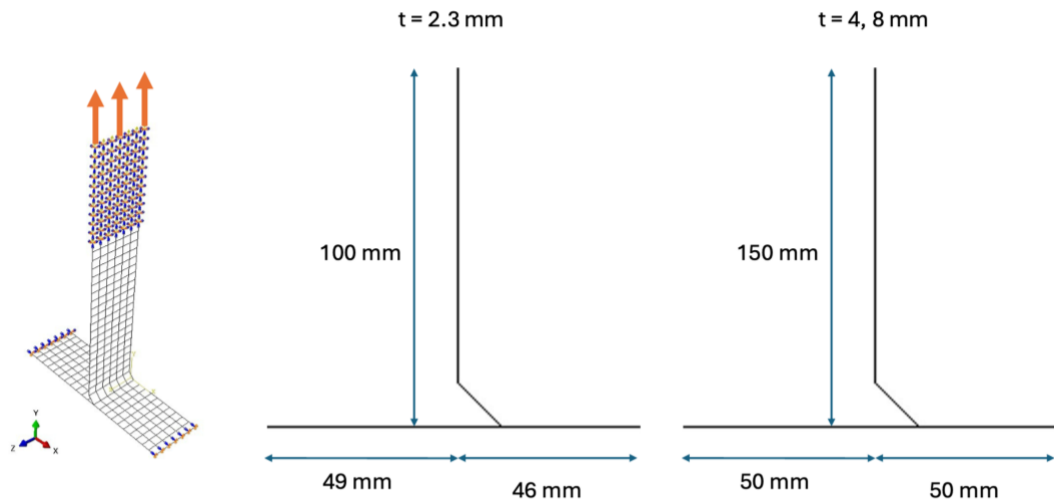


Figure 6-11: Tee joint Fz loading and boundary conditions. Loads distributed over nodes with loaded end boundary conditions.

6.1.2.1. Throat Modeling

Cracks initiated at the weld root for tee joint Fz and lap joint Fx samples, before propagation through the bottom plate and top plate HAZ respectively. A second element can be added to the FEA model to capture separate nodal force and moment values for a representative weld root, as well as to stiffen the modeled joint. The weld root can be extracted separately, as shown in Figure 6-12 and Figure 6-13. This is of particular interest to better capture the stress state for this initiation site.

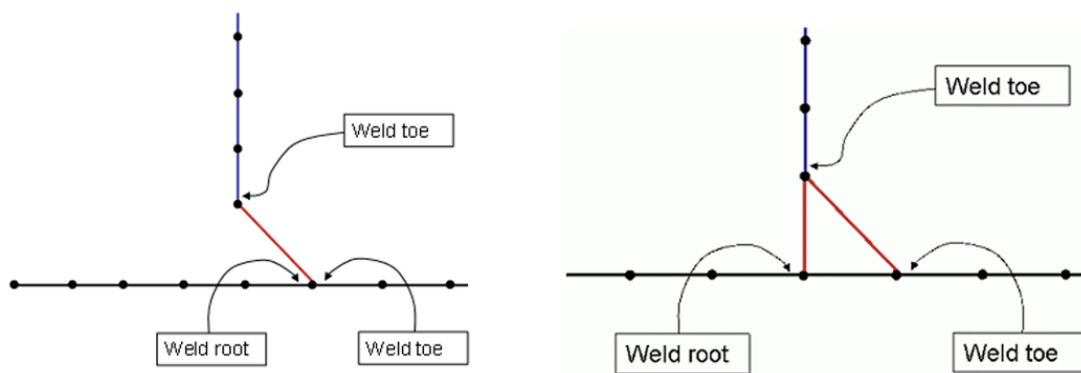


Figure 6-12: 1 vs 2 element method for tee joint

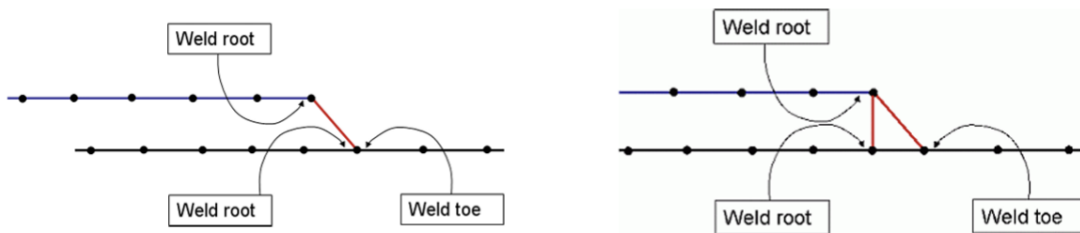


Figure 6-13: 1 vs 2 element method for lap joint

As shown in the table below, the tee joint stress values are identical for one element model at the toe compared with two element root stresses. The root of the lap joint does not display nodal force and moment reactions in the two-element method, so a comparison cannot be directly made. As such the consistent use of the one element method is acceptable to assign stress values to the model.

Table 6-3: 1 Vs 2 element stress comparison

Config	Life	1E	2E root	2E toe
Tee Fz	10000	1.16	1.17	1.06
	1000000	0.40	0.41	0.37
Lap Fx	10000	0.77	-	0.68
	1000000	0.40	-	0.36

Industry guidelines dictate a 4 mm by 4 mm weld height and width, which results in a constant weld element length for any thickness. The lap joint weld width is controlled to 4 mm but the height is an average of the two plate thicknesses. As such the weld element length increases with increasing thickness as shown in Figure 6-14. Sensitivity studies showed an insignificant change in the resultant stresses, so the industry guidelines should be followed consistently for the most repeatable results.

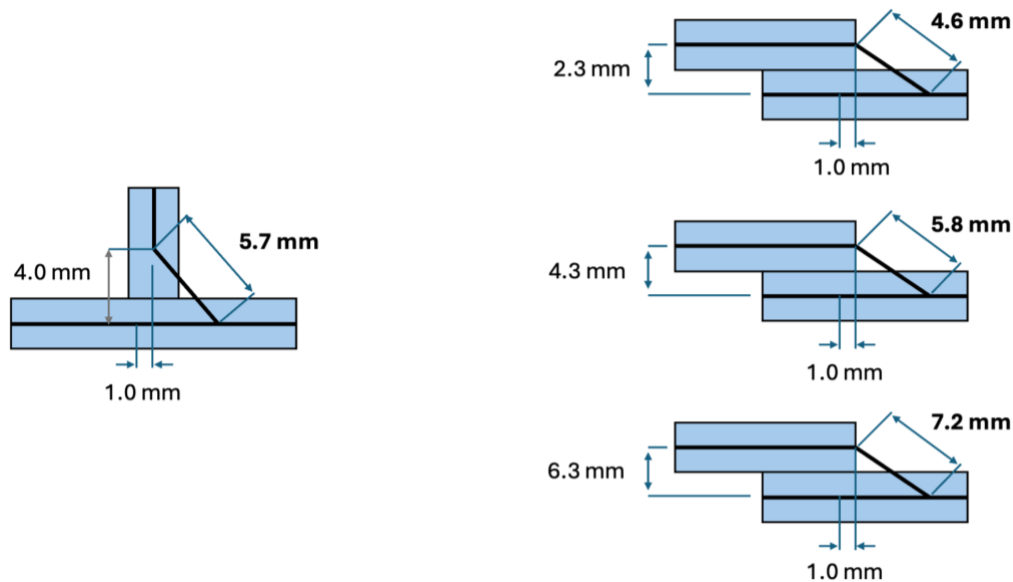


Figure 6-14: Following guidelines results in a consistent weld element length for the tee joint. The lap joint weld height depends on the average thickness of the two plates, so the weld element length increases with increasing thickness.

6.1.2.2. Bending Ratios

Construction of the bending and membrane SN curves and final design curve relies on a diverse population of bending ratios. The lowest bending ratios tested for aluminum GMA welds are 0.57 and 0.66, with similar structural stress values. The membrane curve for steel is used to describe bending ratios $r < 0.5$, with original data including samples with a bending ratio $r = 0.2$, 0.3 [54]. As such the samples with the lowest available bending ratio are used to construct the membrane curve for aluminum. Additional samples with higher bending ratios were not added to the membrane data, since the closest structural stress population had a bending ratio of 1.0, which removes the implied bending ratio trend. The normalized stress for each bending ratio is shown in Table 6-4, with bending ratio varying by sample geometry, loading type and thickness.

Table 6-4: Calculated bending ratios for all tests modeled, with normalized structural stresses at low and high cycle fatigue

Config	Load Direction	Thickness	Bending Ratio	Structural stress at 10,000 cycles	Structural stress at 100,000 cycles	Structural stress at 1,000,000 cycles
Lap	Fx	2.30	0.75	0.35	0.23	0.18
		4.00	0.72	0.26	0.18	0.17
		8.00	0.57	0.20	0.14	0.09
	Fy	4.00	0.66	0.16	0.12	-
		8.00	0.66	0.18	0.10	0.09
	Fz	4.00	0.83	0.63	0.35	0.28
		8.00	0.90	0.48	0.29	0.20
Tee	Fx	4.00	0.96	0.61	0.33	0.19
		8.00	0.93	0.11	0.07	0.05
	Fy	4.00	1.00	0.64	0.31	0.22
		8.00	1.00	0.31	0.21	0.14
	Fz	2.30	1.00	0.43	0.25	0.15
		4.00	1.00	0.50	0.29	0.17
		8.00	1.00	0.43	0.21	0.14

6.1.2.3. Stress Distributions

Each FEA model generates a given structural stress corresponding to the tested life of the experimental samples at that load range. Both the lap joint and tee joint geometries suggest application of an even load along the length or x axis of the weld, with a typical structural stress distribution shown for tee joints in Figure 6-15 and lap joints in Figure 6-16. It is recommended to take the maximum value observed, which typically occurred 5 mm from the end of the weld. Loads applied to the width or y axis of the weld see local hotspots shown in Figure 6-17 and Figure 6-18. The lap joint Fy load is shown to be continuous and as such the maximum value will be reported. Tee joint with load applied in FY is shown to be discontinuous, with a significant drop in the nodal moment across the element boundary. Averaging the two values across this discontinuity resulted in structural stress values consistent with the other joints. Applying a consistent averaging option within the FE solver will yield similar results.

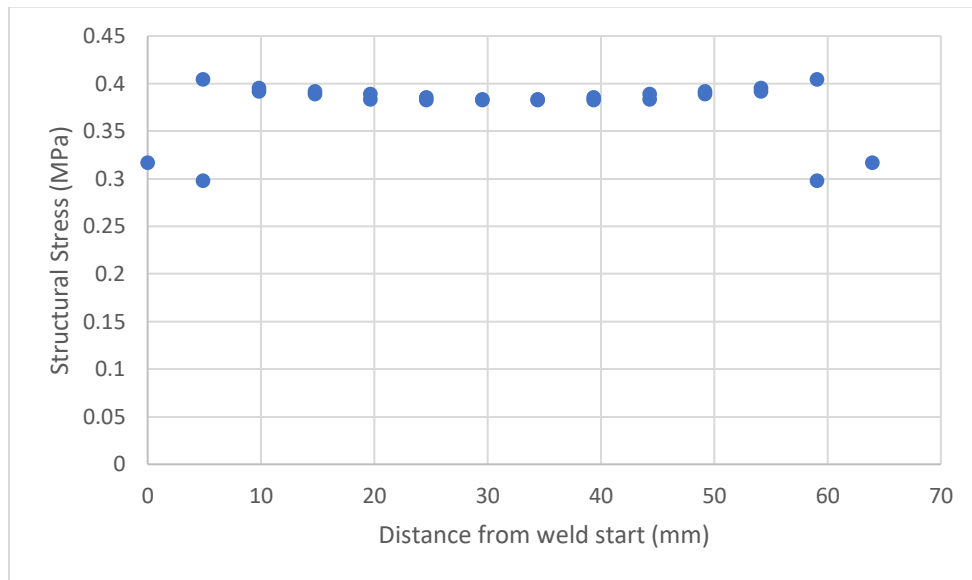


Figure 6-15: Characteristic tee joint normalized stress distribution. Maximum stress is reported for a 2.3 mm thick sample with Fz applied load for 1,000,000 cycle failure

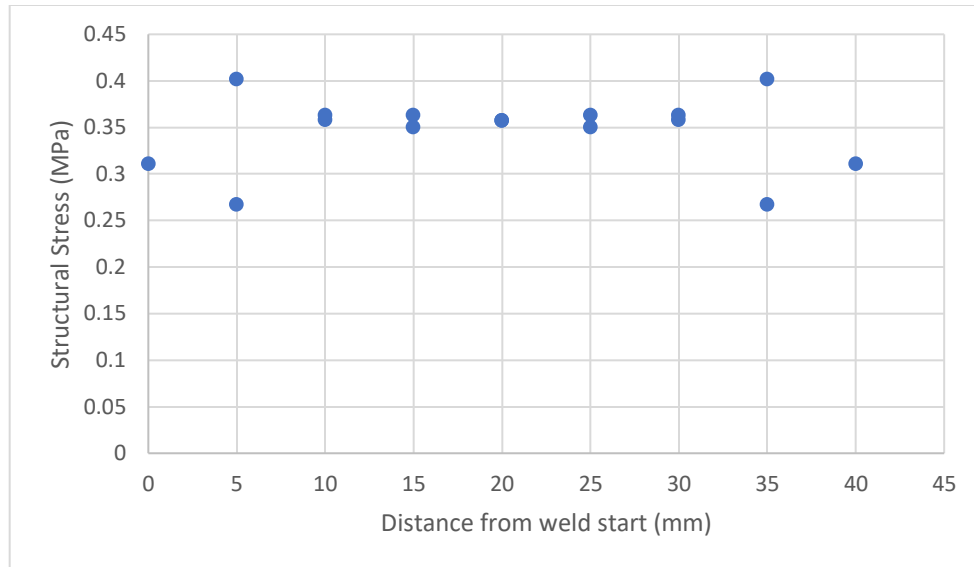


Figure 6-16: Characteristic lap joint normalized stress distribution. Maximum stress is reported for a 2.3 mm thick sample with F_x applied load for 1,000,000 cycle failure

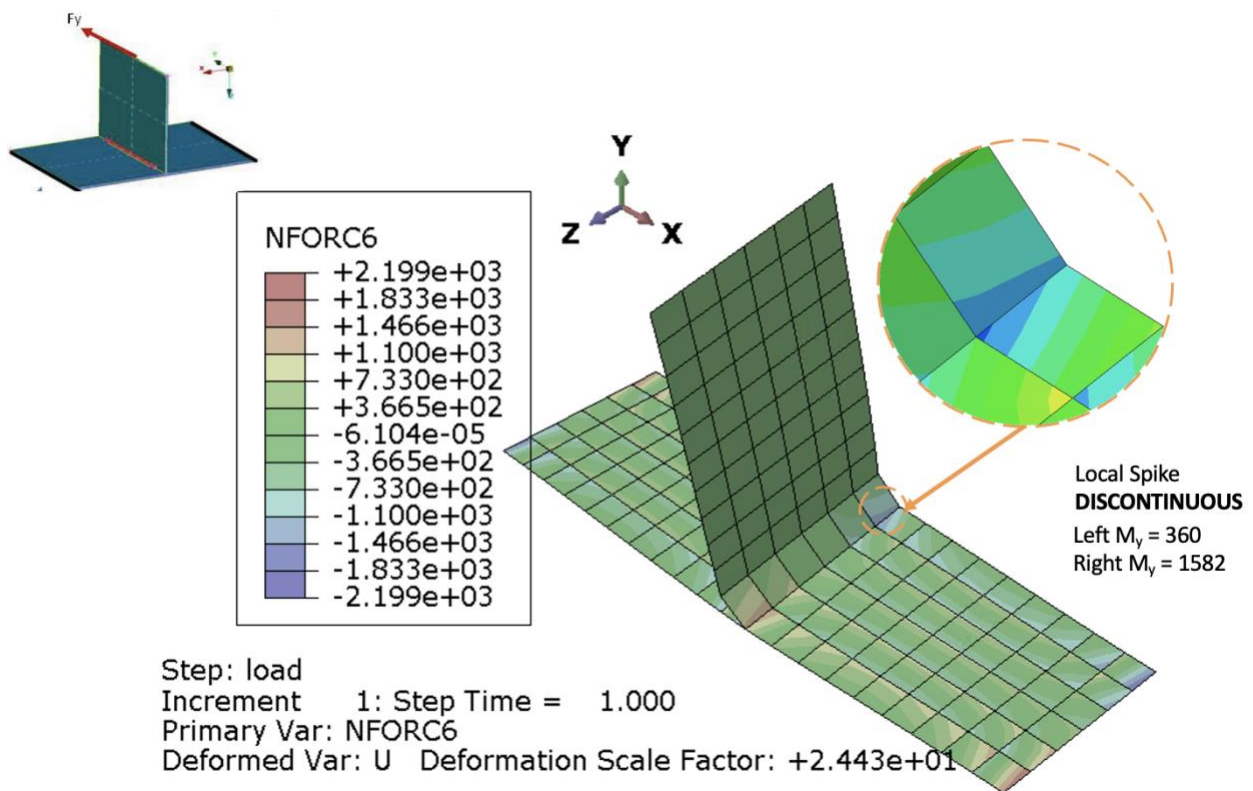


Figure 6-17: F_y discontinuous nodal moment, where the left and right elements report inconsistent nodal moments.

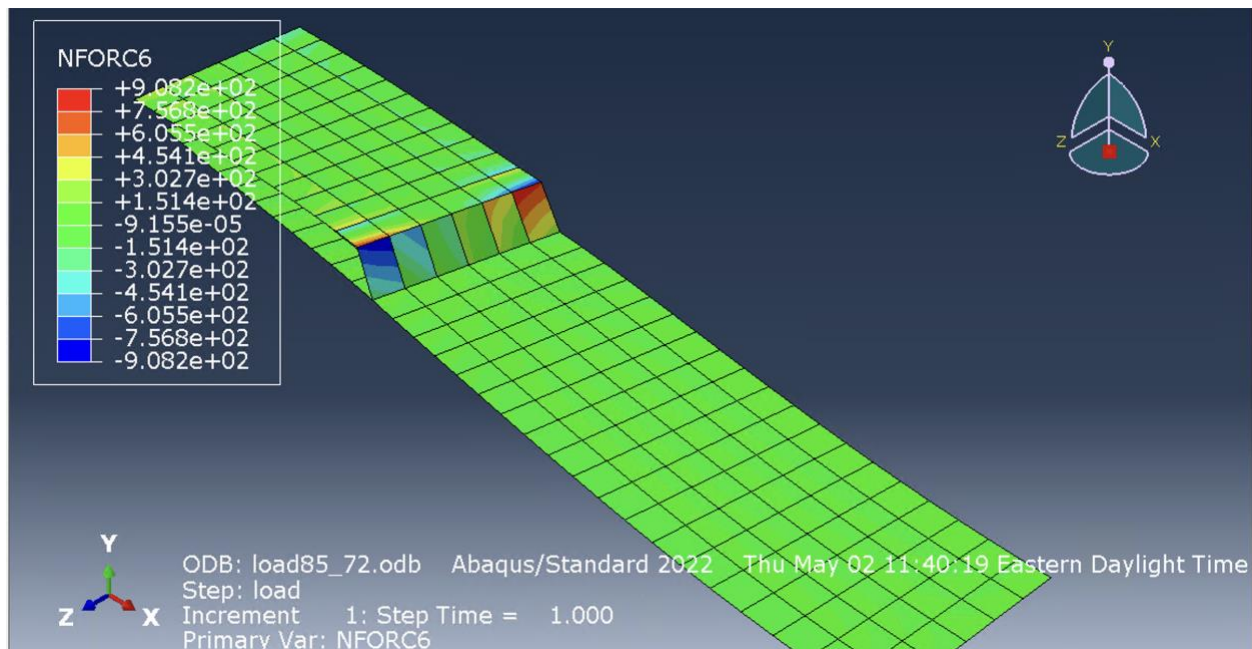


Figure 6-18: F_y continuous nodal moment, where local spikes in the nodal moment are continuous for lap joint samples, with left and right elements reporting a similar value.

6.2. Discussion on mean stress and thickness effects and current approaches in addressing them; potential comparison with results available in literature

6.2.1. Mean Stress Effects and Corrections

Welded joints are normally subjected to predominantly tensile cyclic loads with occasional compressive loads, but not fully reversed loading conditions. Tensile loads are more likely to open pre-existing cracks or flaws within the weld material, promoting crack initiation and growth. Implementing fatigue tests in compression can be more challenging due to the need for specialized fixtures to prevent buckling and to apply compressive loads uniformly. This increases the complexity and cost of the testing process. Most welded samples are tested at $R = 0.1$, but the thinnest tee joint specimens were tested at $R = 0.25$ to ensure a linear stiffness response and ensure precision of load measurements.

The correction of mean stress effects makes use of the Haigh diagram and existing mean sensitivity factors for thin welded sheet structures. Using $M_1 = 0.25$ and $M_2 = 0.097$, Equation 10 is used for $R > 0$ to combine plots for tee joint and lap joint samples.

$$\sigma_a(R = -1) = (1 + M_1) \frac{\sigma_a + M_2 \sigma_m}{1 + M_2} \quad (10)$$

Large automotive frames with multiple welded joints will accumulate distortion and associated mean stresses. Nonetheless existing commercial packages utilize stresses converted to fully reversed loading for the prediction of joints within a larger assembly.

6.2.2. Thickness Effects and Corrections

The original Volvo method tested 1-3 mm steel sheet and provided recommendations for that use. Subsequent studies tested additional samples at similar thicknesses, from 1.6 to 3.2 mm. Commercial software allows for the use of thickness correction factors based on existing welding standards. This correction is often used for thick plate fatigue in ship building applications, where size effects are visible above 25 mm. Standards have moved the reference thickness down to as little as 8 mm. The thickness correction is shown in Equation 11.

$$\sigma = \sigma_{ref} \left(\frac{t}{t_{ref}} \right)^n \quad (11)$$

Welding parameters must be optimized for each thickness, which can lead to weld shape differences and pronounced defects such as undercuts at the weld toe and incomplete fusion at the weld root. The size effect considers the observed decrease in fatigue life with increasing thickness due to the increased presence or size of crack initiating defects. The bending ratio and fixturing setup of the tested samples changes with increasing thickness, which changes the stress state within the weld and the increased out of plane loads from sample misalignment.

Mean stress corrected SN data in Figure 6-19 is compared against mean and thickness corrected SN data in Figure 6-20, where the lower bending ratio samples collapse into one cluster. The reference thickness samples reside at the lower end of the curve, so high stress Fy load samples increase the range of bending curve data. This trend is further displayed in Figure 6-21, where the added thickness correction is moving the population away from the reference thickness.

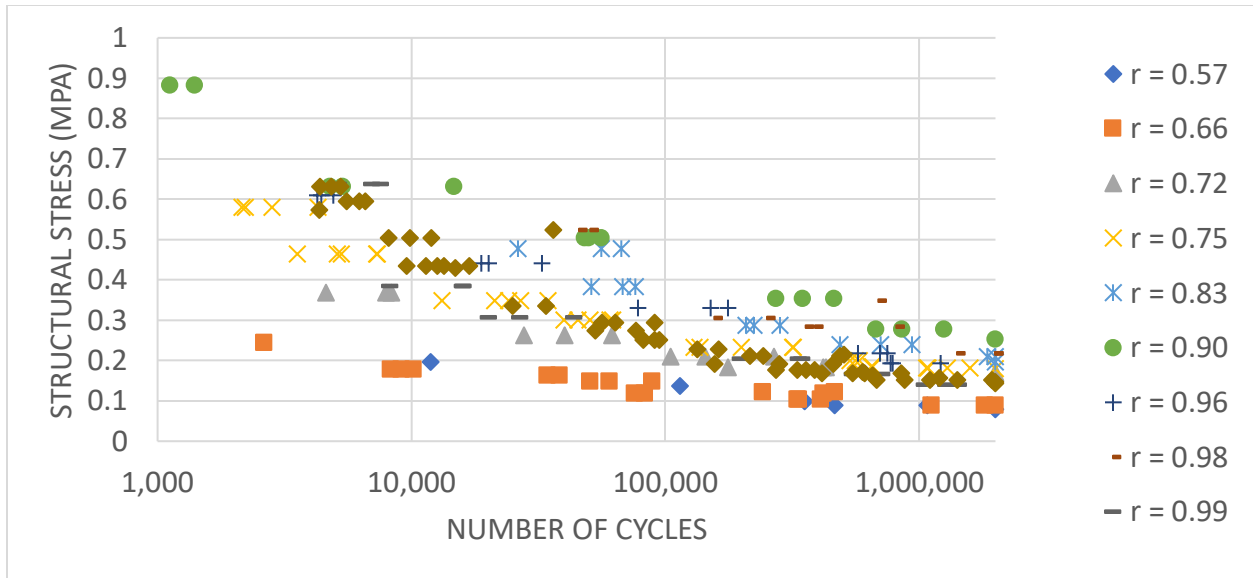


Figure 6-19: Mean stress corrected SN data for 2.3 mm, 4 mm, and 8 mm tee joint and lap joint samples loaded in Fx, Fy, and Fz

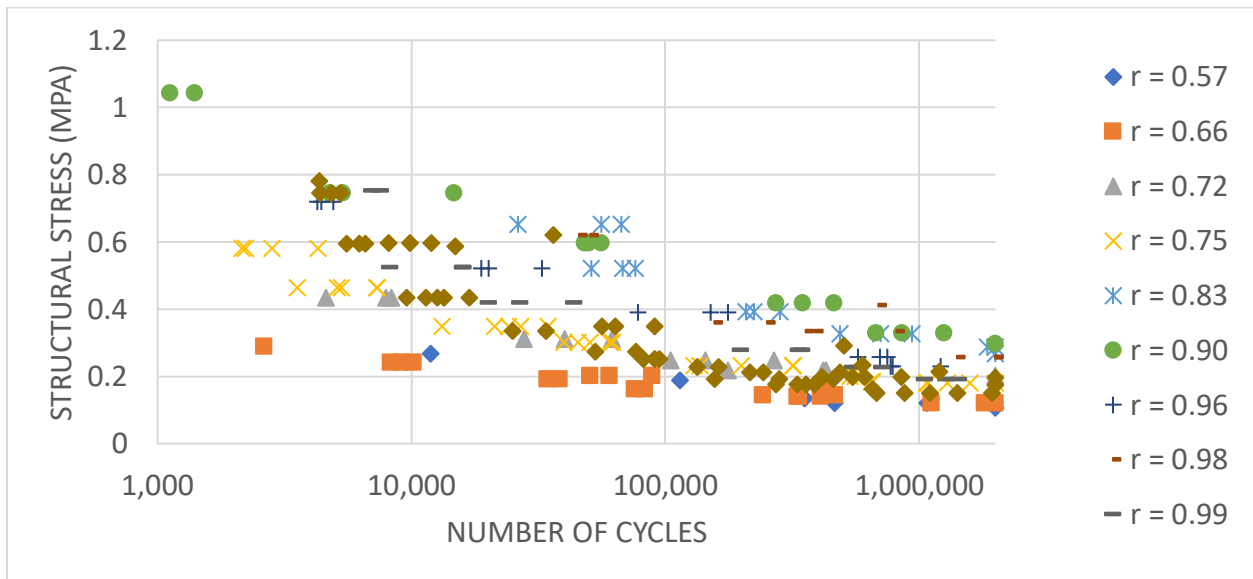


Figure 6-20: Mean and thickness corrected SN data for 2.3 mm, 4 mm, and 8 mm tee joint and lap joint samples loaded in Fx, Fy, and Fz

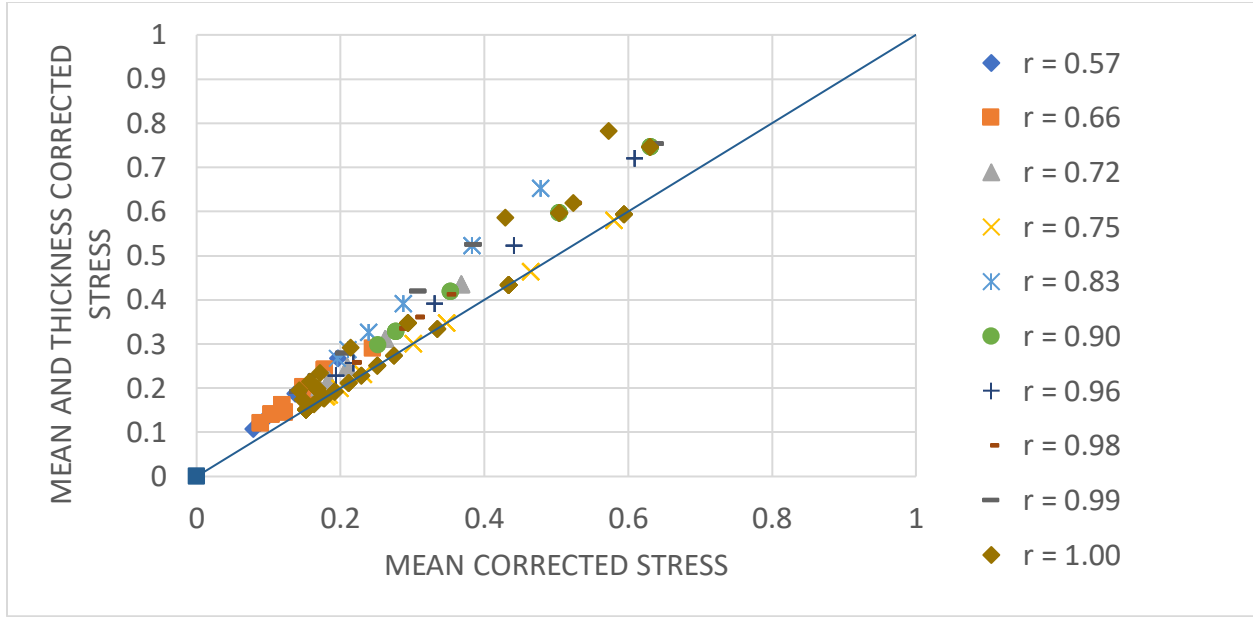


Figure 6-21: Mean vs mean and thickness corrected data. Since thicker specimens report similar or higher structural stresses than the reference 2.3 mm samples, the overall scatter of the model increases at a detriment of fit.

6.2.3. Verity Fracture Mechanics and Corrections

The Verity method utilizes fracture mechanics to collapse multiple geometries to one master SN curve. The fracture mechanics used in this approach is outside the scope of the al GMA weld study but is discussed to show future correction factors. The initial method for converting structural stress range to an equivalent structural stress range starts with Equation 12, which calculates the crack growth rate.

$$\frac{da}{dN} = C(M_{kn})^n(\Delta K_n)^m \quad (12)$$

ΔK_n is based on through thickness bending and membrane stresses and M_{kn} representing the ratio of notch effects on the magnitude of K near the weld toe at $a/t = 0$. Experimental crack growth rate data is used to calculate n and m as constants for the given material. M_{kn} can be approximated using the calculated structural stresses for a given population, leading to Equation 13.

$$N = \frac{1}{C} t^{1-\frac{m}{2}} (\Delta\sigma_s)^{-m} I(r) \quad (13)$$

The structural stress range $\Delta\sigma_s$ is further modified with an interpolation function for the bending ratio r , defined in Equation 14.

$$I(r) = \int_{\frac{a}{t}=0}^{\frac{a}{t}=1} \frac{d\left(\frac{a}{t}\right)}{(M_{kn})^n \left[f_m\left(\frac{a}{t}\right) - r \left(f_m\left(\frac{a}{t}\right) - f_b\left(\frac{a}{t}\right) \right) \right]^m} \quad (14)$$

Once the interpolation function is known an equivalent structural stress parameter can be defined by normalizing the life equation with the C and N terms to generate ΔS_s shown in Equation 15.

$$\Delta S_s = \frac{\Delta\sigma_s}{t^{\frac{2-m}{2m}} I(r)^{\frac{1}{m}}} \quad (15)$$

The final thickness term is used as a ratio of the given thickness over a reference thickness. The equivalent structural stress range has been established for steel, as shown in Figure 6-22, where a large structural stress range varying by thickness, loading type and geometry with similar scatter to the aluminum samples presented collapsed when combined with the thickness and loading correction factors.

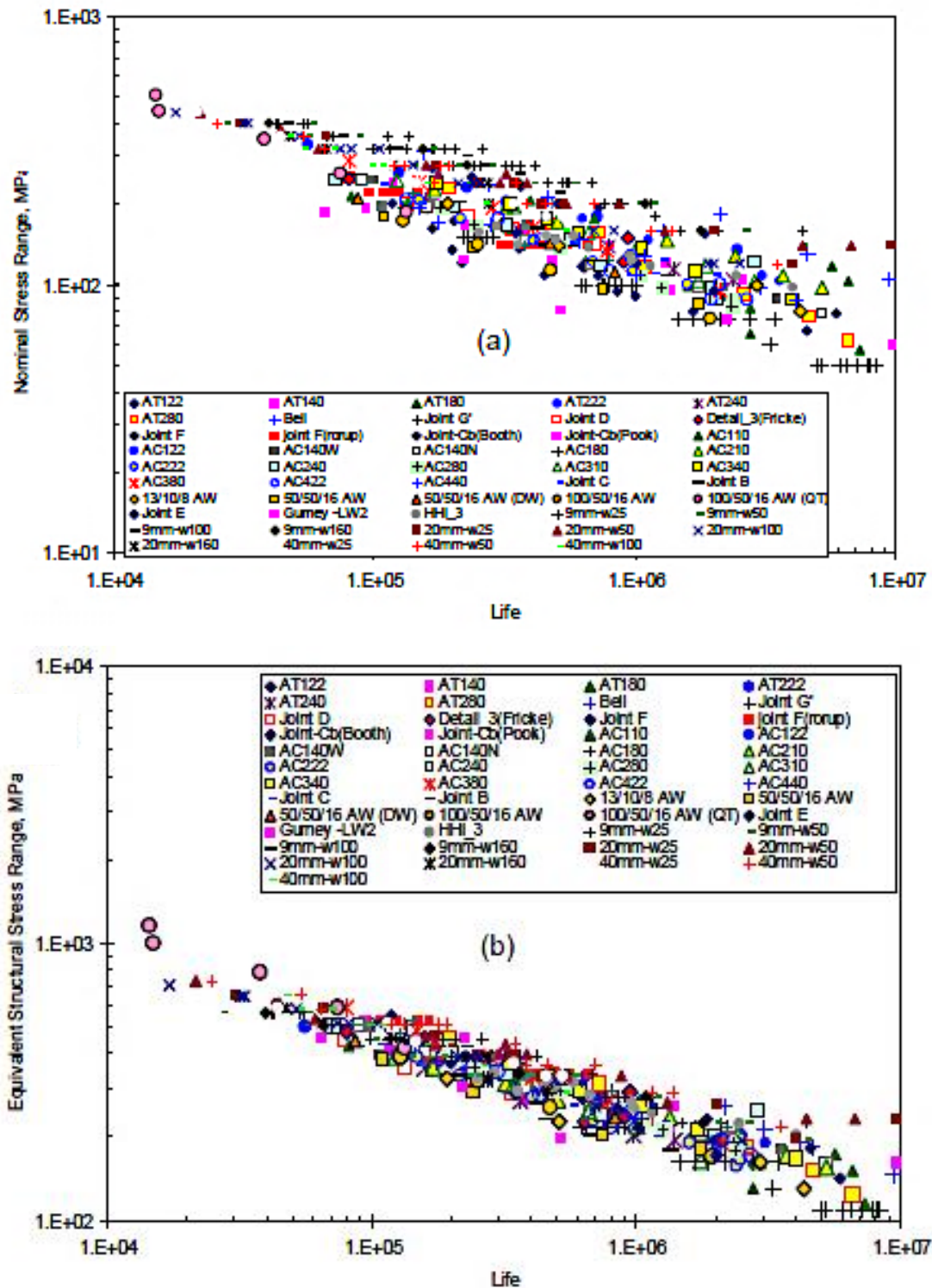


Figure 6-22: Top) Structural stress range data accumulated from literature. Bottom) Equivalent structural stress range showing decreased scatter for the same population. Obtained from [94].

6.3. Establish SN Curve

6.3.1. Full Dataset and Scatter Discussion

The Volvo method used to predict the fatigue life of al GMA welds requires emerging patterns based on the previously calculated bending ratio. The initial paper recommends constructing the lower curve with bending ratio samples between 0 and 0.5. This leaves bending ratio samples of 0.51 to 1.0 for the construction of the upper curve, with a request for further study. The stress life relation of each sample tested is grouped by bending ratio value and displayed in Figure 6-23.

Sources of scatter in the large dataset come from material, sample, and testing conditions. Variations during the welding process were minimized but will still exist. Thicker samples will have a separate weld profile. Multiple samples removed from a larger will also exhibit surface effects on either end. Fixturing, sample alignment and the three loading types will also impart different levels of scatter within the data. Lastly, the conversion of load to structural stress values and approximation of test boundary conditions aims to capture a similar stress state across all samples, but variations will exist. These effects exist independently of the mean stress corrections applied or the proposed thickness corrections that were trialed. The sources of scatter were considered during test setup. Initial results show large scatter, with no proportional pattern emerging between increasing bending ratio and resulting structural stress. The sources of scatter could influence the predicted bending ratio trend and will be discussed below.

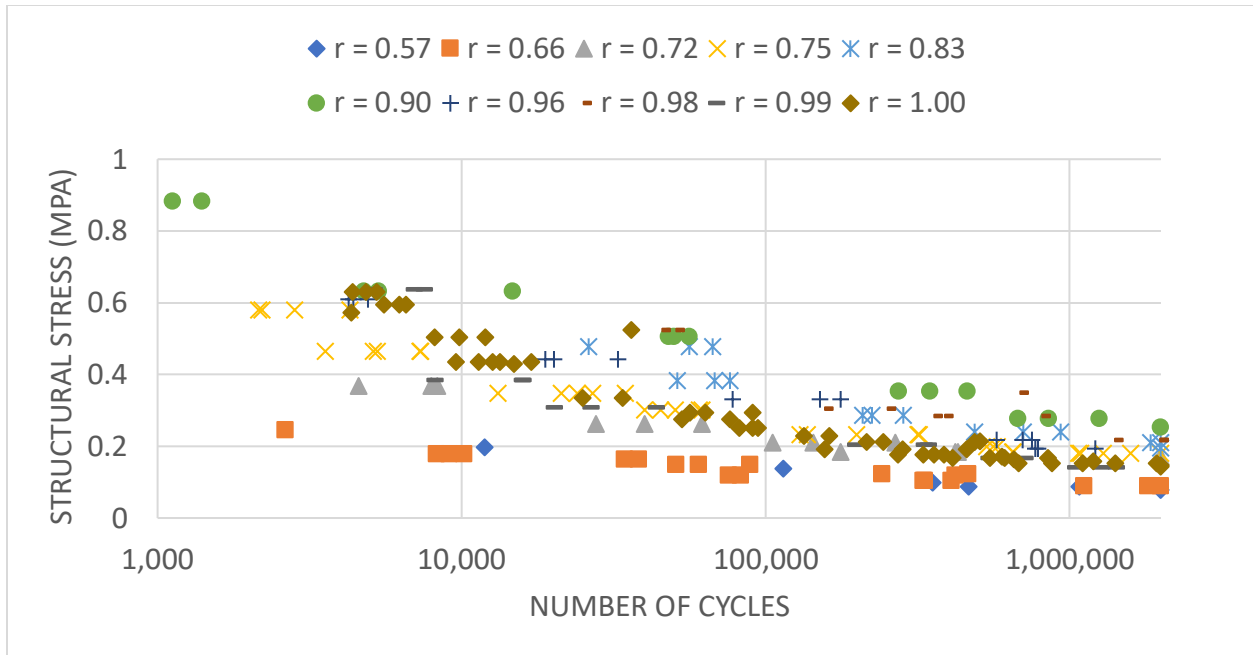


Figure 6-23: Sample stress life relation, grouped by bending ratio.

6.3.2. Membrane Curve

6.3.2.1. Bending Ratio Subset and Regression

The available data for al GMA welds suggests using $r = 0.57$ and $r = 0.66$ for construction of the lower curve. Each sample type collapses well into one power law curve with an R^2 ratio of 0.9274, above the threshold of 0.80 for a good fit shown in Figure 6-24. A regression line of best fit formed with all membrane data shown in Equation 16 is used to compare predicted lives with actual measured lives for a given structural stress. The predictions in Figure 6-25 fall within 3 multiples of the actual life for the measured samples.

$$N = 0.5429\sigma^{-5.983} \quad (16)$$

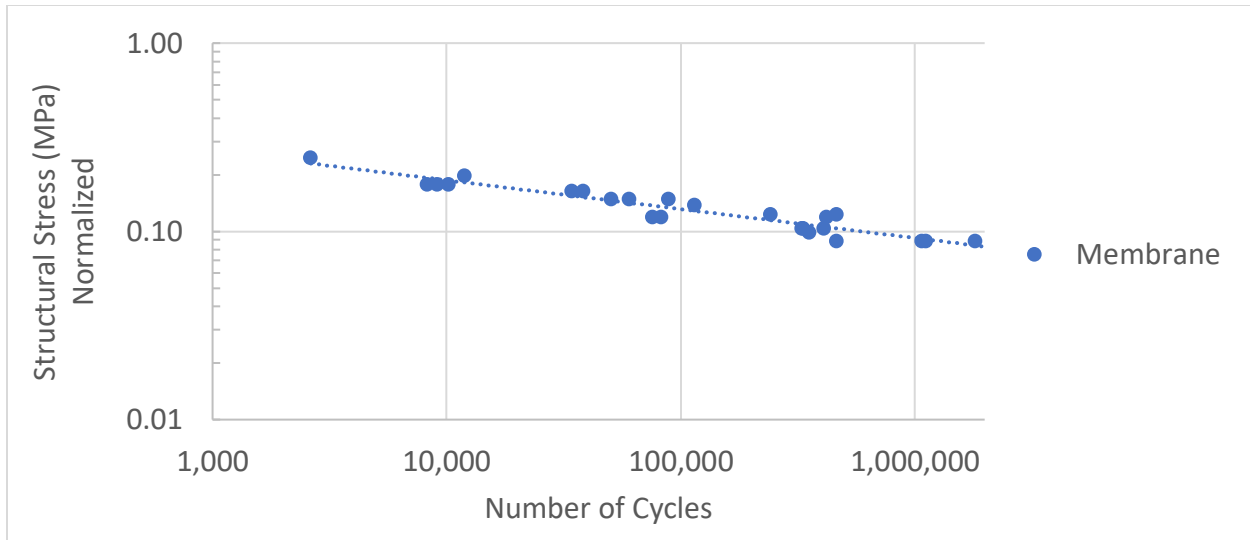


Figure 6-24: Line of best fit for membrane population.

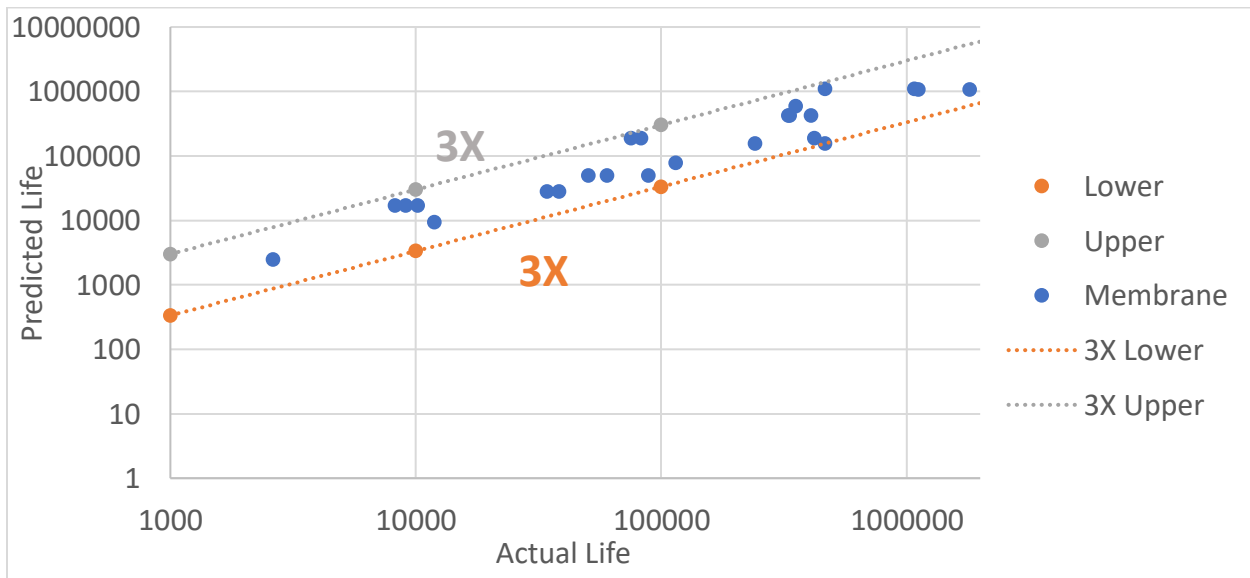


Figure 6-25: Membrane curve prediction performance for membrane population.

6.3.2.2. Prediction of Membrane Curve

4.5 mm thick lap Fy samples are withheld from the regression model to avoid influencing predicted life. The resultant line of best fit is shown in Equation 17, with the remaining datapoints shown in Figure 6-26. The actual vs predicted lives are shown in Figure 6-27, with predicted lives falling within 3 orders of magnitude or 3 folds of the actual life. Membrane prediction has a smaller population and less scatter as a result. Runout samples are excluded from regression.

$$N = 3.0265\sigma^{-5.146}$$

(17)

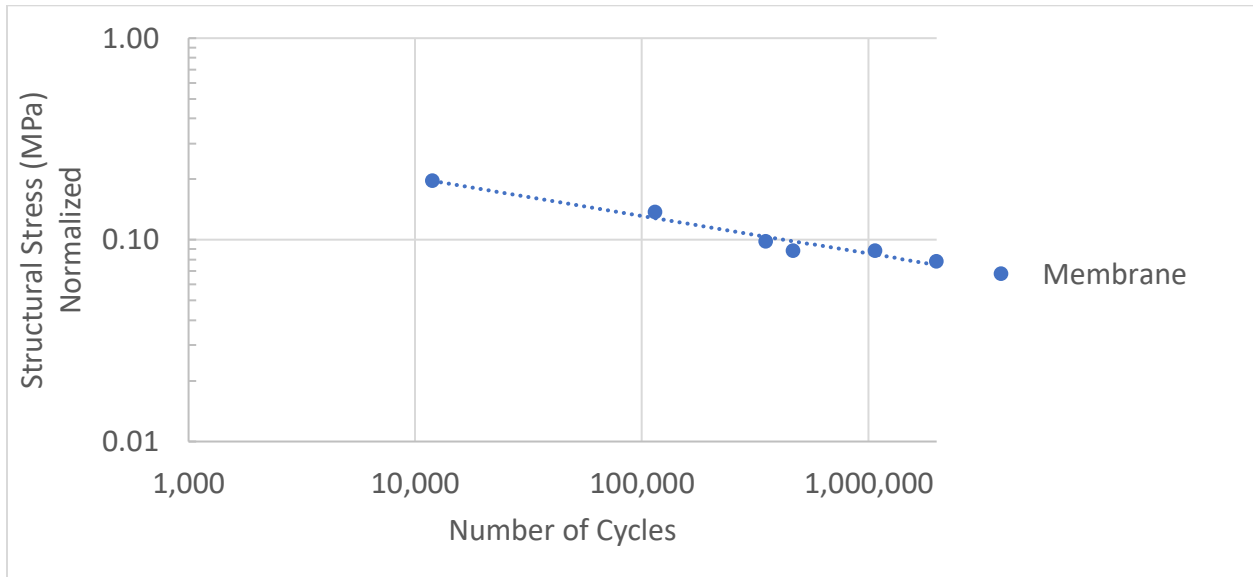


Figure 6-26: Membrane regression curve with lap Fy samples removed for validation.

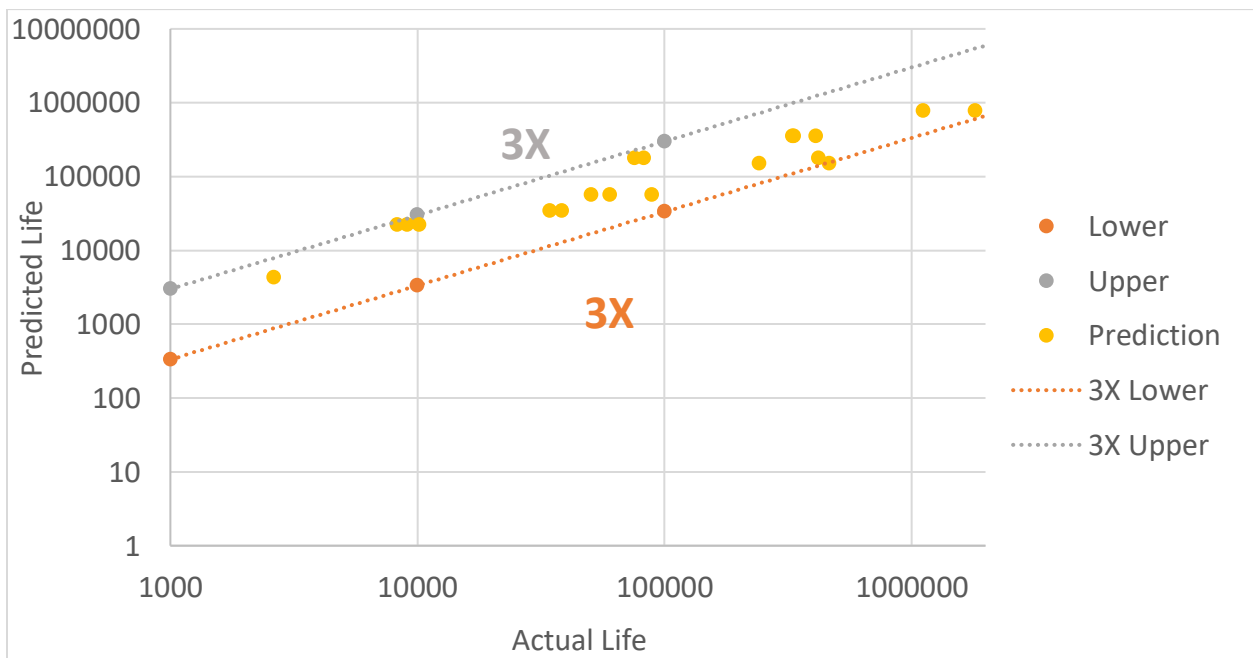


Figure 6-27: Membrane prediction results for lap Fy samples removed for validation.

6.3.3. Bending Curve

6.3.3.1. Bending Ratio Subset and Regression

The remaining population with a bending ratio of 0.75 or higher is used for construction of the upper curve. Each sample type collapses well into one power law curve with an R^2 ratio of 0.7935, close to the required 0.80 for a good fit shown in Figure 6-28. A regression line of best fit formed with all membrane data shown in Equation 18 is used to compare predicted lives with actual measured lives for a given structural stress.

$$N = 849.6\sigma^{-3.912} \quad (18)$$

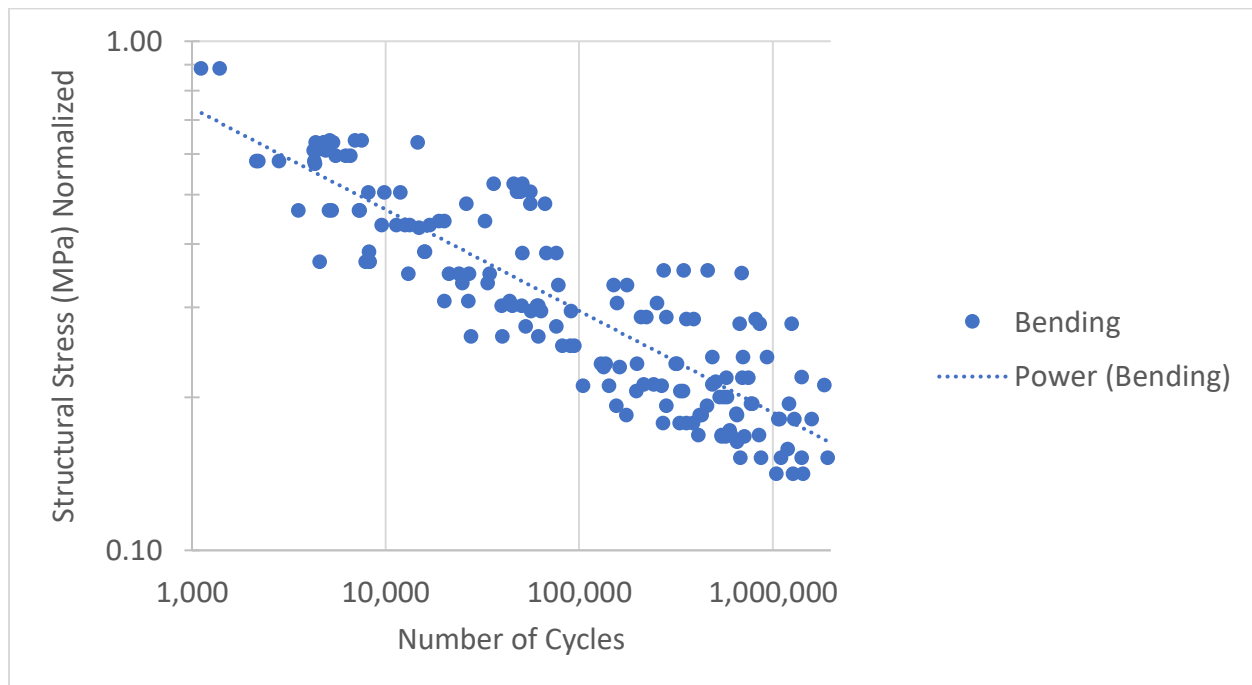


Figure 6-28: Line of best fit for bending population

The predictions shown in Figure 6-29 are centered within 3 orders of magnitude of the line of best fit, with outliers appearing near 1,000,000 cycle and 1,000 cycle lives. The bending curve underestimates life near runout and overestimates life at low cycle fatigue on average. Runout samples are excluded from regression.

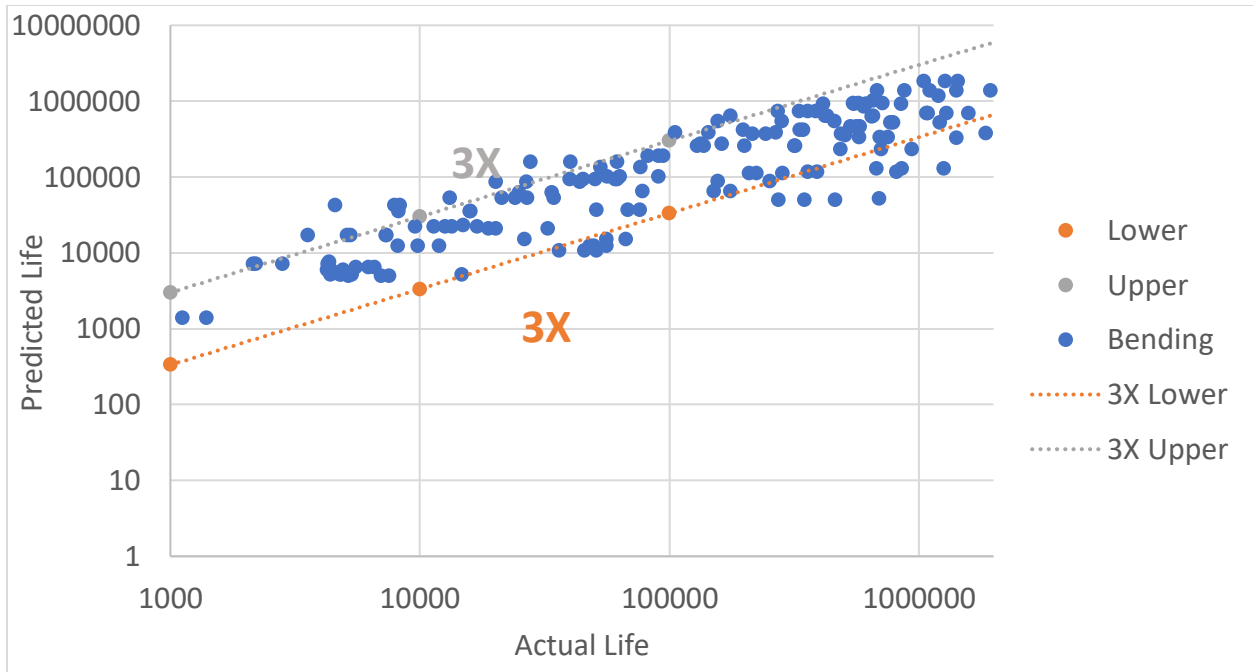


Figure 6-29: Bending curve prediction performance for bending population.

6.3.3.2. Prediction of Bending Curve

8 mm thick lap Fz samples and 4.5 mm thick tee Fx samples are withheld from the regression model to avoid influencing predicted life. The resultant line of best fit is shown in Equation 19, with the remaining datapoints shown in Figure 6-30. The actual vs predicted lives are shown in Figure 6-31, with the model underpredicting the lives of both samples by more than a factor of 3.

$$N = 15.371\sigma^{-6.476} \quad (19)$$

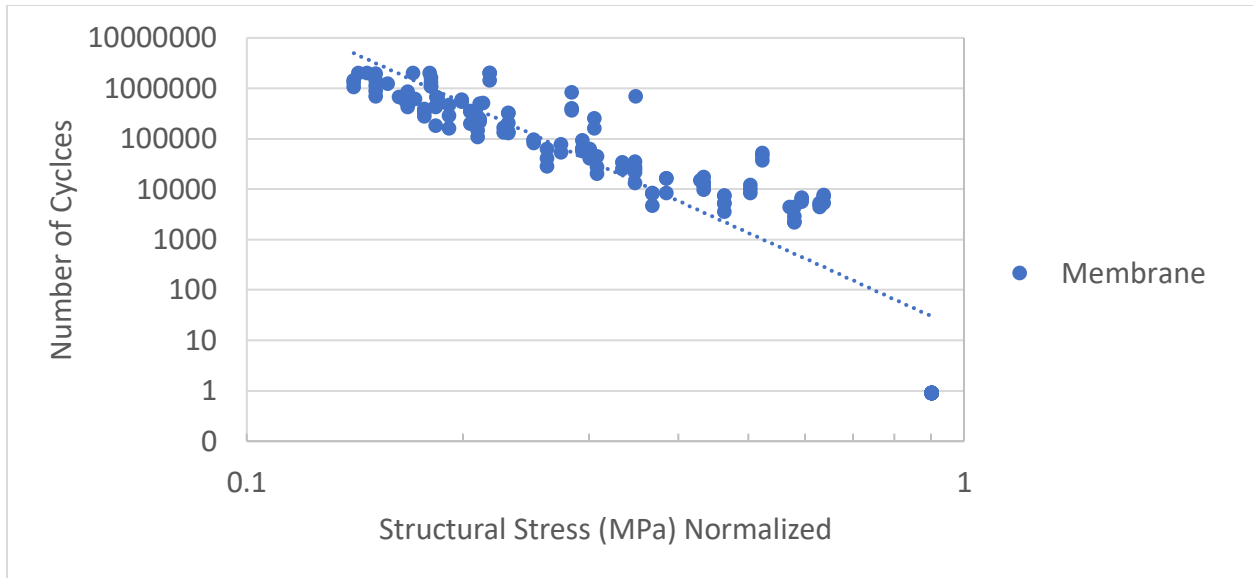


Figure 6-30: Bending regression curve with lap Fz and tee Fx samples removed.

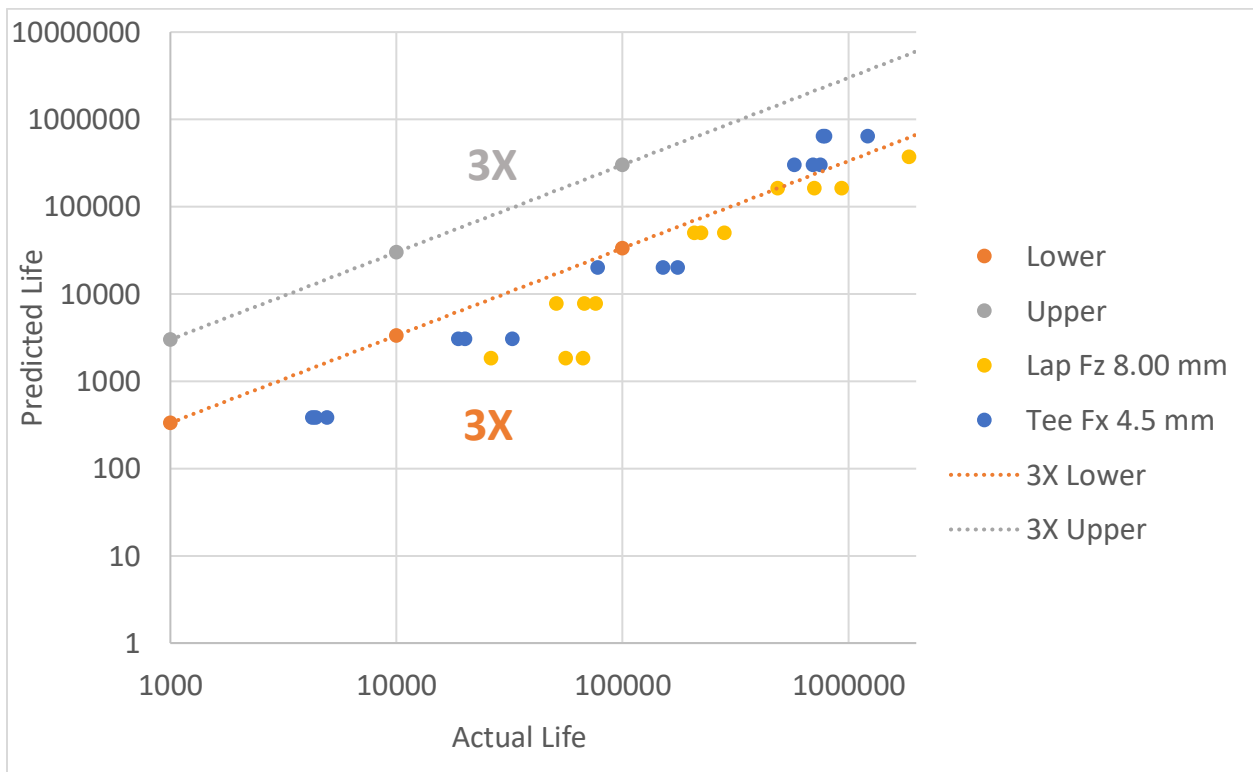


Figure 6-31: Bending prediction performance for lap fz and tee fx samples removed for validation.

The bending curve population includes samples subjected to high bending moments as well as the samples applied in plane shear. The shear samples also saturated the bending ratio at the point of highest structural stress, which further drives scatter in this population. Original investigations did not include shear samples, as the conventional structures and test setups favored uniaxial loading. However, the recent interest in using the Verity method for multiaxial fatigue is driving further interest in FEA guidelines. Hong et al. [82] recently trialed meshing techniques for samples within plane shear loading. Following conventional guidelines resulted in higher structural stresses compared with bending and membrane samples as well as increasing structural stress with increasing element size. The model was made mesh insensitive after the inclusion of an additional element at the weld end, aligning extracted stress values with expected values. The method will not be implemented for SN curve implementation in this thesis, but a trial model resulted in 12.78 % lower shear values for the tee joint 4.5 mm sample loaded in F_y .

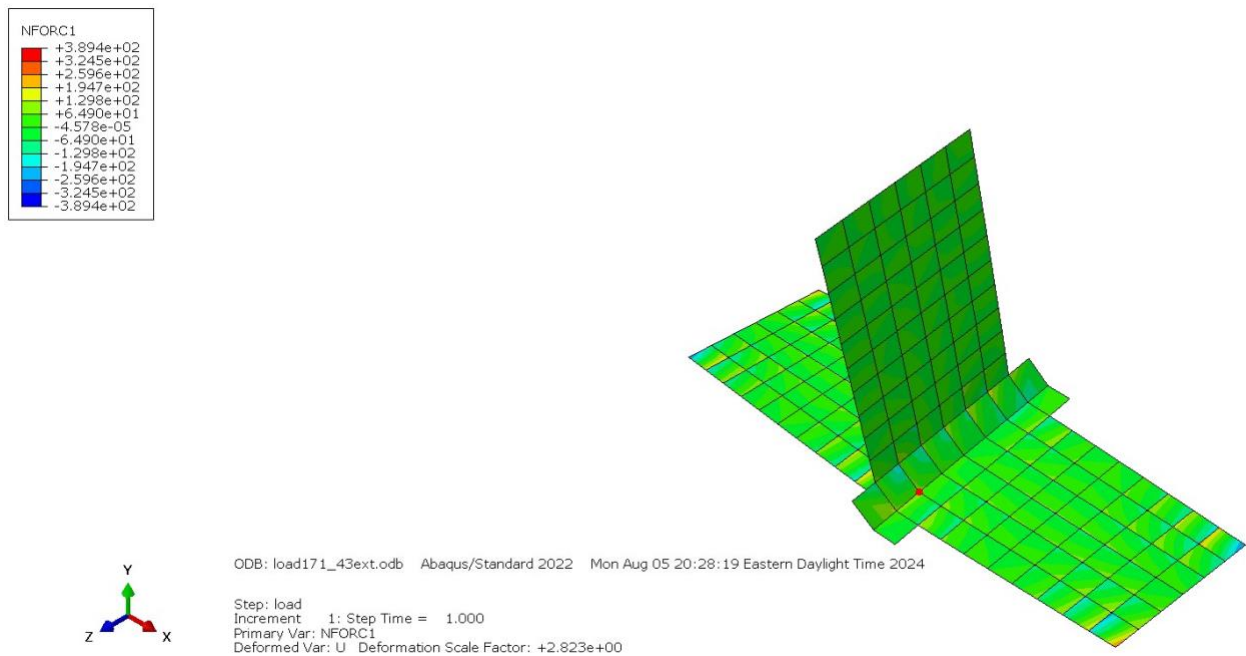


Figure 6-32: Extended element method to ensure consistent in plane shear.

8. Conclusions, Recommendations and Future Work

The primary objective of this thesis was to validate the Volvo method for predicting the fatigue life of thin sheet 2.3 mm AA-6061-T6 with 4043ER filler wire gas metal arc welded (GMAW) joints used in electric vehicle battery packs. The study successfully demonstrated the applicability of the Volvo method for aluminum GMAW welds, characterized by its reliance on multiple structural stress versus life (S-N) curves separated by bending ratio. The findings highlighted the significance of weld geometry and microstructural properties, especially the heat-affected zone (HAZ) and weld metal (WM) interface characterized in Chapter 4, on fatigue life. Detailed microstructural analysis revealed that crack initiation predominantly occurred at the root of the welds, particularly in regions with pre-existing gaps and porosity. The microstructural gradients observed, especially within the HAZ, contributed significantly to the fatigue failure modes, confirming that microstructural features must be carefully managed during weld design and fabrication. The fusion zone microstructure also varies by geometry and thickness due to thermal gradient effects, leading to a further need for modifying factors. Through extensive quasi-static and fatigue testing, the research established a robust load life dataset of lap joint and tee joints loaded in 3 unique loading directions. The fatigue behavior of aluminum GMA welds across different joint configurations and thicknesses was successfully characterized. The Volvo method proved to be a reliable approach for predicting the fatigue life of aluminum seam welded joints, once a new structural stress life curve was constructed from Chapter 5 load life data. However, the method exhibited limitations when applying traditional thickness corrections to in plane shear samples and 4 point bending samples. While the approach provided a reasonable fit for tested data, further refinement is needed to enhance prediction accuracy across a wider range of joint configurations and loading conditions.

Based on the findings of this thesis, several areas of future research are recommended. Constructing an AA-6061-T6 GMAW structural stress life curve allows for more accurate prediction of component fatigue life, but further margins can be achieved with fracture mechanics for a unified curve. Fracture mechanic approaches have been successfully applied for steel welds and can be achieved for aluminum with additional tests and statistical modeling.

The sensitivity analysis conducted in this research indicated that the current modeling approach using the Volvo method remains coarse. Refining the finite element analysis (FEA) models to include more detailed throat modeling and material properties, as well as exploring alternative mesh strategies, could lead to improved fatigue life predictions. Existing literature documented in Chapter 2 and Chapter 6 have highlighted novel methods to ensure mesh insensitivity and consistent reported stresses, but industry standards have not adopted any further practices. Combining consistent modeling with updated fitting parameters for thickness and an improved bending ratio interpolation function is also recommended to reduce scatter.

The current study focused primarily on uniaxial loading conditions. However the intended application is to convert proving ground load data into structural stress life predictions. Implementation of multiaxial fatigue models is being attempted with the Verity method for steel components, which could provide a more comprehensive understanding of the fatigue behavior of welded joints under complex loading conditions when applied to aluminum. This would be particularly relevant for automotive applications where components are subjected to a combination of bending, shear, and axial loads.

The effective notch stress method is not adopted by the automotive industry due to the high computational cost. The use of super elements, advances in FE solver optimization and consistent meshing practices could make use of the effective notch stress method to further explore local geometry and defect fatigue contributions, further guiding the process window and acceptance criteria of aluminum welded joints.

Future work should include experimental campaigns aimed at validating newly proposed prediction methods or refinements to the existing Volvo method, or to capture the required parameters for Al GMAW Verity prediction. These experiments should focus on a broader range of weld geometries, thicknesses, and loading conditions to ensure accurate prediction of all foreseen joint designs. By addressing these areas, the predictive accuracy and applicability of fatigue life models for aluminum GMA welds can be significantly improved, ultimately contributing automotive structures with improved safety and durability.

9. References

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