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Challenges towards Structural Integrity and Performance Improvement of Welded Structures

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CHALLENGES TOWARDS STRUCTURAL INTEGRITY AND PERFORMANCE IMPROVEMENT OF WELDED STRUCTURES

A Dissertation

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Doctor of Philosophy

in

The Department of Mechanical and Industrial Engineering

by

Mohammad Washim Dewan
B. S., Bangladesh University of Engineering Technology, 2007
M.S., Tuskegee University, 2011
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To my parents and wife (Khurshida Sharmin)

for

their unconditional love and sacrifices.
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# NOMENCLATURES

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<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AA</td>
<td>Aluminum alloy</td>
</tr>
<tr>
<td>AH</td>
<td>Age hardening</td>
</tr>
<tr>
<td>AHI</td>
<td>Alternative heat index</td>
</tr>
<tr>
<td>ANFIS</td>
<td>Adaptive neuro-fuzzy inference system</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial neural network</td>
</tr>
<tr>
<td>AS</td>
<td>Advancing side</td>
</tr>
<tr>
<td>AW</td>
<td>As-welded</td>
</tr>
<tr>
<td>CW</td>
<td>Cold weld</td>
</tr>
<tr>
<td>EBSD</td>
<td>Electron backscatter diffraction</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy dispersive spectroscopy</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy dispersive X-ray</td>
</tr>
<tr>
<td>EPP</td>
<td>Electrolytic-plasma-processing</td>
</tr>
<tr>
<td>FCM</td>
<td>Fuzzy C-means</td>
</tr>
<tr>
<td>FSW</td>
<td>Friction- stir- welding</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic algorithm</td>
</tr>
<tr>
<td>gauss2mf</td>
<td>Gaussian combination membership function</td>
</tr>
<tr>
<td>gaussmf</td>
<td>Gaussian membership function</td>
</tr>
<tr>
<td>gbellmf</td>
<td>Generalized bell membership function</td>
</tr>
<tr>
<td>GENFIS</td>
<td>Generate fuzzy inference system</td>
</tr>
<tr>
<td>GMAW</td>
<td>Gas metal arc welding</td>
</tr>
<tr>
<td>GTAW</td>
<td>Gas tungsten arc welding</td>
</tr>
<tr>
<td>HAZ</td>
<td>Heat-affected-zone</td>
</tr>
<tr>
<td>HIF</td>
<td>Heat input factor</td>
</tr>
<tr>
<td>HW</td>
<td>Hot weld</td>
</tr>
<tr>
<td>INFIS</td>
<td>Initial fuzzy inference system</td>
</tr>
<tr>
<td>IP</td>
<td>Incomplete penetration</td>
</tr>
<tr>
<td>IPM</td>
<td>Inch per minute</td>
</tr>
<tr>
<td>JLR</td>
<td>Joint line remnant</td>
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</table>
KB  Kissing bond
LOF  Lack-of- fusion
LOO-CV  Leave-one-out cross validation
LOP  Lack-of- penetration
MF  Membership function
NDE  Non-destructive evaluation
NDT  Non-destructive testing
NW  Nominal weld
OM  Optical microscope
PAUT  Phased array ultrasonic testing
PEO  Plasma electrolytic oxidation
PHI  Pseudo heat index
pimf  \( \pi \)-membership function
PTZ  Plunge transition zone
PWHT  Post-weld heat treatment
PWT  Post-weld treatment
RB  Rotating- bending
RBT  Rotating-bending-torsional
RPM  Rotation per minute
RS  Retreating side
RT  Radiographic testing
SA  Simulated annealing
SCC  Stress- corrosion- cracking
SDH  Side-drilled-holes
SEM  Scanning electron microscope
ST  Solution treatment
STAH  Solution- treatment and age- hardening
STZ  Schedule transition zone
TCG  Time-corrected -gain
TMAZ  Thermo-mechanically affected zone
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>TR</td>
<td>Trenching (surface cavity)</td>
</tr>
<tr>
<td>trimf</td>
<td>Triangular membership function</td>
</tr>
<tr>
<td>TSK</td>
<td>Takagi-Sugeno-Kang</td>
</tr>
<tr>
<td>UF</td>
<td>Underfill</td>
</tr>
<tr>
<td>UT</td>
<td>Ultrasonic testing</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate tensile strength</td>
</tr>
<tr>
<td>W</td>
<td>Welded</td>
</tr>
<tr>
<td>WH</td>
<td>Wormhole (internal cavity)</td>
</tr>
<tr>
<td>WN</td>
<td>Weld nugget</td>
</tr>
<tr>
<td>WZ</td>
<td>Weld zone</td>
</tr>
<tr>
<td>YS</td>
<td>Yield strength</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>N</td>
<td>Spindle rotational speed (rev/mm)</td>
</tr>
<tr>
<td>V</td>
<td>Welding speed (mm/min)</td>
</tr>
<tr>
<td>BHN</td>
<td>Brinell hardness</td>
</tr>
<tr>
<td>d</td>
<td>Specimen diameter at critical section (mm)</td>
</tr>
<tr>
<td>EFI</td>
<td>Empirical force index</td>
</tr>
<tr>
<td>EI</td>
<td>Energy input (kJ/mm)</td>
</tr>
<tr>
<td>F&lt;sub&gt;B&lt;/sub&gt;</td>
<td>Braking force (kN)</td>
</tr>
<tr>
<td>F&lt;sub&gt;z&lt;/sub&gt;</td>
<td>Plunge force (kN)</td>
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<td>Rockwell hardness at B-scale</td>
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<tr>
<td>JE</td>
<td>Joint efficiency (%)</td>
</tr>
<tr>
<td>K&lt;sub&gt;t&lt;/sub&gt;</td>
<td>Acoustoelastic constant in transverse direction (1/MPa)</td>
</tr>
<tr>
<td>M</td>
<td>Bending moment (Nm)</td>
</tr>
<tr>
<td>MAPE</td>
<td>Mean absolute percentage error (%)</td>
</tr>
<tr>
<td>Q</td>
<td>Heat input (kJ/mm)</td>
</tr>
<tr>
<td>R</td>
<td>Dimensionless speed ratio</td>
</tr>
<tr>
<td>r</td>
<td>Pin-tool radius (mm)</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root mean square error (MPa)</td>
</tr>
<tr>
<td>v</td>
<td>Ultrasound velocity in metal (mm/s)</td>
</tr>
<tr>
<td>w</td>
<td>Bending load (kg)</td>
</tr>
<tr>
<td>σ&lt;sub&gt;b&lt;/sub&gt;</td>
<td>Bending stress (MPa)</td>
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<tr>
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<td>Longitudinal residual stress (MPa)</td>
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<tr>
<td>σ&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Transverse residual stress (MPa)</td>
</tr>
<tr>
<td>τ&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Shear stress resulting from torque (MPa)</td>
</tr>
<tr>
<td>µ</td>
<td>Friction coefficient</td>
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ABSTRACT

Welding is a fabrication process that joint materials, is extensively utilized in almost every field of metal constructions. Heterogeneity in mechanical properties, metallurgical and geometrical defects, post-weld residual stresses and distortion due to non-linear welding processes are prime concerns for performance reduction and failures of welded structures. Consequently, structural integrity analysis and performance improvement of weld joints are important issues that must be considered for structural safety and durability under loading. In this study, an extensive experimental program and analysis were undertaken on the challenges towards structural integrity analysis and performance improvement of different welded joints. Two widely used welding techniques including solid-state “friction- stir- welding (FSW)” and fusion arc “gas tungsten arc welding (GTAW)” were employed on two widely utilized materials, namely aluminum alloys and structural steels. Various destructive and non-destructive techniques were utilized for structural integrity analysis of the welded joints. Furthermore, various “post-weld treatment (PWT)” techniques were employed to improve mechanical performances of weld joints. The work herein is divided into six different sections including: (i) Establishment of an empirical correlation for FSW of aluminum alloys. The developed empirical correlation relates the three critical FSW process parameters and was found to successfully distinguish defective and defect-free weld schedules; (ii) Development of an optimized “adaptive neuro-fuzzy inference system (ANFIS)” model utilizing welding process parameters to predict ultimate tensile strength (UTS) of FSW joints; (iii) Determination of an optimum post-weld heat treatment (PWHT) condition for FS-welded aluminum alloys; (iv) Exploration on the influence of non-destructively evaluated weld-defects and obtain an optimum PWHT condition for GTA-welded aluminum alloys; (v) Investigation on the influence of PWHT and electrolytic-plasma-processing (EPP) on the performance of welded structural steel
joints; and finally, (vi) Biaxial fatigue behavior evaluation of welded structural steel joints. The experimental research could be utilized to obtain defect free weld joints, establish weld acceptance/rejection criteria, and for the better design of welded aluminum alloy and steel structures.

All attempted research steps mentioned above were carried out successfully. The results obtained within this effort will increase overall understanding of the structural integrity of welded aluminum alloys and steel structures.
CHAPTER 1: INTRODUCTION

1.1. Research Rationale and Objectives

Structural integrity is the ability of a structure to withstand a designed service load, resisting structural failure due to fracture, deformation, or fatigue. Structural integrity includes tasks in many areas including structural analysis, failure analysis, non-destructive testing, corrosion, creep analysis, metallurgy and materials characterizations, fracture mechanics, fatigue life assessment, welding metallurgy, welding defects, structural monitoring and instrumentation, etc. (James 1998; Alam 2005). Current research deals with the structural integrity analysis of weld joints.

Welding is a fabrication process that joint materials, is an ancient art. Welds are extensively utilized in almost every field of metal constructions including ships, bridges, cranes, off-shore structures, pressure vessels, piping, automotive, aerospace, etc. Weld joint may contain several complications especially complex weld metallurgy, weld defects, distortion, and post-weld residual stresses. In most welded structures, failure usually initiates from a weld joint. In order to maintain structural integrity of welded structures, relationship between welding process, properties, and performance of the structure should be well-understood and established (Koçak 2010). Specific features of each welding and joining process should be well-understood as well, for a particular material. Another important practice of weld joints is post-weld treatment (PWT). Post-weld treatments are required to improve and refine microstructures and enhance performances of weld joints. Each welding method and material requires specific PWT condition to optimize performances.
In this research, structural integrity as well as the effect of weld defects and various post-weld treatments techniques are experimentally investigated on different weld joints. Two different welding techniques including friction-stir-welding (FSW) and gas tungsten arc welding (GTAW) are employed in this research. Widely utilized two different types of aluminum alloys (AA2219-T87 and AA6061-T651) and two different types of steels (AISI-4140 and AISI-1018) are used to cover most important aspects broadly and encompassing all general aspects of the investigation. Details of the scopes and objectives of this research are discussed below.

1.2. Analysis of Friction- Stir- Welded Aluminum Alloys AA2219-T87

Friction-Stir-Welding (FSW) is a solid-state welding process developed in 1991 by The Welding Institute (TWI) (Thomas, Nicholas et al. 1991) for joining aluminum and its alloys. This process made possible to weld a number of aluminum alloys (i.e. 2xxx and 7xxx series aluminum alloys) that were previously not recommended for welding due to the poor solidification microstructure and porosity during fusion welding. In solid state welding process, the joints are produced at temperature below the melting temperature of base metal. Since the development of FSW technique, it has found extensive applications in automotive, aerospace, maritime, and construction industries. In FSW, a rotating pin tool is plunged into the weld seam of a workpiece clamped to a fixture and translated along the seam to stir the sides of the seam together. The spindle rotational speed results in effective stirring mixing of materials around the rotating pin-tool. A shoulder above the pin-tool prevents axial flow of metal up the tool, which would result in plowing instead of welding. The frictional heat generated from the pin-tool permits plastic deformation of the weld metal as the pin-tool traverses along the weld seam. During traversing, soften material from the leading edge moves to the trailing edge due to tool rotation and the traverse movement of pin-tool. The transferred material is consolidated in the
trailing edge of the tool by the application of axial force. During FSW processing, deformation takes place at very high strain rates, leaving a fine equiaxed structure in the weld nugget (WN) region (Stewart, Adams et al. 1998; Colligan 1999; Guerra, Schmidt et al. 2002; Nunes Jr. 2010). FSW is considered as a combination of extrusion, forging, and stirring of the material where a high strain rate and temperature are generated. Further the process involves complex movement of materials and intense plastic deformation. In general, FSW is a complex process that depends on many variables that affect the quality of the weld joint produced. In order to produce a high quality defect-free weld, the welding process parameters (rotational speed, welding speed, and plunge force) and pin-tool design must be chosen carefully (Jata and Semiatin 2000; Colligan 2007; Schneider, Nunes Jr. et al. 2010; Rajakumar, Muralidharan et al. 2011). Since the onset of FSW process two and a half decades ago, investigators have researched the influence of parameters on microstructure and mechanical properties of various aluminum alloy joints.

The current study explores FSW process parameters of a fixed pin-tool to obtain defect formation mechanisms. The study aims to utilize the defect formation mechanism and apply the results to a general understanding of process parameter correlation. The experiments investigated butt-welded 8.13 mm thick AA2219-T87 by varying the three welding process parameters: rotational speed ($N$), welding speed ($V$), and downward plunge force ($F_z$). All other features, including pin-tool geometry and fixture conditions are held constant. Aluminum alloys AA2219-T87 was chosen because of its light-weight and high strength properties as well as extensively employed in present-day aerospace industries. The effect of the various weld schedules on uniaxial tensile strength, toughness, and fracture configuration of tensile specimens are determined. Based on experimental investigations, an empirical correlation has been developed to identify defective and defect-free weld schedule. Then an optimized adaptive neuro-fuzzy
inference system (ANFIS) model has been developed utilizing experimental data to predict tensile strength of FSW-joints. Lastly, an optimized post-weld heat treatment condition has been obtained to achieve optimum tensile properties of FS-welded AA2219-T87 joints.

1.3. Analysis of Fusion Arc Welded Aluminum Alloys AA6061-T651

For aluminum alloys, generally friction-stir-welding (FSW) and fusion arc welding techniques are used to make a weld joint. FSW usually offers better performances on aluminum alloy joint compared to conventional fusion arc welding techniques. Due to higher initial cost and non-portability of FSW machine, it is only utilized in some specific applications; but in general fusion arc welding techniques are utilized in many structural applications to join aluminum alloys. Two of the most common fusion arc welding practices are gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). Among two of them, GTAW is a high quality fusion arc welding technique which is typically utilized for joining heat-treatable aluminum alloys. High coefficient of thermal expansion of aluminum, solidification shrinkage, and high solubility of hydrogen during its molten state creates problem in fusion arc welding of aluminum alloys (Lakshminarayanan, Balasubramanian et al. 2009). Intrinsic weld defects (i.e., porosity in weldment), post-weld residual stresses, and microstructural changes are the key factors for the performance reduction and failure of fusion welded aluminum alloys (Leggatt 2008). The influences of weld defects and post-weld heat treatment (PWHT) on tensile properties of gas tungsten arc (GTA) - welded aluminum alloy AA6061-T651 joints are investigated for this particular project. Aluminum alloys AA6061-T651 was chosen because of its weldability and corrosion resistance properties over many high strength aluminum alloys as well as extensively utilized in many structural applications (Dudas and Collins 1966; Metzger 1967). The objective of this work is to obtain tensile test data for GTA- welded AA6061-T651
joints containing specific weld defects and to correlate these data with the nondestructive phased array ultrasonic testing (PAUT) results. Tensile test data are also correlated with microscopic evaluation; and a comparison is made between these two inspection methods relative to the evaluation of weld discontinuities. The present investigation also included the evaluation of the influences of PWHT on mechanical properties of GTA- welded AA6061-T651 aluminum alloy joints.

1.4. Analysis of Fusion Arc Welded Steels

In many structural applications conventional and alloy steels are utilized for their higher modulus, strength, and toughness properties. For structural steels, different fusion welding techniques are usually employed to make a weld joint. In the current investigation, one type of high strength alloy steel (AISI-4140) and one type of low carbon steel (AISI-1018) are welded using commonly utilized gas tungsten arc welding (GTAW) technique. Unlike aluminum alloy joints, weld defects are not of prime concern for steel joints. By controlling welding conditions and weld process parameters, defect-free weld joint can be obtained fairly easily; but residual stress development, microstructure changes, and unstable brittle fracture are unavoidable active problems for alloy steel joints that require special attention to address these types of problems. To improve mechanical performances of fusion arc welded alloy steel joints, two different post-weld treatment (PWT) techniques e.g., post-weld heat treatment (PWHT) and electrolytic-plasma-processing (EPP) are utilized. The effects of PWHT and EPP on the residual stresses, micro-hardness, microstructures, and mechanical properties of GTA- welded joints are investigated. Finally, tensile tests are carried out to identify the effect on the strength recovery and change of ductility due to different heat treatment processes. At the end, biaxial fatigue
behavior of GTA-welded steel is investigated utilizing specifically designed and fabricated rotating-bending-torsional (RBT) fatigue testing machine.

1.5. Chapters Overview

The research encompassing in this dissertation of the above mentioned studies are presented in chronological order as follows:

- **In Chapter 1**, a rationale for the study of structural integrity analysis and performance improvement of different weld joints are given.

- **In Chapter 2**, an extensive critical literature review related to different welding techniques, welding process parameters, welding defects, non-destructive testing (NDT) of welds, microstructures, residual stresses, mechanical performances of weld joints are discussed. The literature related to post-weld treatments and multiaxial fatigue analysis of weld joints are also reviewed in this chapter.

- **In Chapter 3**, materials and welding techniques utilized in this research are discussed. Different destructive and non-destructive testing utilized for structural integrity analysis of weld joints are also described in this chapter.

- **In Chapter 4**, an analysis of Friction-Stir-Welding (FSW) process parameters, weld defects, and weld quality of friction-stir (FS) butt weld joints of AA2219-T87 are explored. FSW process parameter window and empirical correlation for effective joining of AA2219-T87 are also discussed in this chapter.

- **In Chapter 5**, an optimized *Adaptive neuro-fuzzy inference system (ANFIS)* model has been developed utilizing experimental data to predict tensile strength of FSW joints. This chapter also comprised the development of an optimized predictive *Artificial Neural Network (ANN)* model and comparison with ANFIS model established.
- Effects of post-weld heat treatment (PWHT) on tensile and microstructural behavior of FS-welded AA2219-T87 joints are discussed in Chapter 6.

- The influences of weld defects and post-weld heat treatment (PWHT) on tensile properties of gas tungsten arc (GTA) - welded aluminum alloy AA6061-T651 joints are investigated in Chapter 7.

- In Chapter 8, the influences of two post-weld treatment (PWT) techniques including post-weld heat treatment (PWHT) and electrolytic-plasma-processing (EPP) are investigated on gas tungsten arc (GTA) - welded AISI-4140 alloy steel joint.

- In Chapter 9, the influences of rotating-bending (RB) fatigue loading conditions along with the pulsed torsional load are evaluated on commonly used welded steel (AISI-1018).

- In Chapter 10, conclusions arrived from the findings of this research and recommendations for future work are presented.
CHAPTER 2: LITERATURE REVIEW

2. Introduction

Various welding techniques are extensively utilized in manufacturing sector for different structures ranging from bridges and machinery to all kinds of automobiles, marines, nuclear reactors, and space vehicle, etc. But a weld joint may contain several complications especially complex weld metallurgy, weld defects, distortion, and post-weld residual stresses. These complications are responsible for performance reduction in service conditions as well as failure of welded structures. Hence, structural integrity analysis and performance improvements of weld joints are an important issue which needs to be investigated comprehensively. In the current research, widely utilized two different types of aluminum alloys (AA2219-T87 and AA6061-T651) and two different types of steels (AISI-4140 and AISI-1018) are used to cover broadly, all general aspects of the investigation. Different destructive and non-destructive testing techniques are utilized for structural integrity analysis of weld joints. Different post-weld treatment techniques are utilized for different materials to improve mechanical performances of weld joints. At the beginning of current research, an extensive literature review has been undertaken to appreciate current research topic and obtain essential information which are required to contribute in the field of structural integrity analysis and performance improvement of welded structures. Details of literature review are discussed below.

2.1. Friction-Stir-Welding (FSW) of Aluminum Alloys

The big advancement in aluminum structures came during the World War II when just about every aircraft was produced using this particular non-ferrous material. The extensive applications required for a dependable welding technique to develop. From that time, widely
utilized gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) techniques are usually employed to join aluminum. High coefficient of thermal expansion of aluminum, solidification shrinkage, and high solubility of hydrogen during its molten state (Lakshminarayanan, Balasubramanian et al. 2009) makes it difficult to utilize these two fusion arc welding techniques. Meanwhile different aluminum alloys are devised and makes more complication to apply fusion arc welding techniques. Fusion arc welding in which heat results due to the intrinsic nature of the welding processes causes various weld defects as well as, responsible for strength reduction in heat- treatable aluminum alloy joints. To overcome this problem solid- state friction- stir- welding (FSW) technique has been developed. FSW process has been developed in 1991 by The Welding Institute (TWI) (Thomas, Nicholas et al. 1991). In FSW process, the metal that needs to be welded is not melted during the welding process. Thus the cracking and porosity often associated with fusion welding of aluminum and its alloys are eliminated in FSW (Knipstrom and Pekkari 1997; Liu, Murr et al. 1997; Mahoney, Rhodes et al. 1998; Sato, Kokawa et al. 1999). Now-a-days, the FSW process is widely utilized to weld aluminum and its alloys in order to obtain high quality weld joints. A study using aluminum alloy AA2219-T87 performed to compare three welding techniques, i.e., FSW, gas tungsten arc welding (GTAW), and electron beam welding (EBW) (Malarvizhi and Balasubramanian 2011). The paper illustrated that FS- welded joints had UTS joint efficiency 20% higher than GTAW and 12% higher than EBW. Another three similar studies published by same research group (Malarvizhi and Balasubramanian 2011; Malarvizhi and Balasubramanian 2011; Malarvizhi and Balasubramanian 2012) and showed that the fatigue strength and fatigue life of the AA2219 aluminum alloy greatly reduced by welding processes. Among the three as-welded joints, the joints fabricated by FSW process exhibited higher fatigue strength and fatigue life compared to
GTAW and EBW joints. One more comparative study of GTAW and FSW was conducted in (Lei, Deng et al. 2014) with AA2219-T87 panels. It was concluded that the FSW joints had better mechanical properties than the GTA- welded joints.

2.1.1. Friction-Stir-Welding (FSW) Process

In FSW process, a rotating pin-tool is plunged into the weld seam of a workpiece clamped to a fixture and translated along the seam to stir the sides of the seam together. A shoulder above the pin-tool prevents axial flow of metal up the tool. According to the design of pin-tool, FSW technique is classified into two categories: (a) conventional (fixed-pin) FSW and (b) self-reacting FSW. Self-reacting FSW incorporates two opposing shoulders on the crown and root sides of the weld joint. In self-reacting friction stir welding, the weld forge force is reacted against the crown shoulder portion of the weld pin-tool by the root shoulder. On the other hand, conventional (fixed-pin) FSW incorporates a fixed pin-tool with single shoulder on crown side of the weld joint.

During FSW process, the high plunge force on the immersed pin-tool ensures that it seizing in the weld metal. The mechanical power input from the tool is transformed into heat and results in plastic deformation within the weld metal. Plastic deformation takes place at very high strain rates, leaving a fine equiaxed structure in the weld nugget region (Stewart, Adams et al. 1998; Colligan 1999; Guerra, Schmidt et al. 2002; Guerra, Schmidt et al. 2002; Su, Nelson et al. 2003; Nunes Jr. 2010). FSW process involves four segments which are: (1) plunging phase, (2) dwelling phase, (3) welding phase, and finally (4) exit or retract phase (Figure 2.1). The welding process starts with rotating pin-tool thrusting onto the configured work materials under a constant axial load to generate frictional heat. This process will continuously increase the temperature at the immediate contacting surface of the rotating tool and work material. The
process continue until the temperature at the immediate contact of the rotating tool and the work material increased to a temperature which causes the work material to soften, plasticized and significantly lose its strength. Consequently, these conditions allow the rotating tool to penetrate to a certain depth usually almost to the thickness of work material. This process is known as plunging phase. The end of the plunging phase is signified by the sound contact of the rotating tool shoulder with the immediate work material surface. At this moment, the process enter the dwelling phase where the rotating tool is allowed to dwell for a certain time, causing the temperature to increase further, up to its hot working temperature. Once this condition is reached, thin soft material layers is produced and would stick to the dynamic rotating tool surfaces (pin and shoulder) and being forced to be displaced along. The dwelling phase is followed by welding phase.

Figure 2.1: Friction- Stir- welding (FSW) process phases of a butted work material configuration (AWS 2007)
After the local temperature of work-material under the rotating tool approaches its hot working temperature and is soft enough to be stirred and displaced, the rotating tool is moved transversely along the welding line. This traverse motion caused the plasticized soft material at the leading edge of the rotating tool being squeezed and sheared through a small slit formed by the displaced soft material at the side or lateral of the tool, preferably in the direction of tool rotation. The displaced soft material is then deposited to the gap at the trailing edge, left by rotating pin-tool or probe. In (Schneider and Nunes Jr. 2004), a kinematic flow model is developed to explain material flow during FSW process. They break down the movement of metal flow into 3 incompressible flow fields (Figure 2.2). The first flow component is a plug of metal in rigid body rotation which is separated from rest of the weld metal by a cylindrical shearing surface. The rotating plug is perceived as attached to the friction-stir pin-tool and has same rotational speed of the pin-tool (Figure 2.2a). The second flow-component is a homogeneous and isotropic flow field and moves opposite to the tool travel velocity (Figure 2.2b). The third flow component is a ring-vortex flow field encircling the pin-tool (Figure 2.2c). The ring-vortex flow is driven by threads on the pin and is reversed if the direction of the threads or the direction tool rotation is reversed. These three incompressible flow fields combine to predict metal flow along two possible paths, the Straight-through current and the Maelstrom current (Schneider and Nunes Jr. 2004). At the end or exit phase of FSW process, the rotating tool is retracted away from the work material leaving a cylindrical hole mark that once occupied by the pin-tool.

To produce a high quality defect-free weld, welding process parameters such as: rotational speed, welding speed, and axial plunge force or displacement, and tool pin design must be chosen carefully (Jata and Semiatin 2000; Peel, Steuwer et al. 2003; Colligan 2007; Schneider, Nunes Jr. et al. 2010; Rajakumar, Muralidharan et al. 2011).
For a particular pin-tool, three variables called plunge or forge force \( (F_z) \), spindle rotational speed \( (N) \), and travel or welding speed \( (V) \), are considered the three critical process parameters which are utilized to soften metal near the pin-tool to create a plastic deformation field. Schematic of FSW process and three critical process parameters are shown in Figure 2.3.

Figure 2.2: (a) Rigid body rotation, (b) Uniformly translation along the weld seam, (c) Ring vortex flow through the metal thickness, and (d) Two inter-twined flow paths (Schneider and Nunes Jr. 2004)

Figure 2.3: Schematic of friction- stir- welding (FSW) process showing three critical process parameters \( (F_z, V, N) \) (HILDA)
Since the beginning of FSW process, investigators have researched the influence of parameters on microstructures and mechanical properties of different series of aluminum alloys (Rhodes, Mahoney et al. 1997; Flores, Kennedy et al. 1998; Li, Murr et al. 1999; Abbasi Gharacheh, Kokabi et al. 2006; Khodir, Shibayanagi et al. 2006; Elangovan and Balasubramanian 2007; Record, Covington et al. 2007; Scialpi, De Filippis et al. 2007; Balasubramanian 2008; Cavaliere, Squillace et al. 2008; Colligan and Mishra 2008; Kulekci, Şik et al. 2008; Lakshminarayanan and Balasubramanian 2008; Babu, Elangovan et al. 2009; Commin, Dumont et al. 2009; Moreira, Santos et al. 2009; Rajakumar, Muralidharan et al. 2011; Querin and Schneider 2012; Rajakumar and Balasubramanian 2012; Shashi Prakash 2014) with a view to optimize FSW processes. Among different grades of aluminum alloys, AA2219 has found wide applications in aerospace industry. Presently, AA2219-T87 is used by the National Aeronautics and Space Administration (NASA) for construction of the Space Launch System (SLS) and Orion crew module. The current FSW research study is limited to the investigation of aluminum alloys AA2219-T87.

2.1.2. Critical Evaluation of Existing Literature and Trend in FSW of AA2219

In different research study, heat-treatable AA2219 is utilized at various temper conditions. Different heat treatment results in different mechanical properties. In Table 2.1, various heat treatment techniques with associated mechanical properties are listed for AA2219 (Oberg 2012). It is observed that AA2219-T87 gives better ultimate tensile and yield strengths compared to other heat treatments; however, the elongation percentage is lower. The high strength qualities of this material are the reasons why aerospace companies utilize this particular material.
Table 2.1: Mechanical properties of AA2219 with different temper condition (Oberg 2012)

<table>
<thead>
<tr>
<th>Aluminum alloy</th>
<th>UTS, [MPa]</th>
<th>Yield Strength [MPa]</th>
<th>Elongation in 50.8 mm (%) for 1.59 mm thick specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2219-T87</td>
<td>475.7</td>
<td>393.0</td>
<td>10</td>
</tr>
<tr>
<td>2219-O</td>
<td>172.4</td>
<td>75.8</td>
<td>18</td>
</tr>
<tr>
<td>2219-T81, T851</td>
<td>455.1</td>
<td>351.6</td>
<td>10</td>
</tr>
<tr>
<td>2219-T62</td>
<td>413.7</td>
<td>289.6</td>
<td>10</td>
</tr>
<tr>
<td>2219-T37</td>
<td>393.0</td>
<td>317.2</td>
<td>11</td>
</tr>
<tr>
<td>2219-T42</td>
<td>358.5</td>
<td>186.2</td>
<td>20</td>
</tr>
</tbody>
</table>

A review of literature available in public domain is presented in this section. The literature review analyzes welding procedures including pin-tool type, FSW machine, number of welds conducted, AA2219 temper designations, and essential conclusions. Firstly, works conducted analyzing effects of varying process parameters, mechanical properties, and FSW defects are reported. Secondly, residual stress and post-weld heat treatment (PWHT) analysis of AA2219 are presented. Correlations among FSW process parameters are provided after. Fourthly, works related to model to predict tensile properties of FSW weld joints are reviewed.

2.1.2.1. FSW process development and mechanical properties

Due to the extensive applications of AA2219, a number of research efforts have been conducted pertaining to FSW of AA2219 and analyzed the effect of FSW process parameters. In (Arora, Pandey et al. 2010), reported that plunge force is dependent only on pin-tool shoulder diameter and rotational speed. Welding signal data of plunge force and welding force in the longitudinal, or travel direction were analyzed. The force in the travel direction of the pin-tool was exclaimed to be dependent on the welding speed and pin diameter. In their study a total of 9-weld schedules were used to join AA2219-T62 specimens, followed by microstructural analysis. It was shown that grain structure in the weld zone (WZ) had an average size decrease by a factor of 10 as compared to the base metal.
Xu and his research group utilized AA2219 (Xu, Liu et al. 2009) and AA2219-T6 (Xu, Liu et al. 2009) to analyze temperature evolution, microstructures, and mechanical properties of FS-welded thick plates. The results from their study indicated that advancing side (AS) temperatures are higher as compared to retreating side (RS) temperatures. It was also shown that by increasing rotational speed and decreasing travel speed, heat input into the system as well grain size can be increased. In another study from the same research group (Xu, Liu et al. 2013), investigated the effect of two different pin-tools for FSW of AA2219-T62 with varying travel speed and rotational speed on microstructure variation along the thickness. It was shown that there is a change in apparent grain size at varying thicknesses in a FSW joint. At the top of the weld close to the shoulder, large grain sizes were observed whereas the bottom exhibited smaller grain sizes. It was exclaimed that the pin-tool profile had little effect on the tensile properties, but rather changing travel speed and rotational speed had considerably more significant effects.

Another research group (Chen, Liu et al. 2006) studied FSW characteristics on aluminum alloys AA2219 and AA2219-T6. In their study rotational speed was kept constant with varying travel speeds. It was concluded that the base material tempering conditions had a significant impact in welding morphologies, resulting in significant effects on the tensile properties. Similar to previous study by (Xu, Liu et al. 2009), this research group published another study (Li, Shen et al. 2011). In that study, FSW experiments were carried out on AA2219-T6 thick panels with 14 welds schedules by varying rotational speed and travel speed. The paper presented defects found; consequently, a variety of non-destructive evaluation (NDE) techniques were conducted to illustrate each type’s inherent limitations, which revealed X-ray detection, ultrasonic C-scan testing, phased array ultrasonic testing (PAUT), and fluorescent penetrating fluid inspection were able to successfully detect welding defects. In another study by this group (Liu, Zhang et al.
investigated how process parameters affect welds and their microstructures utilizing AA2219-T6. The study reported 10-weld schedules with various weld defects. The study concluded that with increasing rotational speed the tensile properties increased to a maximum, then slowly decreased where defects were formed. Reported maximum ultimate tensile strength (UTS) was 340 MPa; which is 79% of the base material strength.

Elangovan and Balasubramanian published two research papers (Elangovan and Balasubramanian 2007; Elangovan, Balasubramanian et al. 2008). They investigated the effects of various pin-tool profiles on tensile properties of FS-welded AA2219. It was shown that the square pin-tool geometry produce superior tensile properties. A study by the same research group (Elangovan, Balasubramanian et al. 2008) developed an empirical relation to predict tensile strength of FS-welded AA2219. Similar to their previous study, it was concluded that a square pin-tool with a rotational speed of 1600 RPM, travel speed of 0.75 mm/sec, and plunge force of 12 kN result in superior tensile properties. An optimization investigation was conducted in another study (Babu, Elangovan et al. 2009) on aluminum alloy AA2219. The study involves development of a mathematical model to predict tensile strength by incorporating process parameters and tool profiles. The optimization study was conducted utilizing the Hooke and Jeeves technique. In (Lakshminarayanan, Malarvizhi et al. 2011), a friction-stir-welding window was developed for effective joining of AA2219 aluminium alloy. They showed that the defect-free FSW AA2219 joints are produced under a wide range of rotational and welding speed. The experiments were performed utilizing position control techniques and the effect of plunge force was not considered in that study.

Davis, in his MS thesis showed the effect of different welding process parameters and pin-tool profile on tensile properties of FSW joint of AA2219-T87 (Davis 2010). Querin and
Schneider developed an alternative heat indexing equation for effective FSW of AA2219-T87 plates (Querin and Schneider 2012). In another study by Schneider and other researchers investigated the influence of FSW tool and welding process parameters on weld structure and properties of AA2219-T87 plates (Schneider, Nunes Jr. et al. 2010).

Detailed descriptions of the pin-tool, welding machine, fixture conditions, process parameters, and control settings are often overlooked in most of the reported literatures. FSW research is a costly endeavor, and for this reason university studies are quite limited due to these constraints. Therefore, innovative approaches have been taken to circumvent this issue. One such method is to utilize milling machines that have been converted into FSW machines. This practice, however, has never been evaluated as to whether it affects FSW results and introduces other pitfalls which may lead to an investigation to inaccurate data.

2.1.2.2. Defects in FSW joints

In general, friction- stir- welded joints are generally known to be free from defects like porosity, slag inclusion, solidification cracks, etc., which are common in fusion arc welding of aluminum alloys (Fujii, Cui et al. 2006). But FSW joint efficiency depends on several operating parameters. Generally improper plastic flow and insufficient consolidation of metal result in weld defects in the FS- process region (Rhodes, Mahoney et al. 1997). Internal cavity or Wormholes (WH), Surface cavity or Trenching (TR), Incomplete Penetration (IP), Underfill (UF), and micro-voids are most common weld defects are usually observed in friction- stir-welded aluminum alloy joints (Kim, Fujii et al. 2006). In (Arbegast, Coletta et al. 2001; Arbegast 2004), different types of FS weld defects are discussed (Figure 2.4).
Internal cavity or Wormholes are defined as an advancing side tunnel of inadequately consolidated and forged material running in the longitudinal direction. Wormholes are usually observed in cold welds. Surface cavity or Trenching are known as a continuous or intermittent top surface void on the advancing side of the weld nugget (Chen, Yan et al. 2006). Trenching is also observed in cold welds where plunge force is insufficient. Inadequate pin depth or insufficient metal flow (Sato, Takauchi et al. 2005; Di, Yang et al. 2006) might result in incomplete penetration defect in a cold welds. Unfavorable design of the pin also contributes to IP (Oosterkamp, Djapic et al. 2004). The nomenclature of incomplete penetration is not established and unified in the literature (Le Jolu, Morgeneyer et al. ; Sato, Yamashita et al. 2004; Chen, Yan et al. 2006). IP is also known as lack of penetration (LOP), kissing bond (KB), and joint line remnant (JLR). Flash or underfill resulted for the excessive expulsion of material on
the top surface leaving a corrugated or ribbon like effect along the retreating side of the weld nugget. Underfills are commonly observed in hot welds. A large mass of flash defects are formed at a higher plunge force or rotational speed or a lower welding speed. The large mass of flash is ejected to the outside due to the softening of the metal by the excess heat input during the FSW. In hot weld case, the tip of the tool probe sometimes touches the backing plate. By controlling welding conditions and critical weld process parameters, a defect free aluminum alloy weld joint can be easily obtained utilizing FSW techniques.

2.1.3. Post-Weld Residual Stress and Post-Weld Heat Treatment

Friction-stir-welding (FSW) is an innovative solid phase welding process in which the metal to be welded is not melted during welding rather plasticized sufficiently, thus the cracking and porosity often associated with fusion welding processes are eliminated (Knipstrom and Pekkari 1997). Therefore, the FSW process can also be used to weld heat-treatable aluminum alloys in order to obtain high quality joints. However, some studies (Mahoney, Rhodes et al. 1998; Campbell and Stotler 1999; Liu, Fujii et al. 2003) on the microstructural characteristics and mechanical properties of the friction-stir-welded joints have indicated that FSW gives rise to softening in the joints of the heat-treatable high strength aluminum alloys because of the dissolution or growth of strengthening precipitates during the welding thermal cycle. The softening might result in the degradation of mechanical properties of weld joints. In literature, it is showed that the tensile strength of FS-welded heat treatable aluminum alloy joints varied from 60% to 70% of base metal tensile strength (Elangovan and Balasubramanian 2007; Babu, Elangovan et al. 2009; Moreira, Santos et al. 2009).

During FSW process, generated frictional heat is not uniform. Non-uniform heat generation results in development of non-uniform microstructures and post weld residual stresses
around the weld nugget. In (Xu, Liu et al. 2011), AA2219-T6 panels with 12 mm thickness were FS-welded and top and bottom residual stresses were determined. It was shown that on the top surface of the plate, the residual stresses decreased with increased rotational speed. On the other hand, the residual stress on the bottom surface increased with an increase in rotational speed. Post-weld heat treatment is commonly utilized to remove residual stresses and improve strength of heat treatable aluminum alloy joints. In (Liu, Chen et al. 2006), artificial age-hardening (165 °C for 18h) was employed on FS-welded AA2219-T6 to determine the effects of PWHT on tensile properties. It was shown that PWHT sample exhibited 89% tensile strength of the base material. Fractures in the defect-free tensile specimens (both as-welded and PWHT) were found to occur in the heat-affected-zone (HAZ) of retreating side (RS). In (Chen, Liu et al. 2006), the effect of PWHT conducted on FS-welded AA2219. Their PWHT involves solution treatment at 535 °C for 32 min, followed by quenching at 25 °C and artificial aging at 165 °C for 18h. They showed that the PWHT increases tensile strength of FS-weld joint. In another study (Feng, Chen et al. 2006), the effect of solution temperature was analyzed on FS-welded AA2219 panels. According to that study, higher solution temperature has resulted in higher tensile properties and PWHT had a significant effect on fracture locations of the weld joints.

2.1.4. FSW Process Parameters Correlation

In FSW of any material, the first and foremost issue is defining the processing window to avoid generation of defective welds. In manufacturing settings, determining this operating window is a key task as material, time, and operating conditions are costly. To date, a “trial and error” method is used to establish process parameters for each tool design, material, and setup. There are many research study reported the effect of various weld process parameters on tensile and microstructural behavior of different FSW joints (Rhodes, Mahoney et al. 1997; Flores,
Kennedy et al. 1998; Khodir, Shibayanagi et al. 2006; Moreira, Santos et al. 2009; Rajakumar, Muralidharan et al. 2011; Shashi Prakash 2014). For a particular material and welding condition, FSW process parameter ranges are established by welding over a range of spindle speeds ($N$) and welding speeds ($V$) in displacement control or load control modes and selecting parameter windows to obtain the required weld strength or other desired property. In (Lakshminarayanan, Malarvizhi et al. 2011; Balaji and Mahapatra 2013), have presented an example of parameter window determination for FSW of AA2219. In (Lakshminarayanan, Malarvizhi et al. 2011), derived a process parameter window based on a total of 22 weld schedules with varying rotational speed and travel speed conducted on AA2219-T87 panels with 8 mm thickness. In their study, the welding window was established based upon macro-structural analysis of tensile properties, hardness distribution, and microstructural analysis. In (Balaji and Mahapatra 2013), conducted an experimental and modeling study of AA2219-T87 using only 2- weld schedules with varying rotational, travel, and plunge force values. Ultimate tensile strength (UTS) and percent elongation of welds were evaluated. Analysis-of-variance (ANOVA) result has indicated that the plunge force has the most influencing factor on UTS and percent elongation. An optimized welding schedule was determined by using the multi-response desirability function-based optimization technique. The scope of their studies was somewhat limited.

Some simplified theoretical aids, e.g., similarity indices, have been suggested to assist in the FSW process. An ideal similarity index determines how parameters can be varied together to obtain similar welds. The ideal is seldom achieved in practice, but even an approximation may be helpful. An empirical Pseudo Heat Index (PHI) has been proposed (Kandukuri, Arbegast et al. 2007) to correlate the heat input during FSW with spindle speed and welding speed; if heat input determines weld properties, similar welds are obtained by holding the index constant. The PHI
does not include many process features affecting weld properties and is only good for extrapolations of welding speed and spindle speed for a specified welding situation. Nunes (Nunes Jr. 2010) has proposed a temperature index based on a physical model of the FSW process in which temperature is computed from a balance between estimated mechanical heat input and estimated heat losses. In that model, shear stress is assumed to be linearly related to temperature. Querin and Schneider (Querin and Schneider 2012) have proposed an Alternative Heat Indexing (AHI) equation considering heat generation terms and thermal dissipation. Dehghani et al. (Dehghani, Amadeh et al. 2013) suggested a Heat Input Factor (HIF) to determine weld quality. In their model plunge force is assumed to be constant and welding speed having a linear relation with welding heat generation. None of these indices include plunge force, yet plunge force may make the difference between the presence and absence of a defect. In the work reported by (Ramulu, Narayanan et al. 2013), proposed a simplified equation relating to plunge force or spindle torque with welding speed or spindle rotational speed to identify defective and defect- free weld schedules. They concluded that for an internal defect- free weld, higher tool rotational speed yields to lesser axial force and torque (Ramulu, Narayanan et al. 2013). From their equation, a qualitative comparison needs to be established to identify only internal defect- free weld joint.

A more powerful theoretical aid would be a defect formation criterion, a parametric relationship establishing the boundary between welds (i) with a particular defect and (ii) welds without a defect. To do that, it needs to consider as many defect criteria as there are defect types. In another approach, all the defect criteria can be superposed together to establish a defect-free window in parameter space. Currently, there are no theoretical defect criteria available to determine the operational window. The computations to obtain them are hugely complex.
2.1.5. Model to Predict Tensile Properties of FSW Joints

Development of an appropriate physical model which can predict the process's main characteristics (weld defects and mechanical properties) is really complex. Hence, researchers focused on creation of predictive models based on numerical analysis such as finite element methods or empirical models based on experimental observations (Record, Covington et al. 2007; Elangovan, Balasubramanian et al. 2008; Jayaraman, Sivasubramanian et al. 2008; Lakshminarayanan and Balasubramanian 2009; Rajakumar, Muralidharan et al. 2010; Tansel, Demetgul et al. 2010; Gopalakrishnan and Murugan 2011; Rajakumar, Muralidharan et al. 2011; Bilici 2012; Bozkurt 2012; Dinaharan and Murugan 2012; Rajakumar and Balasubramanian 2012; Pradeep and Muthukumaran 2013). Some study reported on nontraditional optimization algorithm like genetic algorithm (GA)- Taguchi approach (Bilici 2012; Bozkurt 2012) and simulated annealing (SA) (Yang, Srinivas et al. 2009; Chen, Lin et al. 2010; Zain, Haron et al. 2011) to predict tensile strength of FSW joint. Response Surface Methodology (RSM) (Elangovan, Balasubramanian et al. 2008; Jayaraman, Sivasubramanian et al. 2008; Lakshminarayanan and Balasubramanian 2009; Rajakumar, Muralidharan et al. 2011; Dinaharan and Murugan 2012; Rajakumar and Balasubramanian 2012) has been extensively utilized to predict mechanical properties of FS- weld joint. RSM consists of a group of mathematical and statistical techniques that can be used to define the relationships between the response and the independent variables. The major drawback of RSM is to fit the data to a second order polynomial (Baş and Boyacı 2007). Highly nonlinear FSW process parameters and tensile properties might not be well accommodated by the second order polynomial. Some investigators applied Artificial Neural Network (ANN) (Okuyucu, Kurt et al. 2007; Lakshminarayanan and Balasubramanian 2009; Tansel, Demetgul et al. 2010) to predict mechanical responses of FSW joint. Most of them utilized few experimental data and none of them seems to be decisive.
Adaptive network-based fuzzy inference system (ANFIS) is a hybrid predictive model which uses both of neural network and fuzzy logic to generate mapping relationship between inputs and outputs (Jang 1993). Although ANFIS is a powerful tool for prediction of manufacturing processes but there is only one study (Babajanzade Roshan, Behboodi Jooibari et al. 2013) utilized this technique in modeling of FSW process.

Solid-state friction-stir-welding is usually employed on aerospace grade aluminum alloys quite widely. Still in many applications, fusion techniques are employed to join heat treatable medium strength aluminum alloys. For structural integrity analysis that also need to be considered. In next section, critical literatures are reviewed on fusion welding of commonly utilized AA6061.

2.2. Fusion Arc Welding of Aluminum Alloys

Among different aluminum alloys, heat treatable AA6061 (Al- Mg-Si alloys) is most widely used medium strength aluminum alloy, and has gathered wide acceptance in the fabrication of light weight structures for its excellent corrosion resistance and weldability quality (Dudas and Collins 1966; Metzger 1967; Balasubramanian, Ravisankar et al. 2008). Strength reduction after welding is a great challenge for weld joints of aluminum and it alloys. Apart from softening in the weld fusion zone and heat-affected-zone (HAZ); weld defects and hot-cracking are other serious problems in fusion arc welded aluminum alloy joints (Mohandas and Reddy 1996). As discussed earlier, FSW is the best welding technique developed for joining aluminum alloys. Due to cost, design, and portability constraints it cannot be applied in all applications. For these reasons, the most commonly used fusion welding technique is still utilized in many applications. The preferred fusion welding processes for aluminum alloys are gas tungsten arc welding (GTAW- also known as TIG) and gas metal arc welding (GMAW- also known as MIG) due to their comparatively easier applicability and better economy (Reddy, Gokhale et al. 1998).
GTAW is a high quality weld that uses a non-consumable electrode. The use of welding current in GTAW is smaller than in GMAW and it may or may not be used with a filler wire. Lakshminarayana and other researchers studied the effect of GTAW, GMAW, and FSW on the mechanical properties of aluminum alloys AA6061 (Lakshminarayanan, Balasubramanian et al. 2009). The yield strength of the weld joint after GMAW was 141 MPa with the ultimate strength being 163 MPa. There was about 50% reduction in strength was observed in GMAW joint. For GTAW, the yield strength were measure to be 188 MPa and 211 MPa, respectively, resulting in a 37% decrease in strength. The FSW process had the best results, with only a 34% reduction in strength.

2.2.1. Gas Tungsten Arc Welding (GTAW) of AA6061-T651

The weld quality of a GTAW aluminum joints largely depends on degree of heat input; the degree of heat input depends on welding speed, distance between arc-gap, welding current, shielding gas, and filler metals used. In (Kumar and Sundarrajan 2006), studied the effects of welding parameters on the mechanical properties of the GTA-welded aluminum alloy AA6061-T6. *Analysis-of-variance* (ANOVA) technique was applied to investigate which welding process parameter has significant effect on the weld joint UTS. The shielding gas generally utilized to protect the weld pool from oxygen and nitrogen in the atmosphere. Apart from only weld pool protection, shielding gas can also influence the weld strength, ductility, toughness, and corrosion resistance of weld joints. Thus choice and flow rate of shielding is important. There are two different shielding gases are commonly used for arc welding of aluminum, and these are argon and helium. These gases are used as pure argon, pure helium and various mixtures of both argon and helium. Plate-gap distance is another important factor that has influence on weld quality. In (Rao, Liu et al. 2014), it is showed that the gap between two
plates helps to expand the arc plasma and transfer metal. Narrow gap may result in incomplete penetrations defects and large gap result in wider fusion zone. Low welding current might cause lack of penetration and high welding current might result in porosity in fusion zone. Welding speed is also related to different weld defect. Higher welding speed or lower welding voltage can result in lack of fusion in weld joints.

Selection of filler metal is another critical issue for fusion welding. Strength of GTA-welded aluminum alloy joint largely depends of welding technique and filler metal. Two different filler metal series (5xxx and 4xxx) are usually utilized for GTAW of 6xxx series aluminum alloys. If 6xxx series aluminum alloys are welded employing filler metal from 5xxx series, cracking can occur in the partially melted zone (PMZ) as the weld zone solidifies rapidly. To alleviate hot cracking in weldment of AA6061, Si-rich filler metal such as ER-4043 is generally utilized (Mathers 2002; Rahman, Kumar et al. 2010; Cao, Sun et al. 2014; Rao, Liu et al. 2014), which possess high fluidity and exhibit lowest melting point. In a study by Malin (Malin 1995), performed hardness and tensile tests on a piece of AA6061-T6 that has been welded using pulsed gas metal arc welding (GMAW) with a filler metal of AA-4043. The study showed that the hardness profiles in the heat-affected zone were (HAZ) around 70% of the base material. The yield strength of the base material before welding was 305.7 MPa, with an average value of 206.8 MPa after welding. In another study (Coniglio, Cross et al. 2008), it is showed that for an 6xxx series aluminum alloy, AA-5356 filler rod is used for high strength, whereas Aluminum Alloy 4043 is used to improve crack resistance. They concluded that alloy 4043 generally selected because of its weld dilution property which usually decrease the risk of solidification cracking. Although alloy 5356 may increase the strength, a small crack in a thin piece of aluminum can significantly reduce its overall strength and life. When 4xxx series filler
metal is employed, the weld zone doesn’t respond to only post-weld aging as sufficient magnesium is not present for the precipitation of Mg$_2$Si, which is the main strengthening phase. However, these welds respond to solution treatment followed by aging (STA) (Reddy, Mastanaiah et al. 2006).

2.2.2. Fusion Arc Weld Defects in Aluminum Alloy Joints

Fusion arc welding of Aluminum and its alloys is always a great challenge for designers and technologists due to the intrinsic problem of porosity in aluminum welding and its eventual strength reductions. High coefficient of thermal expansion of aluminum (aluminum being a high heat-sink), solidification shrinkage, and high solubility of hydrogen during its molten state creates associated problems during fusion welding of aluminum alloys (Martukanitz 1993; Lakshminarayanan, Balasubramanian et al. 2009). As a consequence, weld defects are quite common, which result in the lower mechanical properties in aluminum alloys joints. The weld defects can be in the form of surface or sub-surface cracks, undercut, porosity, or sub-surface inclusions. The failures of welded structures generally start from preexisting weld defects (Greenberg 1966) which are intrinsic to the fusion arc welding processes. An important decision relating to its structural integrity must be made regarding weld defects and their effects on the strength of welded components. Only a limited number of studies have been reported in the open literatures on the effects of weld defects on mechanical performances (Rudy and Rupert 1970; Morton 1971; Lawrence Jr, Munse et al. 1975; Burk and Lawrence 1976). Rudy and Rupert (Rudy and Rupert 1970) and Lawrence et al. (Lawrence Jr, Munse et al. 1975) studied the effect of porosity on welded AA2xxx and AA5xxx aluminum alloys, respectively. Morton (Morton 1971) showed a linear relationship between fracture strength and projected defect areas of GTA-welded AA2xxx aluminum alloys. However, no conclusive study reported on weld defects and
their effects on GTA-welded AA6xxx aluminum alloy. A relation between non-destructively evaluated weld defects and tensile properties can help in designing a welded structure efficiently.

2.2.3. Residual Stresses in Fusion Arc Welded Aluminum alloy AA6061

During the fusion arc welding process, high amount of heat input and rapid cooling causes the material to yield and results in post-weld residual stresses development along the weld line and in the HAZ (Leggatt 2008). The material in the HAZ effectively becomes softer and more susceptible to failure (Malin 1995). Withers (Withers 2007) investigated the effects of heat input on a material surface. The author concluded that the area at the surface cools much faster once the heat input is taken away from the material. Because of faster cooling, cool surface wants to contract while the inside of the material is still under higher temperatures. This will cause the surface to form tensile residual stresses while the inside of the material will be under compression. The same theory applies to welding. Since the weld line is the last to cool, this results in tensile residual stresses that form at the weld line on the surface and moving to compressive residual stresses below the surface. In some materials, the maximum tensile residual stress reaches almost to the yield strength of the material. Different factors play a role in the magnitude of residual stresses that accumulate around the weldment. The geometry of the weld, the pass sequence (one or multi-pass welds), or the use of fabrication aids, such as jigs, tacks may have influence on where residual stresses arise. The resistant of the welded joint to expand and contract has an effect on the various residual stresses in each direction; transversely, longitudinally, and in the direction normal to the plane of welding. In Figure 2.5, typical residual stress distribution is illustrated for a butt-weld joint (Masubuchi 2013). Longitudinal residual stresses ($\sigma_l$), are generally higher than transverse residual stresses ($\sigma_t$), unless the work-piece has an external constraint that can in part or fully prevent the weld shrinkage. In the case of complete
weld shrinkage prevention the resulting residual stresses, $\sigma_l$ and $\sigma_t$, may reach the yielding strength of the weld material. As it can be seen in Figure 2.5, longitudinal stresses ($\sigma_l$) has reached the maximum in the middle part of the weld, where thermal contraction in the transverse direction is restrained more than in the surrounding of the much cooled base metal. These tensile stresses must be balanced by compressive stresses in the base material.

![Diagram](image)

Figure 2.5: Longitudinal and transverse direction along the but-weld shown in fig (a). Typical distribution of (b) longitudinal ($\sigma_l$) and (c) transverse ($\sigma_t$) residual stresses in a butt joint along weld line and line vertical to the weld line (Masubuchi 2013)

### 2.2.4. Residual Stress Measurement

During the in-service operation of weld parts residual stresses can cause harmful damages. Therefore, measuring the amount of residual stresses in a welded structure has a great importance. Over the last few decades various residual stress measurement techniques have been developed. In general, these techniques are qualified as destructive and non-destructive
techniques. Destructive methods measure by destroying the state of equilibrium of the residual stress and measure only the consequences of stress relaxation occurred by destruction. Most common destructive techniques are the hole-drilling method, the ring core technique, the bending deflection method, and the sectioning method (Ajovalasit, Petrucci et al. 1996; Thompson, Lu et al. 1996; Rossini, Dassisti et al. 2012). These methods are widely used in industry and they are sensitive to the macroscopic residual stress levels. Non-destructive methods are developed on the basis of relationship between residual stress and the physical or crystallographic parameters. Different non-destructive techniques are developed such as the X-ray diffraction method, the neutron diffraction method, the ultrasonic method, and the magnetic method. X-Ray diffraction method is used for measurement of surface and subsurface stresses (Schajer, Roy et al. 1996). It can be defined as a surface method. On the other hand, neutron diffraction method allows measurement up to the depth of 50 mm (Holden and Roy 1996). X-Ray and neutron diffraction methods are expensive and cannot be carried out in-situ and require the removal of components (Rossini, Dassisti et al. 2012). Non-destructive ultrasonic testing can be used in most materials to measure residual stresses. Variations in velocity of the ultrasonic waves can be related to the residual stress state (Sanderson and Shen 2010). Ultrasonic waves and acoustoelasticity allows measurement of surface and subsurface residual stresses. Surface and subsurface stresses can be determined by using shear waves or longitudinal waves. Many attempts have been proposed for this purpose. Recent studies are mostly focused on critically refracted longitudinal (LCR) wave method (Clark and Moulder 1985; Don E. Bray 2001; Uzun and Bilge 2011). This technique allows measurement of in-plane stresses. Surface stresses, as well as bulk stresses can be determined by using ultrasonic longitudinal waves. Longitudinal waves polarize in the same direction that it propagates. Anisotropy in the material caused by stress, affect the propagation
velocity of longitudinal waves. Stresses normal to the wave propagation direction can be measured using the longitudinal waves. Furthermore, related to the development of computer technologies, numerical modeling methods such as finite element method have an important role on prediction of residual stress.

2.2.5. Post-Weld Heat Treatment of GTA-Welded Aluminum alloy AA6061

As discussed above, besides weld defects, residual stresses and microstructural changes are the two other key factors for performance reduction as well as failure of welded heat treatable aluminum alloy joints. During welding process, exposure to high temperature fusion followed by non-linear rapid cooling near the fusion areas cause grain coarsening and post-weld residual stress development in the heat-affected zone (HAZ) and fusion zone of the weld joint (Leggatt 2008). Then again, multipass welding causes strain hardening during the cooling of subsequent passes. The strain hardening also has a significant influence on the residual stress development in the weld zone (Deng, Murakawa et al. 2008). The materials in the HAZ and fusion zone effectively become softer and more susceptible to failure (Malin 1995).

Although a number of research studies have investigated the application of post-weld heat treatment (PWHT) to different aluminum alloy welding joints using several welding processes (Akhter, Ivanchev et al. 2007; Bhanumurthy, Kumbhar et al. 2007; Elangovan and Balasubramanian 2008; Malarvizhi, Raghukandan et al. 2008; Aydın, Bayram et al. 2010; Ahmad and Bakar 2011; Maisonnette, Suery et al. 2011; El-Danaf and El-Rayes 2013; Peng, Shen et al. 2013; Damodaram, Ganesh Sundara Raman et al. 2014; Ding, Wang et al. 2014; Sivaraj, Kanagarajan et al. 2014), but only a few investigations showed the effect of PWHT on fusion welded AA6061 aluminum alloys (Ahmad and Bakar 2011; Maisonnette, Suery et al. 2011; Dewan, Liang et al. 2013; Peng, Shen et al. 2013). Uniformly distributed Mg$_2$Si precipitates, smaller grain size, and higher dislocation
density have been shown to be the reasons of enhanced mechanical properties due to PWHT of AA-6061 (Elangovan and Balasubramanian 2008). Heat treatment involves various heating and cooling cycles to change microstructures in a material. The PWHT contributes to precipitation of alloying elements, grain refinement, and higher dislocation density in welded AA6061 aluminum alloys; and consequently enhanced mechanical properties that can be achieved (Ravindra and Dwarakadasa 1992; Liu, Chen et al. 2006; Elangovan and Balasubramanian 2008). In the literature, it is shown that the improvement in yield strength, tensile strength, and hardness of the welded joints can be achieved by solution treatment followed by artificially aging (Metzger 1967; Periasamy, Sundararajan et al. 1995).

The thermal treatment for aluminum alloy AA6xxx series consists of three main processes: solution heat treatment, quenching, and aging (Garrett, Lin et al. 2005). Solution treatment is done by heating the welded samples above solution temperature followed by quenching. During solution treatment, the precipitates (solute atoms) are dissolved into the solvent (Gao, Stiller et al. 2002). Quenching after solution treatment causes the development of supersaturated solid solution (SSS). During the artificial aging process solution treated quenched material is kept to a specified temperature for an extended period of time, depending on the type of material being used, and the types of precipitates existing within the materials. Ageing can be done artificially by exposing the material to a high temperature, or naturally by letting the material sit before any outside loads are applied to it. During the ageing process, precipitation of the supersaturated solute atoms takes place around the grain boundaries. The atoms then form Guinier-Preston (GP) zones which are connected with the solvent matrix. After a period of time and temperature rise, the “β” phase forms, which are much larger than the GP zones. For the aluminum alloy AA6061, the age-hardening process reaches maximum hardness just after the “β” phase forms. There is a
fine line between precipitation hardening and over-ageing the material. Exposing the material to a temperature for longer than required aging time, can cause the precipitates to grow too large and more widely dispersed within the material (Tan and Said 2009). This effect causes the material eventually to lose its strength. Therefore, optimum aging temperature and time are essentially required for PWHT process to obtain improved mechanical properties. Typical pseudo-binary phase diagram for Al-Mg$_2$Si is shown in Figure 2.6 (ASM-International 2002).

![Figure 2.6: Pseudo-binary phase diagram for Al-Mg$_2$Si (ASM-International 2002)](image)

In many structural applications conventional and alloy steels are utilized for their higher modulus, strength, and toughness properties. So, steels joints are also needed to be investigated to complete the structural integrity analysis of welded structures. In the next two sections,
literatures on most commonly utilized fusion welded high strength alloy steel and low carbon structural steel joints are reviewed.

2.3. Fusion Arc Welding of Alloy Steel

Among different alloy steel, AISI-4140 chromium-molybdenum alloy steel is widely utilized in structural, automotive, petroleum, and gas industries due to its superior hardenability, good corrosion resistance, and higher strength properties. Chromium-molybdenum steel pipe are also considered as major construction material for next generation power plants. The wide applications of alloy steel call for more efficient and reliable welding processes which has always represented a great challenge for designers and technologists. Commonly utilized fusion arc welding techniques are usually employed for joining AISI-4140 steels. Instead of weld defects, unstable brittle fracture of welded alloy steel is an active global problem. A weldment, especially the heat-affected-zone (HAZ), is a complex problem where variable microstructures are formed from different thermal treatments and environmental conditions. This complexity involves inherent mechanical behavior such as strength, ductility, hardness, and fracture toughness. In addition, three-dimensional residual stress field can result in significant decrease of fracture toughness values in the HAZ area (Mac Henry and Potter 1990; Venkata Ramana, Madhusudhan Reddy et al. 2010). It is well known that the post-weld heat treatment (PWHT) of welded structure strongly affects their microstructure and their mechanical properties (Olabi and Hashmi 1995; Smith, Pistorius et al. 1997; Ahmad and Bakar 2011). Besides PWHT, a number of other post-weld treatment operations such as grinding, shot peening, re-melting, and ultrasonic peening are also utilized to remove post-weld tensile residual stresses and induce compressive residual stresses in welded structures (Abdullah, Malaki et al. 2012).
2.3.1. Post-Weld Heat Treatment (PWHT) of AISI-4140 Steel Joint

Post-weld heat treatment (PWHT) is a common practice to relieve undesirable post-weld tensile residual stresses and improve mechanical properties of welded low alloy and high strength steel structures by grain refinement. PWHT can encompass many different potential treatments. Depending on the heat treatment, the microstructure of alloy steel can be different. Sometimes it becomes ferritic - pearlitic (Jahazi and Egbali 2000; Korda, Miyashita et al. 2007) or tempered martensitic or even bainitic (Tau, Chan et al. 1996).

![Figure 2.7: Schematic of typical pre-heating, welding, and post-weld heating process for chromium-molybdenum alloy steel](image)

The degree of PWHT embrittlement is dependent upon heating rate, holding time or duration of treatment, applied stress, and grain size of the weld and HAZ microstructures (Zhang, Yang et al. 2013). The filler metal composition is also important on the degree of PWHT embrittlement. After heat treatment, the properties of the deposited weld can be considerably different than the “as-welded” properties. For chromium-molybdenum alloy steel, PWHT usually performed
around 675 °C to 700 °C temperature range to relieve post-weld residual stresses (Funderburk 1998). Particularly for AISI-4140, stress relieving can be performed by hardening at 500 °C to 550 °C or by annealing at 600 °C to 650 °C. In Figure 2.7, typical heating and cooling cycle for chromium-molybdenum alloy steel joint is illustrated schematically.

Sometimes, PWHT is difficult to control and apply, as well as it is expensive and time-consuming. For this reason the authors have explored different surface processing technique such as, electrolytic-plasma-processing (EPP), a new and environmentally friendly technique.

### 2.3.2. Electrolytic- Plasma- Treatment of Welded Alloy steel

Electrolytic-plasma-processing (EPP) is an effective surface engineering technique that combines cleaning and coating of metals (Kellogg 1950; Ryabkov 2003). EPP involves electrolysis and electrical discharge phenomena (Meletis, Nie et al. 2002). During EPP-treatment, Direct Current (DC) voltage is applied to the electrodes in the aqueous electrolyte, which produces plasma at the surface of the submerged workpiece. In Figure 2.8, the schematic of EPP technique is illustrated.

![Figure 2.8: Schematic of electrolytic-plasma-processing (EPP)](image-url)
During EPP, high temperature plasma is created within the small size hydrogen bubbles in the thin electrolyte layer on the surface of the workpiece. This causes not only localized melting but also shock waves from the collapsing of the bubbles and thus, strong surface forces on small molten patches of steel (Meletis, Nie et al. 2002).

Thermal, chemical, electrical, and mechanical effects caused by EPP to the workpiece produce unique surface features (Meletis, Nie et al. 2002; Gupta, Tenhundfeld et al. 2005). Until now, EPP is fully developed for industrial applications in specific processes; and is being researched for other possible commercial applications. EPP- treatment results in sub-micro-grained surface structure and low martensite volume fraction at the top surface. This provides the benefits of combination of high hardness and good corrosion resistance properties (Meletis, Nie et al. 2002; Liang, Wang et al. 2011). It is reported that welded metals are poor corrosion resistant when exposed to corrosive environment (Dadfar, Fathi et al. 2007). Therefore EPP might be an important processing for post-weld treatment process to improve both corrosion resistant and mechanical properties of welded structures. Only a few handfuls of studies are reported in the open literature on the use of Plasma- Electrolytic- Oxidation (PEO) coating on welded structures, corrosion, and stress corrosion cracking related studies (Prasad Rao, Janaki Ram et al. 2008; Srinivasan, Blawert et al. 2008).

In previous sections, weld qualities are analyzed utilizing different destructive and non-destructive testing techniques. Uniaxial tensile test is typically employed for mechanical performance analysis of weld joints. But in many structural applications, fatigue test data especially multiaxial fatigue performances of welded structures are important. In the last section of this study, biaxial fatigue performance of welded steel is analyzed. Literatures related to multiaxial fatigue behavior of welded steel are reviewed below.
2.4. Fatigue Test of Welded Steel

Fatigue, as understood by materials researchers, is a process in which damage accumulates due to the repetitive application of loads that may be well below the yield point. Stresses responsible for fatigue failure are usually below the accepted values for static loading. Fatigue failure was first believed to be sudden and not having any apparent causes (Callister 2010). The first known fatigue testing machine was constructed by Albert in 1838 to determine the fatigue life of conveyor chains. Likewise, fatigue life prediction started gaining importance in order to prescribed maintenance scheduling for rotating equipment. Eventually, rotating-bending machines for materials were designed by Wöhler (1960) to obtain more accurate and reliable results (Schütz 1996). The S-N curve was introduced to characterize fatigue behavior of a material. A typical S-N is consists of three different zones as shown in Figure 2.9.

![Figure 2.9: Typical fatigue test results in S-N curve](image)
The endurance limit can be interpreted as the maximum stress that can be applied repeatedly without causing failure of the test piece. Its value ranges from 40 to 60 percent of the tensile strength for steel (Callister 2010). However, this value can be affected by different variables such as materials, surface condition, loading condition, specimens size, etc. For steels, there is a knee at $N = 10^6$ cycles; but for non-ferrous metals, such as aluminum, the horizontal section does exist. The finite section of the S-N diagram behaves as straight line. However, slopes are different for low cycle (for $N < 10^3$) and high cycle (for $10^3 \leq N \leq 10^6$). This behavior is a consequence of the high stresses being applied for low cycle, where the yield strength is reached and the failure occurs by deformation rather than by fatigue.

2.4.1. Multiaxial Fatigue Test

Uniaxial fatigue and rotating-bending fatigue studies are common analysis for welded structures (Gurney 1979; Mac Henry and Potter 1990; Schütz 1996; Almaraz, Tapia et al. 2010). But many structural welded components are experience torsional loading along with rotating bending loading (Bäckström and Marquis 2001; Carpinteri, Spagnoli et al. 2009). It is important to know the combined effect of rotating-bending and torsional load on structural components. Earliest works on multi-axial loads can be attributed to Lanza (Lanza 1886), and the first systematic research on multi-axial fatigue was performed by Gough and Pollard (Gough and Pollard 1935; Gough, Council et al. 1951). They have produced the bending-torsion test data and has used later for producing Gough models. Moreover, evaluating the damage mechanisms and crack nucleation, McDiarmid (McDiarmid 1994) introduced damage models using the “Critical Plane” concept. The most currently used theory in predicting fatigue failure for multi-axial loads is critical plane strain-based approach (Fatemi and Shamsaei 2011).
Conventional rotating-bending fatigue testing machine consists of a motor coupled to a chuck to hold the specimen on one end and bending weight is suspended from the other end. In that design the load being applied is pure bending at constant load amplitude, but the bending moment is not uniformly applied over the length of the specimen. This is considered to be acceptable for notched or tapered specimens. A constant bending moment is required to produce uniform stress over the test section of non-tapered specimens. If the specimen can be supported from both ends, a uniform bending moment can be obtained along the specimen length during rotating-bending fatigue test. R.R. Moore type rotating-bending fatigue machine (Figure 2.10) was designed and built to apply fully reversed uniform bending load (ASM-International 2002). In (Stefanov and Stoychev 2004), designed a rotating-bending machine which permitted the application of constant torsion. The torsion was applied using a weight system coupled to a clamping pulley which allows easy torque calculation; however, due to design constraints the maximum torque applied was 0.3 times of that of the bending stress.

Figure 2.10: Schematic of R.R. Moore reversed-bending fatigue machine (ASM-International 2002)
2.4.2. Multiaxial Fatigue Test of Welded Steel

Some study reported on the effect of biaxial loading (e.g., bending and torsion) on different welded structures (Yung, Lawrence et al. 1985; Sonsino 1995; Sonsino and Kueppers 2001; Takahashi, Takada et al. 2003; Pelton, Fino-Decker et al. 2013). In (Costa, Abreu et al. 2005), biaxial fatigue behavior of tubular Al-Mg-Si welded specimens was investigated. The influence of stress ratio ($R = S_{\text{min}}/S_{\text{max}}$) and bending–torsion stress ratio were analyzed. They concluded that the static torsion has only a slight detrimental influence on fatigue strength. In (Kueppers and Sonsino 2006), a suitable calculation procedure based on a combination of local normal and shear stresses in the critical plane for multiaxial loaded aluminum welds has been developed. Wahab and Sakano studied the effect of corrosion and biaxial fatigue on simulated heat-affected-zone metal (Wahab and Sakano 2003). From their study, it was concluded that both secondary thrust (torsional load) and corrosion results in reduced fatigue life as compared to pure bending fatigue life. The fatigue strength of welded specimens under multiaxial cyclic loading is still unclear due to lack of data and complexity of weldment analyses (i.e. microstructures, residual stresses, weld defects, etc.) involved in weld joints. The lack of clarities in estimating the residual stresses and fatigue life under multiaxial loads has led to conservative assumptions in the current fatigue design of welds.

2.5. Summary

An extensive critical literature review was conducted on four different welded structural materials. Microstructural changes, weld defects, and residual stresses are the key factors for the performance reduction of welded structures. From the innovation of welding techniques, there are many research studies conducted to understand behavior of a weld joint. But weld metallurgy is really complex and many questions are still un-answered. On the other hand,
innovation of new welding techniques as well as new materials requires more research study to understand structural integrity of newly designed weld joints. Key summaries derived from the above literature review are listed below.

- To produce a high quality defect-free friction-stir-welding (FSW) joint, the welding process parameters such as: rotational speed, welding speed, and axial plunge force or displacement, and tool pin design must be chosen carefully. Since the beginning, FSW investigators have researched the influence of parameters on microstructures and mechanical properties with a view to optimize FSW processes. As discussed above, there is no conclusive study reported to correlate all critical weld process parameters. A parametric relationship establishing the boundary between defective and defect-free weld schedules will be helpful for finding optimum weld schedules.

- For FSW, development of an appropriate physical model which can predict the process's main characteristics (weld defects and mechanical properties) is really complex. As discussed above, researchers focused on creation of predictive models based on numerical analysis or empirical models based on experimental observations. Adaptive network-based fuzzy inference system (ANFIS) is a hybrid predictive model which uses both of neural network and fuzzy logic to generate mapping relationship between inputs and outputs. Although ANFIS is a powerful tool for prediction of manufacturing processes but there is only one study on FSW has been presented (Babajanzade Roshan, Behboodi Jooibari et al. 2013) and utilized this technique and had some limitations. Development of an optimized ANFIS model to predict weld quality from weld process parameters will be an important step for FSW research.

- In addition, strength reduction of FS-welded high strength aluminum alloys due to
dissolution of precipitation elements is another important apprehension for design engineers. Post-weld heat treatment (PWHT) is a common practice to improve mechanical performances of welded aluminum alloys. But optimum PWHT condition is required for each welded materials to obtain best performances. An extensive experimental analysis on PWHT of FS-welded AA2219-T87 aluminum alloys will help design engineers to design safer and more reliable structures.

- Welding defects and post-weld residual stresses are the foremost problems for fusion welded aluminum alloys joints. An important decision relating to its structural integrity must be made regarding weld defects and their effects on the strength of welded components. Only a limited number of studies have been reported in the open literatures on the effects of weld defects on mechanical performances. However, no conclusive study reported on weld defects and their effects on GTA-welded AA6xxx aluminum alloy. A relation between non-destructively evaluated weld defects and tensile properties can help in designing a welded structure efficiently and cost-effectively. Besides weld defects, residual stresses and microstructural changes are the two other key factors for performance reduction as well as failure of welded heat-treatable aluminum alloy joints. Post-weld heat treatment (PWHT) is a common practice to reduce residual stresses and improve mechanical performances of weld joints. But only a limited number of investigations reported on the effects of PWHT on fusion welded AA6061-T651 aluminum alloys. More research is needed for better understanding of the influences of weld defects and post-weld heat treatment (PWHT) on gas tungsten arc (GTA) welded aluminum alloy AA6061-T651 joints.

- In many structural applications, alloy steels are utilized for its high strength and high
stiffness properties. Unlike aluminum alloy joints, weld defects are not of prime concern for welded steel joints. Residual stress development, microstructure changes, and unstable brittle fracture are all unavoidable active problems for alloy steel joints. Post-weld heat treatment (PWHT) is a common practice to relieve undesirable tensile residual stresses and improve mechanical properties of welded alloy steel structures by grain refinement. Sometimes, PWHT is difficult to control and apply according to the recommendations, as well as it might be expensive and time-consuming. For this reason the authors have explored different surface processing technique such as, Electro-plasma-processing (EPP).

- Most welded structures are subjected to multiaxial fatigue load in real service situations and majority of the fatigue failures are initiated from weld joints. Therefore, it is important to evaluate multiaxial fatigue behavior of commonly utilized welded materials. Uniaxial fatigue and rotating-bending (RB) fatigue analysis is common for welded structures. A handful studies reported on the effect of biaxial loading (e.g. bending and torsion) on different welded structures. Thus more multiaxial fatigue study is required for structural integrity analysis of different weld joints.
CHAPTER 3 : EXPERIMENTAL PROGRAM OF WELD JOINTS

3. Introduction

Structural integrity analysis and performance improvements of weld joints are one of the important topics in welding area. Depending on applications, different types of materials as well as different types of welding processes are utilized to fabricate welded structures. In this current research, four different types of materials along with two different welding techniques are utilized to understand the structural integrity of different weld joints. Two materials are chosen from aluminum alloys which are commonly utilized for lightweight engineering structures. Other two materials are chosen from steels which are widely utilized for heavy structures where strength and stiffness are of prime concerns. Friction-stir-welding (FSW) which is a solid-state welding technique has been utilized in joining aerospace grade aluminum alloy. For other materials, commonly employed fusion arc welding technique (i.e. Gas Tungsten Arc Welding) is utilized. Along with microscopic analysis, different non-destructive and destructive testing techniques are utilized to ascertain structural integrity analysis of weld joints. Commonly utilized non-destructive ultrasonic testing (UT) is employed in this study. In some cases, radiographic and microscopic analysis is employed to verify UT data. Widely utilized uniaxial tensile testing, rotating bending fatigue testing, and micro-hardness testing are employed to measure mechanical performances of different weld joints. This chapter details the materials, welding procedures, and experimental procedures utilized in this research.

3.1. Materials Selection

Each material has a defined and distinct set of characteristics that makes it the right or the wrong kind of material for particular applications. Among different types of materials, steel and aluminum are the two most popular engineering materials used in many structural applications.
Aluminum alloys are desirable due to lightweight and higher strength to weight ratio. But aluminum alloys have some limitations in application where higher temperature resistance and higher stiffness are required. In such cases, different types of steels are mostly utilized. In the current research, widely used two different types of aluminum alloy (AA2219-T87 and AA6061-T651) and two different types of steel (AISI-4140 and AISI-1018) are selected for structural integrity analysis and performance improvement of weld joints.

3.1.1. Aluminum Alloys

Aluminum alloys find wide applications in aerospace, automobile industries, railway vehicles, offshore structure topsides, and high speed ships such as catamarans, due to its lightweight and higher strength to weight ratio. Widely available and applicable two different grades of aluminum alloys (AA2219-T87 and AA6061-T651) are utilized in this current study. Two different series aluminum alloys have different alloying element and different properties. Series 2xxx aluminum alloys are alloyed with copper and can be precipitation hardened to improve strength which is comparable to steel; but 2xxx series aluminum alloys are susceptible to stress corrosion cracking. Among different 2xxx series aluminum alloys, AA2219-T87 is widely utilized in aerospace industry. Then again, 6xxx series aluminum alloys are alloyed with magnesium and silicon. They are easy to machine, are weldable, and can be precipitation hardened, but not to the high strengths that 2xxx can reach. Among different 6xxx series aluminum alloys, AA6061-T651 is one of the most commonly used general-purpose aluminum alloy.

Aluminum alloy AA2219-T87:

Aluminum alloy AA2219 is the mostly used material for the construction of space shuttle and liquid cryogenic rocket fuel tanks. It has a unique combination of properties such as, its good
weldability, high strength to weight ratio, and superior cryogenic properties (Srinivasa Rao, Sivadasan et al. 1996). Aluminum alloy AA2219-T87 is a high strength aluminum alloy with an alloying element nominal composition 6% copper, 0.3% manganese, and 0.2% zirconium. The T87 designation describes the treatment of aluminum alloy, indicates the material is solution-heat treated, cold-worked by stretching, and then artificially aged. AA2219-T87 exhibits an ultimate tensile strength of 440 MPa and yield strength of 350 MPa (ASM-International 1993). The chemical composition and tensile strength of AA2219-T87 are listed in Table 3.1. In the current investigation, 8.13 mm thick × 152 mm wide × 609 mm long AA2219-T87 aluminum alloy plates are utilized for friction-stir-welding.

Table 3.1: Chemical composition and tensile strength of AA2219-T87 aluminum alloys (ASM-International 1993)

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>Zn</th>
<th>V</th>
<th>Zr</th>
<th>Al</th>
<th>YS,</th>
<th>UTS,</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA2219-T87</td>
<td>5.8-6.8</td>
<td>&lt;= 0.3</td>
<td>&lt;= 0.2</td>
<td>0.2-0.4</td>
<td>&lt;= 0.2</td>
<td>0.02-0.1</td>
<td>&lt;= 0.1</td>
<td>0.05-0.15</td>
<td>0.1-0.25</td>
<td>91.5-93.8</td>
<td>350</td>
<td>440</td>
</tr>
</tbody>
</table>

**Aluminum Alloy AA6061-T651:**

Fusion welding of aluminum alloys is a great challenge for material researchers. Among different aluminum alloys, medium strength heat-treatable AA6061 appears to have good weldability and wider applications over high strength aluminum alloys. Mechanical properties and chemical composition of AA6061-T651 are listed in Table 3.2. In the current investigation, 300 mm long × 76 mm wide × 6.35 mm thick AA6061-T651 aluminum alloy plates are utilized for gas tungsten arc welding (GTAW). Selection of filler metal is a critical issue for fusion arc welding. Two different types of filler rods usually utilized in GTAW of AA6061-T651. If 6xxx series aluminum alloys are welded employing filler metal from 5xxx series, cracking can occur
in the partially melted zone (PMZ) as the weld zone solidifies rapidly. To avoid this cracking problem these alloys are typically welded with 4xxx, which possess high fluidity and exhibit lowest melting point. When 4xxx series fillers are employed, the weld zone does not respond to post-weld aging, as sufficient magnesium is not present for the precipitation of Mg$_2$Si, which is the main strengthening phase. However, these welds may respond to “solution treatment and aging (STA)”. In this investigation, ER-4043 filler metal was utilized. Chemical composition and mechanical properties of ER-4043 filler metal are listed in Table 3.2.

Table 3.2: Chemical composition and tensile strength of base metal (AA6061-T651) and filler rod (ER-4043) (ASM-International 1990)

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>Zn</th>
<th>Al</th>
<th>YS, MPa</th>
<th>UTS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA6061-T651</td>
<td>0.04-0.35</td>
<td>0.15-0.40</td>
<td>&lt;0.70</td>
<td>0.80-1.2</td>
<td>&lt;0.15</td>
<td>0.40-0.80</td>
<td>&lt;0.15</td>
<td>&lt;0.25</td>
<td>95.8-98.6</td>
<td>305</td>
<td>334</td>
</tr>
<tr>
<td>ER-4043</td>
<td>--</td>
<td>&lt;0.30</td>
<td>&lt;0.80</td>
<td>&lt;0.05</td>
<td>4.50-4.60</td>
<td>&lt;0.20</td>
<td>&lt;0.10</td>
<td>92.3-95.5</td>
<td>124</td>
<td>186</td>
<td></td>
</tr>
</tbody>
</table>

In some structural applications, instead of aluminum alloys different types of steels are needed. In the next section, composition and tensile properties of two different types of steels, which are used in this study, are discussed.

3.1.2. Alloy Steels

Different grades of steels are required for different structural applications. In the current investigation, one high strength alloy steel (AISI-4140) and one low carbon steel (AISI-1018) are utilized. Among different alloy steels, AISI-4140 offers higher strength, good atmospheric corrosion resistance, and reasonable strength up to around 315 ºC. Then again, AISI-1018 low carbon steel offers good toughness and ductility. AISI 1018 also offers excellent weldability and machinability compared to high strength alloy steel.
Alloy steel AISI-4140:

AISI-4140 chromium-molybdenum alloy steel is widely used in structural, automotive, petroleum, and gas industries due to its superior hardenability, good corrosion resistance, and higher strength. The chromium content provides good hardness and the molybdenum content ensures uniform hardness and high strength. Lower carbon (0.40%) and manganese (0.85 %) offers better toughness values and can be heat-treated to improve mechanical properties. AISI-4140 is difficult to weld, but welding can be performed using any of the common welding practices. Welding of AISI-4140 chrome-molybdenum steel in the annealed condition is widely preferred. When welding AISI-4140 steel (in any condition), only low hydrogen electrodes should be used. In the current investigation, rolled plates of AISI-4140 annealed multipurpose alloy steel with 300 mm × 76 mm × 6.35 mm dimensions are GTA- welded with SAE-4130 chromoly filler rod. Chemical composition and tensile strength of AISI-4140 alloy steel and SAE-4130 filler rod are listed in Table 3.3.

Table 3.3: Chemical composition and tensile strength of base metal (AISI-4140) and filler rod (SAE-4130) (ASM-International 1993)

<table>
<thead>
<tr>
<th></th>
<th>wt.%</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Mo</th>
<th>P</th>
<th>Si</th>
<th>S</th>
<th>Fe</th>
<th>YS, MPa</th>
<th>UTS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI-4140</td>
<td>0.38-0.43</td>
<td>0.8-1.1</td>
<td>0.75-1.0</td>
<td>0.15-0.25</td>
<td>0.035</td>
<td>0.15-0.30</td>
<td>0.04</td>
<td>96.7-97.7</td>
<td>415</td>
<td>655</td>
<td></td>
</tr>
<tr>
<td>SAE-4130</td>
<td>0.28-0.33</td>
<td>0.8-1.1</td>
<td>0.4-0.6</td>
<td>0.15-0.25</td>
<td>0.035</td>
<td>0.15-0.35</td>
<td>0.04</td>
<td>97.3-98.2</td>
<td>460</td>
<td>560</td>
<td></td>
</tr>
</tbody>
</table>

Low carbon steel AISI-1018:

Among different engineering materials, AISI-1080 steel is commonly used structural materials in different industrial applications for its easy weldable and surface hardenable quality (G.M. Almaraz, M. Tapia et al. 2010). It is especially suitable for carburized parts requiring soft
core and high surface hardness, such as gears, pinions, worms, ratchets, etc. In this study, general purpose cold drawn AISI-1018 low carbon steel rod with 19.05 mm diameter is welded utilizing GTAW technique. Welding was done according to AWS welding codes for steel (AWS D1.1/D1.1M 2010) utilizing ER70-S2 filler rod. Chemical composition and tensile strength of AISI-1018 alloy steel and ER70-S2 filler rod is listed in Table 3.4.

Table 3.4: Chemical composition and tensile strength of base metal (AISI-1018) and filler rod (ER70-S2) (ASM-International 1993)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Ti</th>
<th>Zr</th>
<th>YS, MPa</th>
<th>UTS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER70-S2</td>
<td>0.04</td>
<td>0.55</td>
<td>1.08</td>
<td>0.0003</td>
<td>0.005</td>
<td>0.2</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>400</td>
<td>482</td>
</tr>
<tr>
<td>AISI-1018</td>
<td>0.18</td>
<td>--</td>
<td>0.68</td>
<td>≤ 0.04</td>
<td>0.043</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>415</td>
<td>485</td>
</tr>
</tbody>
</table>

3.2. Welding Procedures

Two different types of welding techniques were employed in this study. Solid-state friction-stir-welding (FSW) technique was utilized for joining aerospace grade AA2219-T87 aluminum alloy. Widely utilized gas tungsten arc welding (GTAW) technique was employed for joining AA6061-T651 aluminum alloy, AISI-4140 alloy steel, and AISI-1018 low carbon steel.

3.2.1. FSW Procedure of AA2219-T87

Solid state friction-stir-welding (FSW) technique requires specific equipment and tooling, experimental setup, and experimental schedules. Details are discussed below.

3.2.1.1. Equipment and tooling

The NASA Michoud Assembly Facility (MAF) in New Orleans houses the National Center for Advanced Manufacturing (NCAM) that has a state-of-the-art FSW facility. This
facility was utilized to conduct all welds reported in this study; specifically, models *I-Stir PDS* and *UWS #2* FSW machines were employed.

![FSW tool images](image)

Figure 3.1: FSW fixed pin-tool (top), I-Stir PDS (left), and UWS #2 (right) FSW machines (*Courtesy NCAM*) located at the *Michoud Assembly Facility* (MAF)-New Orleans

The tool utilized is a two-piece fixed pin-tool. The shoulder was made from H13 steel with 30.48 mm diameter and 0.76 mm deep counter clockwise (CCW) spiral scroll of 2.92 mm pitch. The pin, which is interchangeable, is a 10° tapered cone of MP159 Nickel-Cobalt based multiphase alloy, 10.16 mm average diameter at the shoulder and extending to a depth of 7.112 mm. The pin was threaded with an 18 TPI UNC LH thread. Figure 3.1 illustrates the pin-tool utilized during welding with PDS and UWS #2 FSW machines.
3.2.1.2. Experimental setup and procedure

The material welded is AA2219-T87 with each panel having dimensions of 609.6 mm long, 152.4 mm wide, and 8.13 mm thick. Two panels were welded in a typical butt-joint configuration. The fixture that was utilized for welding entailed a steel anvil. Steel bars (often called “chill bars”) were placed on the Advancing Side (AS) and Retreating Side (RS) of the panels and were used for clamping down the panels (Figure 3.2).

![Figure 3.2: FSW process showing three critical weld process parameters (downward plunge force $F_z$, spindle rotational speed $N$, and welding speed $V$)](image)

Side compression screws were used on the RS. Before the panels were clamped down into the fixture, the area that would come into contact with the pin-tool was lightly grinded to remove top layer of material to ensure oxide particles would not be pulled into the weld. The panels were wiped with an alcohol solution and were inserted into the fixture. During welding, a 0° lead angle was used with no index-offset from the centerline. Both FSW machines are instrumented with several sensors. During experiments, signals including forces, torque, rotational speed,
welding speed, and pin-tool positions were recorded with a 60 Hz sampling rate. Temperature was collected with a Midi Logger GL820 acquisition system with a sampling rate of 200 ms utilizing 20-“k”-type thermocouples.

3.2.1.3. Experimental schedules

With any welding process determination of acceptable ranges of process parameters that can be used for a pin-tool, fixture condition, and material used must be determined. FSW conditions can greatly change when any of these variables are altered. For this reason, at the onset of the research, two welds were conducted with the chosen fixture, material, and pin-tool type to illuminate appropriate process parameter windows. The two initial welds utilized the position-control setting. Based on prior experience and trial and error technique, spindle rotational and travel speeds were estimated and employed. Consequently, a range of appropriate plunge force values were determined where the pin-tool can operate. FSW experiments were thereby conducted in the rest of the work with the load-control setting allowing the three process parameters (spindle rotational speed, welding speed, and plunge force) to be varied. Typically in manufacturing and production, weld schedules for a particular welding environment have been optimized and consequently deemed acceptable. As the outcome of these weld schedules are known, load-control is utilized which provides precise control of the welding parameters and achieves steady-state welding conditions throughout the weld; consequently, variation in welding forces are minimized.

A large number of weld schedules is needed to obtain a surface plot of three weld process parameters and identify anticipated weld quality. But each welding and experiment involves additional cost. To minimize the number of required weld schedules and cost, two process parameters (welding speed and spindle rotational speed) were grouped together and coined as
“dimensionless speed ratio (R)”. In this study, a total of 66 weld schedules with different combinations of plunge force, welding speed, and spindle rotational speed were welded utilizing FSW technique. The panels, 304 mm wide × 609 mm long, each comprised of two plates, 152 mm wide × 609 mm long, joined together by a weld along the panel center as illustrated in Figure 3.3. To save material two schedules were employed on each panel. Parameters comprising the weld schedules ranged: spindle rotational speed (N), 200 rpm to 450 rpm; welding speed (V), 76.2 mm/min to 266.7 mm/min; and plunge force (Fz), 12.46 kN to 37.80 kN.

Figure 3.3: A plan view of FS-welded panel crown surface showing weld segments with different schedules are marked. (AS-Advancing Side and RS-Retreating Side)

At the onset of the experimental program, the UWS #2 FSW machine was utilized due to machine availability. Consequently, after the first-set of experiments were conducted, the new I-Stir PDS FS welder was installed and utilized for the remaining welds. Upon transition to the PDS welder, three tests were conducted to verify weld quality and condition was similar with exact weld schedules run on the UWS #2 FSW machine. Results from the tests showed similar weld qualities and tensile properties which verify switching between the two I-Stir FS- welders does not have any noticeable effect on welding results.
Using two weld schedules per panel has been introduced two non-steady-state areas on the panel. Transition located at the onset of a welding is called plunge transition zone (PTZ) and transition of between weld schedules is called schedule transition zone (STZ). At the start, the initial plunge can generate more heat than is indicative of the actual weld schedule which lead to inaccurate results due to heat pulled into the weld. In a similar manner, a transition area is required in the area where the schedule changes. As an example, the transition and steady-state conditions of the PTZ and STZ can be seen in Figure 3.4.

Figure 3.4: Schematic of FS- welded panel with acceptable and transition areas with magnified images a plunge transition zone (PTZ) and schedule transition zone (STZ)

On the bottom left image, heat has been pulled from the plunge stage which gives the appearance of a defect- free weld schedule; however, after the heat dissipates the actual quality of the weld schedule is illuminated. On the bottom right image, illustrations of the transition area between two schedules showing the change in ripple patterns. The current welding configuration plunges at a distance equal to roughly 27 mm from the edge of the panel. Roughly 101.6 mm of longitudinal travel distance after the plunge is considered the PTZ. After the PTZ, steady-state
conditions occur until the weld schedule changes at 304.8 mm (middle of panel). In a similar fashion, schedule transition zone (STZ) occurs 101.6 mm after the second schedule begins (transition area lengths will vary depending on the weld schedule). Lastly, the pin-tool is extracted 27 mm before the end of the panel.

### 3.2.2. GTAW of AA6061-T651

Rolled plates of AA6061-T651 aluminum alloy with 300 mm × 76 mm × 6.35 mm dimensions were GTA-welded utilizing ER-4043 filler rod according to AWS structural welding codes for aluminum (AWSD1.2/D1.2M: 2008). The direction of welding was normal to the rolling direction and all necessary care was taken to avoid joint distortion while clamping the plates at suitable positions. Multipass (3 passes: 1st- root pass, 2nd- filler pass, and 3rd -surface pass) welding was used to fabricate the butt-joints. An inert shielding gas mixture of Argon/Helium (50/50) was used as this mixture helps in the constriction of the arc and concentrates the heat within a restricted weld nugget area, thereby reducing the size of the heat-affected -zone (HAZ) (Howse and Lucas 2000). The welding speeds were calculated manually from the time required to weld a particular length and maintained in the range of 60 - 70 mm/min. Welding specifications are listed in Table 3.5.

**Table 3.5: GTAW specifications for AA6061-T651 Aluminum alloy**

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Filler Metal</th>
<th>Welding type</th>
<th>Shielding gas</th>
<th>Welding current</th>
<th>Electrode</th>
<th>Groove type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA-6061-T651 plate (6.35mm thick)</td>
<td>ER-4043 (1.6 mm dia.)</td>
<td>TIG (Manual)</td>
<td>Argon/Helium (50/50) (25-30 CFH)</td>
<td>DCSP (120-140 amps)</td>
<td>Tungsten (2.38 mm dia.)</td>
<td>Single V-offset (30° bevel angle)</td>
</tr>
</tbody>
</table>

Welding was followed by natural air cooling at room temperature (25 °C) and grinding afterwards. The dogbone tensile test specimens were cut from welded plates according to ASTM
standard (ASTM-International 2011). Figure 3.5 shows the schematic diagram of weld groove, welded plate, and the configuration of the dogbone specimen.

![Figure 3.5: Welding configuration, welded plate, and tensile specimens (all dimensions in mm)](image)

3.2.3. GTAW of AISI-4140 Alloy Steel

Rolled plates of AISI-4140 annealed multipurpose alloy steel with 300 mm × 76 mm × 6.35 mm dimensions were GTA- welded with SAE-4130 chromoly filler rod according to AWS welding codes for steels (AWSD1.1/D1.1M 2010). The direction of welding for the specimens tested were normal (transverse) to the rolling direction; and all necessary care was taken to avoid joint distortion by clamping the plates at suitable positions. Multipass welding was used to fabricate the butt joints. The welding specifications are listed in Table 3.6.

Table 3.7: GTAW specifications for AISI-4140 alloy steel

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Filler Metal</th>
<th>Welding type</th>
<th>Shielding gas</th>
<th>Welding current</th>
<th>Electrode</th>
<th>Groove type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI4140 alloy</td>
<td>SAE4130</td>
<td>TIG (Manual)</td>
<td>Pure argon</td>
<td>DCSP (240-350 amps)</td>
<td>2% Thoriated (3.2 mm dia.)</td>
<td>Single V-offset (30° bevel angle)</td>
</tr>
<tr>
<td>Steel plate</td>
<td>(3.2mm dia.)</td>
<td>(10-18 CFH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(6.35mm thick)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Welding was followed by natural air cooling at room temperature. After welding, the panels were grinded utilizing manual hand grinder to remove weld reinforcement. Figure 3.6 shows the schematic diagram of welding groove and welded plate after grinding.

![Welding configuration and welded plate after grinding (all dimensions in mm)](image)

Figure 3.6: Welding configuration and welded plate after grinding (all dimensions in mm)

### 3.2.4. GTAW of AISI-1018 Steel

In this program, low carbon steel rod was welded utilizing GTAW technique. Before welding, a 254 mm long rod was cut into half and 33° bevel groove was machined on both pieces as shown in Figure 3.7. For alignment during welding process, the specimens were placed in horizontal position using a three jaw chuck and rotated at 5 rpm while multi-pass welding (Figure 3.7) was completed. The welding specifications are listed in
Table 3.8. Welding was followed by natural air cooling at room temperature. Once welding is done, specimens were machined according to ASTM E466-07 standard (ASTM-International 2007) to obtain dog-bone specimens.

Figure 3.7: Welding configuration and sample preparation

Table 3.8: GTAW specifications for AISI-1018 low carbon steel

<table>
<thead>
<tr>
<th>Base Metal</th>
<th>Filler Metal</th>
<th>Welding Type</th>
<th>Shielding Gas</th>
<th>Current</th>
<th>Groove Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI-1018</td>
<td>ER70-S2</td>
<td>GTAW (Manual)</td>
<td>100 % Argon (3.5 CFM)</td>
<td>DCEN (100-120 amps)</td>
<td>V (33° bevel angle)</td>
</tr>
</tbody>
</table>

3.3. Experimental Procedures

Two different non-destructive testing procedures, uniaxial tensile testing, and microscopic analyses were employed throughout the project to analyze weld quality of different weld joints. Along with quality analysis, different post-weld treatment techniques (post-weld
heat treatment and electrolytic-plasma-processing) are also employed to improve performances of different weld joints. Details of the experimental techniques are discussed below.

3.3.1. Non-Destructive Evaluation (NDE)

A variety of NDE techniques are available depending on the applications; each with its own advantages and disadvantages. Among the number of NDE techniques, radiography and ultrasonic testing are most widely utilized for the inspection of weld defects. In this study, state-of-the-art phased array ultrasonic testing (PAUT) technique was utilized to find defects in both friction- stir and fusion arc weld joints. Consequently, a comparison to X-ray radiography is also included for friction- stir- welded aluminum alloy joints.

3.3.1.1. Phased array ultrasonic testing (PAUT)

After welding each welded panels were non-destructively inspected utilizing phased array ultrasonic testing (PAUT). Using PAUT one can find the A, B, C, and S scan views to find size, shape, and location of defects. If there is a defect present in the scanned samples, it can be visualized with 6-dB color change (Olympus-NDT 2007; ASTM-E2491 2008; Dewan, Liang et al. 2014). Specifically, the A-scan represents waveforms which are the reflections from one sound beam position in a test piece. The B-scan is an image showing a cross-sectional profile through one vertical slice of the test piece, showing the depth of reflectors with respect to their linear position. The C-scan is a two dimensional presentation of data displayed as a top or planar view of a test piece. Lastly, the S-scan or sectorial scan represents a two-dimensional cross-sectional view derived from a series of A-scans that are plotted with respect to time delay and refracted angles. The horizontal axis corresponds to location of the defect from probe position, and the vertical axis to depth of the test piece. The S-scan is perhaps the most useful asset to current PAUT post-weld evaluation due to the ability to steer the sound waves in a range of
angles which allows for easy visualization of a specimen (Crowther 2004). The actual size, shape, and location of the defect can be detected utilizing C and S scan views. In the current research program, Olympus “Omniscan MX2.0” non-destructive phased array ultrasonic testing (PAUT) unit was utilized (Figure 3.8). Angle beam wedge (30° - 70°) with 5 MHz and 10 MHz frequencies, 16 and 32 elements linear phased array ultrasonic probe was used for the PAUT inspection. Before inspections, the PAUT probes and wedges were calibrated with standard calibration blocks made of the same material to be inspected. PAUT calibration included velocity, wedge delay, sensitivity, and sizing calibration.

Figure 3.8: Phased array ultrasonic testing unit showing A, S, and C- scan views
3.3.1.2. Defect sizing capability of PAUT

Before inspection, PAUT unit was calibrated according to pressure vessel and piping welding code (International 2013). Figure 3.9 shows ASTM E2491 calibration block along with S-scan view showing side drill holes (SDH).

![PAUT wedge and probe, Calibration block, PAUT S-scan view](image)

Figure 3.9: Determination of phased array probe resolution with ASTM E2491 phased array calibration block (resolution determines flaw definition and sizing accuracy)

For defect sizing in PAUT, two important parameters need to be considered: (i) gain and (ii) index offset. In this study, defects were measured with (-2 dB), (-3 dB), and (-6 dB) color drop techniques and was compared with actual defect sizes. Higher gain value results in higher A-scan amplitude; and higher A-scan amplitude leads to oversize estimation. It is also observed that the higher color drop (-6 dB) technique implies larger defect sizing compared to smaller color drop (-2 dB) techniques (Figure 3.10). Hence, during post-weld inspection the defect size is dependent on the peak A-scan amplitude and color drop technique. The index offset is the
distance of the tip of the wedge from the weld-centerline. For constant A-scan amplitude, a higher index offset results in higher defect size estimation (Figure 3.11).

![Graph showing the effect of A-scan amplitude and color drop (dB) on defect size estimation](image1.png)

Figure 3.10: Effect of A-scan amplitude and color drop (dB) on defect size estimation

![Graph showing the effect of index offset and color drop (dB) on defect size estimation](image2.png)

Figure 3.11: Effect of index offset and color drop (dB) on defect size estimation (fixed gain value)
Another important calibration parameter is “Time-Corrected-Gain (TCG)”. If the TCG calibration is not performed, the A-scan amplitude will decrease with the increase of index offset, which results in error in defect size estimation. After TCG calibration, A-scan peak amplitude remains constant with the variation of index offset (Figure 3.12).

![Figure 3.12: Variations of A-scan amplitude with index offset to illustrate the effect of “Time-Corrected- Gain (TCG)” calibration](image)

To find the detectability and defect sizing capability of PAUT, varying sizes (0.79 mm, 1.58 mm, 1.98 mm, 2.38 mm, and 2.78 mm, 4.76 mm, and 6.35 mm diameters) of seven holes were prepared on an AA2xxx plate and scanned with a calibrated PAUT unit. Figure 3.13 shows the C-scan view of the plate with varying-hole sizes. The PAUT unit can precisely detect the sizes and locations of the holes. To identify the defect sizing precision and accuracy of PAUT, different size side-drilled-holes (SDH) were bored into an Aluminum Alloy 2xxx block at varying depths and were measured. The variation in measurement is shown in Table 3.9.
Figure 3.13: Aluminum alloy plate with seven varying-hole sizes with associated C-scan view and echo-dynamic A-Scan view (encoded and XY-scanning A-scan data are combined)

Table 3.9: Comparison of defect sizing utilizing PAUT technique

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Actual Dia. (mm)</th>
<th>Meas. Dia. (mm)</th>
<th>Δ Dia. (mm)</th>
<th>Actual Depth (mm)</th>
<th>Meas. Depth (mm)</th>
<th>Δ Depth (mm)</th>
<th>Actual Dist. (mm)</th>
<th>Meas. Dist. (mm)</th>
<th>Δ Dist. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>2.8</td>
<td>3.1</td>
<td>0.3</td>
<td>8.1</td>
<td>8.25</td>
<td>0.15</td>
<td>16.1</td>
<td>16.6</td>
<td>0.5</td>
</tr>
<tr>
<td>25.5</td>
<td>2.8</td>
<td>3</td>
<td>0.2</td>
<td>14.1</td>
<td>14.2</td>
<td>0.1</td>
<td>10.8</td>
<td>11.4</td>
<td>0.6</td>
</tr>
<tr>
<td>25.5</td>
<td>3.5</td>
<td>3.6</td>
<td>0.1</td>
<td>12.5</td>
<td>11.9</td>
<td>-0.6</td>
<td>18.5</td>
<td>19.0</td>
<td>0.5</td>
</tr>
<tr>
<td>8.35</td>
<td>1.6</td>
<td>1.5</td>
<td>0.1</td>
<td>4.2</td>
<td>3.9</td>
<td>-0.3</td>
<td>4.1</td>
<td>3.6</td>
<td>-0.5</td>
</tr>
<tr>
<td>8.35</td>
<td>2.4</td>
<td>2.0</td>
<td>-0.4</td>
<td>4.2</td>
<td>3.8</td>
<td>-0.4</td>
<td>3.6</td>
<td>3.0</td>
<td>-0.6</td>
</tr>
<tr>
<td>8.35</td>
<td>2.8</td>
<td>2.8</td>
<td>0</td>
<td>4.5</td>
<td>4.2</td>
<td>-0.3</td>
<td>12.5</td>
<td>12.4</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

Absolute error in height, depth, and location sizing was 0.24 ± 0.20 mm, 0.28 ± 0.18 mm, and 0.46 ± 0.17 mm, respectively. It is generally accepted that the tolerance for PAUT is 0.5-1.0 mm depending on how stringent the application requirement [13]. It was observed that there is overestimation for thicker plates and underestimation for thinner plates. This exemplifies one of
the characteristics of waves propagating through a material. For a defect at larger thicknesses, the sound waves travel a larger distance which causes the wave to expand. This results in the elongation of the defect image; alternatively, for defects at smaller depths, the wave has not reached its focal length and thereby underestimates the defect. In other words the defect image depends on the near and far fields focusing distances of the wave. These results indicate that PAUT has the ability to accurately detect defect sizes and locations.

3.3.1.3. Radiographic testing (RT)

One of the widely used NDT methods for volumetric examination is radiography. In the current study FS-welded plates were analyzed employing digital X-ray radiography and compared with PAUT results.

![Schematic of basic set-up for film radiography](image)

Figure 3.14: Schematic of basic set-up for film radiography (GE-IT 2007; ASME-International 2013)
In radiography, X-rays or gamma-rays are used to produce a radiographic image obtaining differences in thickness, defects (internal and surface), and changes in structure. The procedure for producing a radiograph is to have a source of penetrating (ionizing) radiation (X-rays or gamma-rays) on one side of a specimen to be examined and a detector of the radiation (radiographic film) on the other side, as shown in Figure 3.14. One important challenge of radiographic analysis is the data interpretation and defect classification. For this reason, X-ray images that are acquired are compared with standard radiographic images (GE-IT 2007; ASME-International 2013).

3.4. Ultrasonic Testing to obtain Residual Stresses

Post-weld residual stresses of fusion arc welded aluminum alloy and AISI-4140 alloy steel joints were calculated utilizing nondestructive ultrasonic testing (UT). Ultrasonic longitudinal waves are propagated through the thickness of the material and wave transit time is measured. The sound velocity can be calculated by knowing the thickness and the measured time. As a result of these measurements average residual stress through the thickness of the material can be measured (Dewan 2012; Javadi, Akhlaghi et al. 2013). During the welding process, microstructure of the material changes and this causes the variations of wave velocities. Effect of stress on wave propagation was investigated by Hughes and Kelly in their study entitled “Second-Order Elastic Deformation of Solids”, in 1953. The expression relating to the velocity of a wave propagating in the longitudinal direction to an internal stressed field can be written as equation (3.1). If the measurement is made in a single propagation direction, the above equation can be simplified and expressed as equation (3.2). For the majority of materials studied $K_1 \gg K_2$ (Thompson, Lu et al. 1996), so the equation (3.2) can be reduced as equation (3.3).

$$\frac{(v - v_0)}{v_0} = K_1 \sigma_1 + K_2 (\sigma_2 + \sigma_3)$$  \hspace{1cm} (3.1)
\[
\frac{(v - v_0)}{v_0} = K_1 \sigma_1 + K_2 \sigma_2 \quad (3.2)
\]
\[
\sigma_1 = \frac{(v - v_0)}{(K_1 \times v_0)} \quad (3.3)
\]

Here, \(v_0\), \(v\) are sound speeds in an unstressed and stressed medium, respectively. \(\sigma_1, \sigma_2, \text{ and } \sigma_3\) are principal stresses, and \(K_1, K_2\) are the acoustoelastic constants. The acoustoelastic constant \(K_1\) relates to the ultrasonic velocity to the stress, and can be obtained experimentally (Javadi, Akhlaghi et al. 2013). This constant is calculated by observing wave velocity variations due to applied stress. From the slope of the wave velocity change vs. stress, acoustoelastic constant is determined. In this study, I have used acoustoelastic constant \(K_1 = 5.05 \times 10^{-6} (MPa)^{-1}\) for AA6061-T651 and \(K_1 = -2.36 \times 10^{-5} (MPa)^{-1}\) for AISI-4140 alloy steel. This acoustoelastic constant is applicable in the elastic range of the material.

After nondestructive testing and residual stress measurement, different destructive mechanical test performed to understand structural integrity of different weld joints.

**3.5. Uniaxial Tensile Test**

Uniaxial tensile test specimens were prepared and tested according to ASTM E8/8M-11 standard (ASTM-International 2011) to determine transverse tensile properties and weld quality. Tensile properties were determined at room temperature using a displacement rate of 1.0 mm/min in an MTS-810 universal testing machine. The tensile strain was measured using a 25.4mm (1") gage length extensometer which was attached to the middle of the specimen near the weld zone (Figure 3.15). The yield strength was obtained employing the 0.2% offset yield strength method. Tensile toughness value was calculated from the area under the tensile stress-strain curve.
3.6. Rotating-Bending-Torsional (RBT) Fatigue Testing

Many structural welded components has experienced torsional loading along with rotating-bending loading (Bäckström and Marquis 2001; Carpinteri, Spagnoli et al. 2009). It is important to know the combined effect of rotating-bending and torsional load on structural components. Stefanov and Stoychev (2004) designed a rotating-bending (RB) machine which permitted the application of constant torsion (Stefanov and Stoychev 2004). The torsion was applied using a weight system coupled to a clamping pulley which allows easy torque calculation; however, due to design constraints the maximum torque applied was 0.3 times of that of the bending stress.

In the current study, a four-point bending test configuration was adopted to provide constant bending and stress moment along the specimen surface (Figure 3.16). A pinned-roller arrangement was used to support the apparatus that simplified the stress and deflection calculations. A sliding mechanism incorporated into the design to compensate different size
specimens and ease to hold the specimens for the testing purposes. A spider coupling is used in between the motor and the rotating shaft to transmit smoother power with lower vibration and also compensates parallel and angular displacements. Parallel and angular shaft alignments were performed to avoid unwanted loads and vibrations that might affect experimental results. To eliminate the difference in applied and actual bending moment, bending load was applied along the neutral axis of the test specimen.

![Schematic of a rotating bending fatigue testing unit including four points bending load configuration](image)

Bending moment \( (M) \) and bending stress \( (\sigma_b) \) were calculated using following equations.

\[
M = \frac{wL}{2} \quad (3.4)
\]

\[
\sigma_b = \frac{16wL}{\pi d^3} \quad (3.5)
\]
Where, \( w \) is bending load, \( L \) is the length from pivot point of the both platforms to the load application point, and \( d \) is the diameter of the specimen at critical (gage length) section.

The torsional load was applied using a newly designed braking mechanism (Figure 3.17). The resulting braking force was high enough to stop the rotating shaft. A force sensor was inserted in between braking pad and disk to measure applied braking load. Resulted braking force \( (F_B) \), normal to the braking disk is calculated by multiplying braking load \( (P_B) \) and friction coefficient \( (\mu) \). Then the braking torque \( (T) \) is determined by multiplying braking force by the disk radius \( (R_{disc}) \) as follow:

\[
T = R_{disc} \times F_B = R_{disc} \times (\mu \times P_B)
\]

Now the resulting shear stress from the torque:

\[
\tau_T = \frac{16T}{\pi d^3}
\]
The maximum torque that can be applied to the system is limited by the maximum torque provided by the motor and the rotational speed.

3.7. Micro-Hardness Analysis

For better understanding the effect of welding on metallurgical and microstructural changes during welding process, the hardness values across the weld surface were measured using Rockwell hardness tester (Type: FUTURE-TECH Rockwell type hardness tester, Model: Digital FR-3e). For a weld joint, hardness values are usually sensitive to welding condition, welding process, heat input, preheat or inter-pass temperature, electrode compositions, and plate thickness. Before hardness testing, the welded specimens were grounded and polished according to ASTM standard (ASTM E18-14). For aluminum alloys (FS- welded AA2219-T87 and GTA-welded AA6061-T651), 1.58 mm (1/16 inch) diameter steel ball indenter was utilized. For steels (GTA- welded AISI-4140 and AISI-1018), diamond cone indenter was utilized. Before using micro-hardness tester, it was calibrated utilizing appropriate calibration block. Hardness values were taken to correlate with tensile and fatigue strength of the welded specimens.

After all mechanical tests are completed, microscopic analysis was performed to understand fracture behavior and to correlate with mechanical test data.

3.8. Microscopic Analysis

To understand the effect of welding on microstructural variations, welded specimens were sectioned and mirror polished utilizing diamond suspensions (6µm to 0.25µm) following ASTM E3-11 standard (ASTM-International 2011). Polished specimens were then chemically etched according to ASTM E407-07 standard (ASTM-International 2007) to reveal the constituents and microstructures. Different metal and alloys required different types of etchant.
In the current study, Keller reagent was utilized for Aluminum alloys (AA2219-T87 and AA6061-T651) and 2% Nital solution was utilized steels (AISI-4140 and AISI-1018). Keller reagent is composed of 1.0 mL HF, 1.5 mL HCL, 2.5 mL HNO₃, and 95 mL H₂O. On the other hand, Nital (2%) solutions comprise of 2 mL HNO₃, and 98 mL ethyl alcohol. Chemically etched specimens were then inspected under metallographic digital light optical microscope (OM) and scanning electron microscope (SEM) to obtain micrographs. Fracture surfaces of the tensile tested specimens were analyzed with a Quanta 3D FEG scanning electron microscope (SEM) to understand microstructural and fracture behavior of weld joints.

3.8. Summary

During welding process, the non-linear heating from the welding results in microstructure changes as well as development of residual stresses in weld joints. Moreover, weld joints may contain weld defects which are detrimental to weld quality. Above mentioned destructive and non-destructive testing techniques were employed throughout this study to access structural integrity of different weld joints. The experimental data were collected utilizing the above mentioned experimental techniques; which are aimed for safe and efficient design of welded structures. Results obtained from the experimental investigations are discussed in the next six Chapters.
CHAPTER 4: FRICTION-STIR-WELDING DEFECTS LINKED TO WELDING PROCESS PARAMETERS

4. Introduction

Friction-stir-welding (FSW) is comparatively a new solid-state joining process invented by The Welding Institute (TWI) in 1991 (Thomas, Nicholas et al. 1991). Since the development of FSW process, welding community is utilizing this technique for joining high strength aluminum alloys for special applications (i.e. aerospace, space shuttle, high speed naval vehicles, and automotive) and researchers are looking for its potential applications in other materials. Friction-stir-welding (FSW) technique involves many critical process variables that affect the quality of the weld; consequently, it is difficult to accurately predict the most favorable process parameters to acquire high quality defect-free welds. Weld-defects generally occur during the welding process and not due to the application of service loading. In this chapter, an analysis of FSW process parameters, weld defects, and weld quality of friction-stir butt-weld of AA2219-T87 aluminum alloys are explored. The effects of three critical weld process parameters including spindle rotational speed \((N)\), welding speed \((V)\), and plunge force \((F_z)\) are investigated. All other features including pin-tool geometry and clamping conditions are held constant. Spindle rotational speed is defined as tool revolution per minute (rpm); welding speed is defined as tool travel speed along the weld seam (mm/min); and plunge force is defined as the downward vertical downward force applied on work piece (kilo newton). For a particular pin-tool, these three process parameters are primarily responsible for the amount of frictional heat generation during the welding process. The effect of the various weld schedules (i.e. combination of the variations in these three critical process parameters) on weld defects formation, uniaxial transverse tensile strength, toughness, and fracture configuration (i.e. fracture initiation side and
fracture surface morphology) are determined. In the current investigation, a FSW process parameter window and empirical correlation is also established for effective joining of AA2219-T87.

4.1. Scope

The quality of a FSW joint depend on several factors including tool design, welding parameters (i.e. machine), clamp design, and materials need to be welded. Causes and effects diagram of FSW is shown in Figure 4.1. For a particular welding condition, the geometry of the pin-tool and weld process parameters play important roles in dictating the path that the material takes. To produce a high quality defect-free weld, the welding process parameters such as: spindle rotational speed, welding speed, and axial plunge force or displacement, and pin-tool design must be chosen carefully (Jata and Semiatin 2000; Peel, Steuwer et al. 2003; Colligan 2007; Schneider, Nunes Jr. et al. 2010; Rajakumar, Muralidharan et al. 2011). Some researchers studied the effect of different shape of pin-tool and found that tapered threaded pin-tool can produce better quality weld (Boz and Kurt 2004; Zhao, Lin et al. 2005; Elangovan and Balasubramanian 2007; Schneider, Nunes Jr. et al. 2010). In this current investigation, the most commonly utilized threaded standard pin-tool was utilized and analyzed the effect of critical weld process parameters. Since the beginning of FSW technique origination, investigators have researched the influence of parameters on microstructures and mechanical properties (Rhodes, Mahoney et al. 1997; Flores, Kennedy et al. 1998; Li, Murr et al. 1999; Abbasi Gharacheh, Kokabi et al. 2006; Khodir, Shibayanagi et al. 2006; Elangovan and Balasubramanian 2007; Record, Covington et al. 2007; Scialpi, De Filippis et al. 2007; Balasubramanian 2008; Cavaliere, Squillace et al. 2008; Colligan and Mishra 2008; Kulekci, Şik et al. 2008; Lakshminarayanan and Balasubramanian 2008; Babu, Elangovan et al. 2009; Commin, Dumont
et al. 2009; Moreira, Santos et al. 2009; Rajakumar, Muralidharan et al. 2011; Querin and Schneider 2012; Rajakumar and Balasubramanian 2012; Shashi Prakash 2014) with a view to optimize FSW processes. In particular, studies of FSW applications to high strength aluminum alloy AA2219-T87 of aerospace interest and the subject of this present study are often found in the literature (Elangovan and Balasubramanian 2007; Babu, Elangovan et al. 2009; Davis 2010; Schneider, Nunes Jr. et al. 2010; Lakshminarayanan, Malarvizhi et al. 2011). To date, only a “trial and error” method has been used to establish process parameters for each tool design and setup. For a particular material and welding condition FSW process, parameter ranges are typically established by welding over a range of spindle rotational speeds ($N$) and welding speeds ($V$) in displacement control or load control modes and selecting parameter windows to obtain the required weld strength or other desired property. Reference (Lakshminarayanan, Malarvizhi et al. 2011) presents an example of such a parameter window determination for an application of AA2219. Effects of plunge force on weld quality are not considered in that study.

![Figure 4.1: Line diagram showing factors that affect the quality of a FSW joint](image_url)

Figure 4.1: Line diagram showing factors that affect the quality of a FSW joint
Some simplified theoretical similarity indices (i.e. combinations of critical process parameters) have been suggested to assist in the FSW process. An ideal similarity index determines how parameters can be varied together to obtain a similar quality welds. But in reality, the similar quality weld is rarely achieved. An empirical *Pseudo Heat Index* (PHI) has been proposed by Kandukuri and his research group (Kandukuri, Arbegast et al. 2007) to correlate the heat input during FSW with spindle rotational speed and welding speed; if heat input determines weld properties, similar welds are obtained by holding the index constant. The PHI does not include many process features affecting weld properties and is only good for a certain range of weld speed and spindle speed for a specified welding situation. Nunes (Nunes Jr. 2010) has proposed a temperature index based on a physical model of the FSW process in which temperature is computed from a balance between estimated mechanical heat input and estimated heat losses. In that model, shear stress is assumed to be linearly related to temperature. Another research group (Querin and Schneider 2012) has proposed an *Alternative Heat Indexing* (AHI) equation considering heat generation terms and thermal dissipation. A linear approximation was used to capture thermal softening with temperature and eliminate flow stress term. But in reality, flow stress might not be linearly related with temperature. Dehghani and other researchers (Dehghani, Amadeh et al. 2013) suggested a *Heat Input Factor* (HIF) to determine weld quality. In their model, plunge force is assumed to be constant and welding speed having a linear relation with welding heat generation. None of these indices include plunge force, yet plunge force may make the difference between presence or absence of a defect (Kandukuri, Arbegast et al. 2007; Querin and Schneider 2012; Dehghani, Amadeh et al. 2013).

A more powerful theoretical aid would be a defect formation criterion, a parametric relationship establishing the boundary between welds with a particular defect and welds without
a defect. There are as many defect criteria as there are defect types. All the defect criteria superposed together to establish a defect-free window (if such a defect-free window exists) in parameter space, in other words the operational window for the process. Currently, there are no theoretical defect criteria available to determine the operational window. The computations to obtain them are generally complex. The current study constitutes a preliminary exploration to see the extent an empirical defect criterion may be established for a particular FSW situation and to obtain information about defect formation mechanisms that may be applicable to a more general understanding of what determines the operational parameter window for FSW in general. The situation investigated is a friction-stir butt-weld of AA2219-T87. Three weld parameters are varied: spindle rotational speed ($N$), welding speed ($V$), and plunge force ($F_z$). Pin-tool design and clamping condition are other important factors for FSW. But within the limit of this research, all other features including pin-tool geometry are held constant. The effect of the various weld schedules on uniaxial tensile strength, toughness, and fracture configurations of the tensile specimens are determined.

From the next section, results obtained from various experimental investigations are discussed. Initial analysis started with microstructure analysis of FSW joints followed by weld defect classifications, tensile test results, and fracture surface analysis. At the end of this section, an empirical correction will be established to predict weld quality utilizing weld process parameters.

4.2. Microstructure of FSW Joints

Microscopic analysis is important to understand weld quality of a FSW joint. Unlike conventional welding process, two sides of the FS-welded plates are different. Tool rotation identical as traversing direction is commonly known as the ‘advancing side (AS)’ and tool rotation opposes the traversing direction is known as the ‘retreating side (RS)’ (Threadgill,
Leonard et al. 2009). In general, a FSW joint is composed of four distinct regions: “weld nugget (WN)”, “thermo-mechanically affected zone (TMAZ)”, “heat-affected-zone (HAZ)”, and “base” metal (Figure 4.2).

Figure 4.2: Typical cross-sectional view of a FSW joint. A FSW weld joint is composed of weld nugget (WN), thermo-mechanically affected zone (TMAZ), heat-affected-zone (HAZ), and base metal.

The weld nugget (WN) zone is called fully recrystallized area. It is also known as stir zone, which refers to the zone previously occupied by the pin-tool. Weld nugget zone is surrounded by TMAZ which normally has a significantly different microstructure. In this region, the tool has plastically deformed the materials, and the heat from the process will also have exerted some influence on the material. Further away from the weld is called HAZ, which has experienced a thermal cycle and modified the microstructure of the material. However, there is no plastic deformation occurring in this area. Materials remote from the weld center and not affected by plastic deformation and heat in terms of microstructures is called base materials. In Figure 4.2, optical macrographs are taken from polished and chemically etched FSW specimen and it has revealed four distinct regions as discussed above. The dotted lines (red, blue, and
yellow) are drawn schematically to distinguish weld nugget, TMAZ, HAZ, and base metal area into an optical macrograph of FSW joint.

Figure 4.3 illustrates optical micrographs of a FSW joint at different location. There is a clear difference observed between advancing and retreating sides’ microstructures of a FSW weld joint. In FSW, frictional heat is usually generated due to high axial pressure and shearing action of pin-tool and its shoulder. If generated temperature reaches to 80% - 90% of melting temperature, plasticized softened zone is created around the tool. This softened material cannot escape as it is constrained by the pin-tool shoulder (see Figure 3.1).

Figure 4.3: Optical micrographs of defect- free FSW AA2219 joint. Micrographs are taken at different locations of weld joints showing variations in microstructures
As the pin-tool is traversed along the joint line, material is swept around the tool probe. Most of the deformed material is extruded past the retreating side of the tool and results an asymmetrical weld joint (Threadgill, Leonard et al. 2009). From near-weld and TMAZ interface, an evidence of plastic deformation can be seen in the grain structures. In the outer part of the TMAZ, deformed grain structure with the formation of sub-grain structures are observed. At weld nugget, higher strains and temperatures allowed the formation of the recrystallized nugget with a fine equiaxed structure. In general, the nugget comprised of dynamically recrystallized grains, whereas, TMAZ comprised of deformed sub-grains separated by low angle grain boundaries (Rhodes, Mahoney et al. 2003). The microstructure of the advancing side is characterized by a sharp boundary between the weld nugget (WN) and TMAZ. The retreating side of the FSW joint has a more complex microstructure, with no clear boundary between the WN and TMAZ.

For further investigations of grain sizes at different regions, SEM micrographs are analyzed (Figure 4.4). It observed that the weld nugget (WN) is invariably composed of equiaxed grains with an average grin size of 5 μm. A clear boundary between weld nugget and TMAZ can easily be identified at the advancing side (AS); but in retreating side (RS) it was not easy to identify the clear boundary between the WN and TMAZ, which is also confirmed from optical micrographs (Figure 4.3) and electron backscatter diffraction (EBSD) images (Figure 4.5). The TMAZ in both AS and RS observed to have elongated grains structures.
FSW defects are related to microstructures of a weld joints. In next section, different FSW defects are analyzed utilizing microscopic analysis, tensile test data, and non-destructive phased array ultrasonic and radiographic testing.
4.3. Weld Defect Classifications

The quality of a FS-welds are largely depends on heat generated (Q) during the welding process by plastic flow processes. For a particular pin-tool and clamping condition, “Q” mainly depends on the three critical process parameters (spindle rotational speed (N), weld speed (V), and plunge force (Fz)). Spindle speed and weld speed determine the weld temperature. High temperatures promote small voids and underfill. Low temperatures promote Wormholes (WH), i.e. internal cavities, Trenching (TR) defects, i.e. surface cavities, and incomplete penetration (IP). Plunge force reduces the tendency for internal surfaces to open (WH and TR) and pushes the crown surface down to maintain full pin length and prevent Incomplete Penetration (IP).

Microscopic analysis and non-destructive testing (NDT) of the FS-welded aluminum alloy AA2219-T87 panels with 66 different schedules revealed welding defects for 32 schedules, leaving “no-defects” for 34 schedules. Three weld categories were distinguished based on weld process parameters and anticipated weld defects. These are (i) hot weld (high spindle speed, low weld speed, and high plunge force), (ii) cold weld (low spindle speed, high weld speed, and low plunge force), and (iii) nominal weld (optimum spindle speed, welding speed, and plunge force). Nominal welds observed to have no visible weld defects. Both hot and cold welds were associated with characteristic weld defects.

4.3.1. Microscopic Analysis to Classify Weld Defects

In cold welds, the defects observed include Wormholes (WH), Incomplete Penetration (IP), and Trenching (TR). A cold weld schedule produced wormholes (WH) inside the nugget metal on the advancing side of the nugget and incomplete penetration (IP) on the original seam line below the nugget as shown in Figure 4.6. The IP presumably occurs when the tool shoulder rides higher on colder and harder metal, retracting the end of the pin from the root side of the
weld panel. A cold weld schedule also produced surface cavities, known as Trenching (TR), on the advancing side. The TR surface appears much like the WH surface except that the TR surface opens to the weld crown surface.

Figure 4.6: Cold-weld showing Trenching (TR), Wormholes (WH), and Incomplete Penetration (IP) defects

In Figure 4.7 shows optical macro and micrographs representing underfill and micro-voids in hot welds. The hot welds exhibited flash and underfill as anticipated for heat-softened metal and high plunge force compared to the metal flow stress. In some cases, internal voids are present within the nugget metal on the advancing side of the hot weld. The shape of the voids, more “penny-shaped” than round like a gas pore, and their internal surfaces, exhibiting relatively smooth un-dimpled expanses, suggest poorly bonded regions inside WN (Klages 2007). Close to the free surface of the weld crown, the pressure under the tool shoulder may not be adequate to fully bond the weld surface. The pressure rise gradient under the shoulder is less if the metal is hotter and softer; lack of sufficient pressure to bond may extend deeper along the trace of the
weld seam for hotter schedules. Underfill occurs just outside the nugget material on the advancing side (AS) due to the tool shoulder plunging too deep, expelling material out of the weld seam.

![Figure 4.7: Hot-weld showing underfill (UF) and small voids defect](image)

4.3.2. Non-Destructive Evaluation to Classify Weld Defects

Two different non-destructive evaluation (NDE) techniques (i.e. digital radiographic and phased array ultrasonic testing-PAUT) were utilized to find friction-stir-weld defects. Figure 4.8 shows digital photographs and digital radiographic images of FS-welded panels with internal defect, surface defect, and underfill. Internal cavity, surface defect, and underfill can easily be detected from radiographic testing (RT). However, small voids in hot welds cannot be detected from radiographic testing.
Figure 4.8: Surface photographs (above) with corresponding radiographic images (below) of FSW panels: (a) cold weld with wormhole (internal cavity), and (b) cold weld with trenching (contraction of weld width observed at trench suggesting shoulder slip appropriate for colder harder metal), (c) hot weld with flash and underfill

The following Figure 4.9 shows representative optical images and phased array ultrasonic testing (PAUT) S-scan views of different weld defects. Both external and internal cavities as well as small voids in hot welds can be detected from PAUT’s S-scan views. From S-scan views, size and location of the detected defects can easily be identified (Dewan;, Wahab; et al. 2014).

Figure 4.9: Optical image (above) and PAUT’s S-scan view (below): (a) wormhole (WH) in cold weld, (b) trenching (TR) defect in cold weld, and (c) void in hot weld
One challenging effort for NDE techniques is to detect incomplete penetration (IP). This type of defect has been also called “lack-of-penetration (LOP)”, kissing-bond (KB), and sometime “joint-line-remnant (JLR)” in literature. In the present study, X-ray radiography had difficulty in detecting IP defects. Alternatively, PAUT was able to discover IP defects; however, an increase in gain value was needed in order to provide PAUT’s A-scan signal peak amplitude values near acceptable limits with the aforementioned calibration, which allowed 80% A-scan peak amplitude for 0.79 mm defects. The “signal to noise ratio” of the system was still decent with this increase in gain. Few IP defects were unable to be discovered by the PAUT system, not because the size of the defect wall, but rather due to large defects present in the same specimen (wormholes and trenching). As the gain values were increased, large wormhole or trench defects caused high noise, and in some cases, distorted the location where the IP defects reside. In Figure 4.10 incomplete penetration (IP) defect with associated S-scan view is shown. By analyzing location of the defects, it was identified as IP.

Figure 4.10: Optical image (left) and associated S-scan image (right) of IP defect

After weld defects are classified from NDT and microscopic analysis, uniaxial tensile tests were performed to correlate weld defects with tensile properties of FS-welded AA2219-T87 joints.
4.4. Tensile Properties of FSW Joint

Uniaxial ultimate tensile strength (UTS) and toughness have been investigated to understand the effects of varying weld schedules. These two properties are important to define weld quality. Defect-free weld joints usually observe to have highest UTS and toughness as compared to defective weld joints. Tensile test was conducted along the transverse direction of weld seam. The UTS of the welded specimens are compared with base metal’s UTS (471 MPa) and joint efficiency (JE) results are reported in Table 4.1.

Table 4.1: Welding process parameters, tensile test results, and weld defects of FS welded AA2219-T87 panels (WH = wormhole; IP = incomplete penetration; TR = trenching; UF = Underfill)

<table>
<thead>
<tr>
<th>SL #</th>
<th>N (rpm)</th>
<th>V (mm/min)</th>
<th>Fz (kN)</th>
<th>UTS (MPa)</th>
<th>Toughness (MJ/m³)</th>
<th>JE (%)</th>
<th>UTS</th>
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<td>15.57</td>
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<td>22.24</td>
<td>362.08</td>
<td>41.91</td>
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As discussed above, the welds were classified into three categories (nominal, hot, and cold welds) based on the three critical process parameters, weld defects, and tensile properties. Typical tensile stress-strain curves for base metal, nominal, hot, and cold welds are shown in Figure 4.11. Defect free nominal welds exhibited UTS and toughness values equal or more than 66% and 43% of base metal values.

![Stress-strain plots of base and FS welded AA2219-T87 specimens (base, nominal, hot, and cold welds)](image)

Figure 4.11: Stress-strain plots of base and FS welded AA2219-T87 specimens (base, nominal, hot, and cold welds)

The variation in tensile strength and toughness values of nominal, hot, and cold welds are related to weld defects and microstructure. Typical weld nugget (WN) microstructures of nominal, hot, and cold welds are shown in Figure 4.12. The grain growth in weld nugget (WN) zone is related to heat input during the welding process (Arora, Pandey et al. 2010). The weld nugget of a defect free FSW joint is commonly composed of fine equiaxed grains (Figure 4.12a). The high heat input in hot weld has resulted in growth of dynamically recrystallized grain in WN zone (Figure
4.12b). Alternatively, low heat input in cold welds hinder formation of fully dynamically recrystallized equiaxed grain (Figure 4.12c). The presence of weld defects and variations in microstructures are related to lower tensile properties of cold and hot welds joints.

![Figure 4.12: Typical SEM micrographs showing microstructure in weld nugget (WN) of (a) nominal weld (NW), (b) hot weld (HW), and (c) cold weld (CW) joints](image)

Both UTS and toughness values of welded specimens decreased with the increase of defect size. Nominal welds were observed to have the highest average UTS (332 MPa) and toughness (37 MJ/m³) values, followed by hot-welds with underfill (311 MPa and 24 MJ/m³), cold-welds with IP (271 MPa and 15 MJ/m³), cold-welds with WH (273 MPa and 10 MJ/m³), and cold-welds with TR (170 MPa and 5 MJ/m³). The following Figure 4.13 illustrates variations of UTS and toughness values with different types of weld defects.
After tensile test, it is important to understand fracture behavior of tensile test specimens and correlate with microstructures. The following section includes the fracture surface analysis of tensile tested specimens.

### 4.5. Fracture Surface Analysis

All defective specimens (hot and cold welds) failed on the Advancing Side (AS) of the weld nugget and the defect-free nominal weld samples failed on the Retreating Side (RS) of the thermo-mechanically affected zone (TMAZ) and heat-affected-zone (HAZ). The following Figure 4.14 - Figure 4.17 show the fracture surfaces and related microstructural features of tensile tested samples of a nominal, hot, and cold welds. Fracture surface of the nominal weld with no-defects is shown in Figure 4.14. Fracture occurred on the 45° maximum shear line in the
heat-affected region outside the weld nugget on the retreating side of the weld. Beyond the nugget in the TMAZ and HAZ, the softening effect of over-aging (Sato, Kokawa et al. 1999) predominates and presents a weakened path for fracture. The fracture surface exhibits ductile rupture dimples (Rhodes, Mahoney et al. 1997) of a larger size corresponding to the larger parent metal grains outside the nugget zone.

![Nominal Weld](image)

**Figure 4.14:** Nominal weld showing no defect. A 45° maximum shear fracture is on retreating side of tool outside the weld nugget in heat-affected base metal. Fracture surface exhibits ductile fracture dimples, larger corresponding to base metal and weld nugget.

The following Figure 4.15 illustrates optical images and fracture surfaces of a tensile tested hot weld specimen. All hot welds observed to have underfill (UF) on advancing side of the weld nugget. In some cases, internal voids were present within the nugget metal on the advancing side of the weld. The voids might be entrained from a free surface by ring vortex circulations and un-bonded regions on the weld seam trace. Close to the free surface of the weld
crown, the pressure under the tool shoulder may not be adequate to fully bond the weld surface. The internal surface of the voids does show patches of ductile fracture dimples, but also smooth surfaces with some regular linear grooves that suggest ripples produced on an internal un-bonded surface in the same way that they are produced on the crown surface in the wake of the weld. (Sometimes such ripples can be seen at the bottom of a crack in the rippled surface following the tool.) The fracture is no longer a shear fracture, but now, judging by the orientation normal to the test coupon surface, a tensile fracture.

![Image of weld showing internal voids](image)

**Figure 4.15:** Hot weld showing internal voids. Fracture is on advancing side of tool inside the weld nugget. Fracture surface exhibits equiaxed ductile fracture dimples, smaller corresponding to base material. Unbonded void surface exhibits some regularly space curved lines that may be internal ripples

A cold weld schedule produced wormholes (WH) inside the nugget metal on the advancing side; and incomplete penetration (IP) on the original seam line below the weld nugget (Figure 4.16). It is also referred to as Joint- Line- Remnant (JLR), Kissing- Bond (KB), weak bond or root flaw. In weld (Oosterkamp, Oosterkamp et al. 2004), showed that kissing bond is a
solid-state welding defect where two pieces of material are in contact but have failed to create any metallic weld-like bonds. The cause of JLR defect in FSW has been linked to slipping conditions between the tool surface and metal in the shear zone and the oxide layers brought into the. It is also reported that kissing bond originates from insufficient mixing of matter close to the initial butt surfaces (Sato, Takauchi et al. 2005; Di, Yang et al. 2006). The IP presumably occurs when the tool shoulder rides higher on colder and harder metal, retracting the end of the pin from the root side of the weld panel. Under load control, colder and harder metal is more difficult to indent because the pin will be pushed out of the seam and a compensatory increase in plunge force will not occur which leads to IP. The WH exhibits two distinct surfaces: a smooth surface following the nugget edge on the trace of the shear surface and rounded surfaces incorporating ripples that appear on the free surface, trailing the weld shoulder (Figure 4.16). The surfaces are separated by cusps. Above and below the WH defect the fracture surface exhibits ductile rupture dimples. The streamlines of weld metal flow (Colligan 1999) past the upper portion of the pin does not get close enough to the pin for the threads to produce an impression on the weld metal. The pumping action on the weld metal due to slight eccentricity of the rotating pin-tool is responsible for the ripples in the wake of the weld as well as internal bonding texture and ripples on any internal open surface. Both apparently un-bonded clean ripples and adjacent periodic bonded dimpled surfaces that appear to be banding texture are visible in SEM fractographs. The fracture surface follows a less defined 45° line through a defect and along a direction suggesting minimal shear strength. A small vertical fracture segment at the weld root indicates IP.
Figure 4.16: Cold weld showing internal cavity. Fracture is on the advancing side of tool inside the weld nugget. Fracture surface exhibits ductile fracture dimples, smaller corresponding to nugget material. Unbonded cavity surface appears to exhibit surface ripples.

Figure 4.17: Cold weld showing trenching (TR) defect at weld crown and incomplete penetration (IP) at weld root. Fracture is on advancing side of tool inside the weld nugget. Fracture surface exhibits ductile fracture dimples, smaller corresponding to nugget material. Unbonded trench surface exhibits surface ripples.
The cold weld also exhibits trenching (TR) with ripples on the trench surface (Figure 4.17). The internal cavity on the advancing side of the cold weld has enlarged and moved to the surface of the cold weld. The fracture surface is almost at 45° implying a shear mechanism. With colder, harder metal under load control the shoulder may not press as deeply into the metal so that the effective pin depth is reduced. As a result the IP at the weld root is more pronounced, as anticipated, for load control operation.

4.6. Micro-Hardness of FSW Joint

To understand the fracture behavior of nominal, cold, and hot weld joints hardness profiles are investigated. Rockwell hardness values (60-kgf, diamond cone, HRA scale) are measured at the middle of the cross section of a FSW joint. Measured hardness profile is plotted against distance from weld centerline, illustrated in Figure 4.18. Weld-nugget (WN) zone exhibited higher hardness values compared to AS (Advancing Side) and RS (Retreating Side) thermo-mechanically affected zones (TMAZ). Higher hardness values at the WN zone is related to equiaxed fine grain structure. A lower hardness value near TMAZ is related to deformed and elongated microstructure. The lowest hardness value (about 24 HRA) is exhibited near the TMAZ on the RS, which correlates well with optical micrographs. As a result, tensile tested nominal weld joint failed from retreating side of the weld nugget. However, the difference in hardness values at AS and RS is not significant to dictate failure sites in defective joints in the case of tensile test. Weld-defects generally act as a stress concentration and fracture initiation site during tensile tests of defective weld. As discussed earlier, hot and cold welds observed to have weld defects at the AS of weld nugget. Therefore, hot and cold weld joints fail from the AS of the weld nugget.
In previous sections, FSW process parameters, weld defects, and tensile properties of FSW joints are discussed. Tensile properties are varied with the variation of critical weld process parameters. In next section, the effects of critical process parameters on tensile properties are discussed.

4.7. Tensile Properties Related to Welding Process Parameters

For a particular pin-tool and clamping condition, the quality of a FS- weld largely depends on the three critical process parameters (spindle rotational speed ($N$), weld speed ($V$), and plunge force ($F_z$)). Alternatively, all these three parameters ($N, V, F_z$) act together to control weld strength. An empirical correlation of these parameters yielding optimal strength has been obtained for this study by comparing the influence of individual process parameters on tensile properties.

In a FSW process, the spindle speed ($N$) and welding speed ($V$) has opposite consequences on the frictional heat generation (Colligan 2007). It is believed that a better way to represent welding process parameters in a more concise manner can be achieved by combining $N$
and \( V \) together (Gharacheh, Kokabi et al. 2006) for the purpose of creating a 2-D plot to represent weld schedules. A dimensionless speed ratio (\( R \)) has been proposed as a function of \( N \) and \( V \) for correlating with plunge force (\( F_z \)). To obtain a dimensionless speed ratio, \( N \) was multiplied with the circumference of the pin-tool (\( 2\pi r \)) and divided with \( V \). After multiplying \( N \) with (\( 2\pi r \)), a unit similar to welding speed is obtained (i.e. \( mm/min \)). The dimensionless speed ratio (\( R \)) is expressed as equation (4.1). Here, \( r \) is the pin-tool radius.

\[
R = \frac{2\pi r N}{V} \tag{4.1}
\]

Now an attempt has been taken to obtain a correlation among weld process parameters and identify nominal, hot, and cold weld schedules. Saying this, in Figure 4.19 speed ratio (\( R \)) vs. UTS and toughness has been plotted for two different plunge forces (\( F_z = 22.25 \, kN \) and \( F_z = 26.69 \, kN \)). As the plunge force increases, a lower speed ratio is required to obtain better tensile strength and toughness of a FSW joint. Higher plunge also reduces the speed ratio window to obtain defect free nominal weld with higher tensile properties. The trend indicates that lower speed ratio causes cold welds. As the speed ratio is increased, a peak value indicating a nominal weld occurs; thereafter, as the speed ratio (\( R \)) increases hot welds form. The spindle rotational speed generates frictional heat as well as stirs and mixes plasticized material around the pin-tool (Mishra and Ma 2005). Lower spindle rotational speed (\( N \)) causes lower heat generation and lack of stirring around the weld nugget (Nami, Adgi et al. 2011). The net result is poor consolidation of material which leads to poor UTS and toughness at lower tool rotational speeds. Higher spindle rotational speeds result in higher heat generation than required and release excessive stirred material. Excessive stirring causes improper flow of plasticized material resulting in the creation of micro level voids and underfill.
The weld speed ($V$) prompts the translation of material from the front of the pin-tool to the back (Mishra and Ma 2005). The rubbing of tool shoulder and pin with the workpiece generates frictional heat; consequently, the weld speed determines the exposure time of this frictional heat per unit length of weld (Karthikeyan, Senthilkumar et al. 2010). All other things being equal, slower weld speed ($V$) leads to higher heat generation and causes improper consolidation of stirred material. On the other hand, higher weld speed causes lower heat generation and stirring of plasticized material becomes insufficient. Thus the material present in the advancing side of the tool does not travel through to the retreating side (Cavaliere, De Santis et al. 2009). Optimum stirring and translation of stirred material is required to produce defect-free weld joints with fine recrystallized grains. Lack of stirring and improper consolidation from lower speed ratios might results in lower tensile properties. Micro-voids and dissolution of alloying element precipitates in hot welds cause reduction in tensile strength and toughness at higher speed ratios.

In Figure 4.20, plunge force vs. UTS and Toughness has been plotted at two different speed ratios ($R$). As the plunge force increases, tensile strength and toughness values increase; thereafter both strength and toughness values begin to decrease. The reasons UTS and toughness
values are low at the left and right portions of the plot are due to the defects in cold and hot welds. Heat generated by weld metal deformation around the pin-tool softens the weld metal and reduces the axial force required to indent the weld metal. Axial force also extends the plunge depth of the pin (Elangovan, Balasubramanian et al. 2008; Kumar and Kailas 2008). For a FS-weld joint, the pressure across the weld seam must be high enough to push down asperities (several times the flow stress of the material) for joining to occur. Lower heat generation causes higher flow stress and hence weld defects due to improper consolidation of material (Elangovan, Balasubramanian et al. 2009) and results in lower tensile strength. Higher plunge force remedies the effects of colder welds but excessive plunge force causes deeper tool shoulder penetration depth which causes flash generation, local thinning (underfill) of the welded plate, and reduced tensile strength. Optimum plunge force is required for avoidance of cold and hot defects and production of sound weld joints. Speed ratio determines optimum plunge force. At lower speed ratios higher plunge force is required to obtain nominal welds. For a particular pin-tool, all three weld process parameters ($N, V, F_z$) need to be controlled to obtain defect-free welds.

Figure 4.20: Effect of plunge force ($F_z$) on (a) ultimate tensile strength (UTS) and (b) Toughness at two different speed ratio (R)
To verify the effect of dimensionless speed ratio (R), six weld schedules were conducted at three different speed ratios (Table 4.2). For a particular plunge force, two welds were conducted by varying rotational and weld speed while speed ratio remained the same. The results indicate that at a constant speed ratio similar weld quality can be obtained. However, there is a difference in UTS and toughness values observed between two schedules which are still in the error limit. Therefore for a constant speed ratio and plunge force the schedules are analogues.

Table 4.2: Verification of the effect of speed ratio (R)

<table>
<thead>
<tr>
<th>N (rpm)</th>
<th>V (mm/min)</th>
<th>Fz (kN)</th>
<th>Dimensionless Speed Ratio, R</th>
<th>UTS (MPa)</th>
<th>Toughness, MJ/m³</th>
<th>JE(%), UTS</th>
<th>Defect</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>237.0</td>
<td>26.7</td>
<td>47.1</td>
<td>359.96</td>
<td>38.57</td>
<td>76.32</td>
<td>None</td>
</tr>
<tr>
<td>300</td>
<td>203.2</td>
<td>26.7</td>
<td>47.1</td>
<td>318.59</td>
<td>27.52</td>
<td>67.55</td>
<td>None</td>
</tr>
<tr>
<td>300</td>
<td>76.2</td>
<td>17.8</td>
<td>125.6</td>
<td>320.65</td>
<td>31.23</td>
<td>67.98</td>
<td>None</td>
</tr>
<tr>
<td>400</td>
<td>101.6</td>
<td>17.8</td>
<td>125.6</td>
<td>337.37</td>
<td>37.8</td>
<td>71.53</td>
<td>None</td>
</tr>
<tr>
<td>350</td>
<td>266.7</td>
<td>30.2</td>
<td>41.9</td>
<td>356.56</td>
<td>41.78</td>
<td>75.55</td>
<td>None</td>
</tr>
<tr>
<td>300</td>
<td>228.6</td>
<td>30.2</td>
<td>41.9</td>
<td>326.33</td>
<td>39.64</td>
<td>69.19</td>
<td>None</td>
</tr>
</tbody>
</table>

By observing characteristic defect types identifiable by non-destructive evaluation of radiographic testing (RT) and PAUT as well as metallographic procedures, the schedule-based classification of friction- stir- welds as nominal, hot, and cold welds can be expanded to include not just weld spindle rotational and travel speeds, but also plunge force. The characteristic of no-defect microstructure of a nominal weld which is a category between hot and cold weld, can be obtained for a wide range of speed ratios by altering plunge force. At lower speed ratios, higher plunge is required to obtain nominal welds, while lower plunge force is required for higher speed ratios. Consequently, the plunge force (Fz) vs. (R) ratio was plotted in Figure 4.21 for different weld schedules to determine hot, cold, and nominal welds schedules.
Figure 4.21: FSW process parameters for hot, nominal, and cold welds group together into fields with distinct boundaries

Any schedule within the bounded field produces defect-free welds. Two lines have been superimposed to illustrate the (nominal/hot weld) and (nominal/cold weld) boundaries. Schedules above the bounded line contribute to hot welds and schedules below the bounded line produce cold welds. Among 66 weld schedules, 34 were classified as nominal welds, 18 cold welds, and 14 hot welds.

From above discussions it is understand that the three critical process parameters (i.e. spindle rotational speed, welding speed, and plunge force) have direct influence on the quality of a FSW joint. In the next section, an empirical correlation between the FSW three process parameters has been established to identify weld quality by looking at only weld process parameters.
4.8. Correlation of Weld Process Parameters and Weld Quality

In accord with above discussion, each weld can be classified as hot, nominal, and cold welds. Both hot and cold welds are observed to have weld defects and result in lower tensile properties. Furthermore, defect-free nominal (good quality) welds exhibited higher tensile properties. It is obvious that the quality of a friction stir weld is directly linked to weld process parameters.

Initial study started with the analysis of experimental results utilizing literature suggested indices (Kandukuri, Arbegast et al. 2007; Pew, Nelson et al. 2007; Hamilton, Dymek et al. 2010; Querin and Schneider 2012; Dehghani, Amadeh et al. 2013). In (Pew, Nelson et al. 2007; Hamilton, Dymek et al. 2010; Dehghani, Amadeh et al. 2013), suggested energy input to determine weld quality. In that model, heat input is assumed to be related to torque, spindle rotational speed ($N$), and welding speed ($V$). Heat input per unit length can be expressed as equation (4.2).

$$\textit{Energy Input (EI)} = \frac{\textit{Torque} \times N}{V} \quad (4.2)$$

In Figure 4.22a, UTS values are plotted against energy input and failed to separate nominal, cold, and hot weld schedules. In their model, plunge force is assumed to be constant and weld speed having a linear relation with welding heat generation.

Kandukuri and his research group (Kandukuri, Arbegast et al. 2007) proposed an empirical Pseudo Heat Index (PHI) to correlate the heat input during FSW with spindle speed and welding speed. If heat input determines weld properties, similar welds are obtained by holding the index constant. The PHI can be expressed as equation (4.3).

$$\textit{PHI} = \frac{N}{10,000 \times V} \quad (4.3)$$
In Figure 4.22b, PHI vs. UTS value plotted and again failed to separate nominal, cold, and hot weld schedules. The PHI does not necessarily include many process features affecting weld properties and but is good for extrapolations of weld speed and spindle speed for a specified welding situation.

Querin and Schneider (Querin and Schneider 2012) have proposed an Alternative Heat Indexing (AHI) equation considering heat generation terms and thermal dissipation. The AHI can be express as equation (4.4).

$$AHI = \frac{T-T_0}{\tau} = A \frac{N}{B+V}$$ (4.4)

Where, A and B are constants; related to material properties, heat transfer coefficients, and pin-tool geometry; see reference (Querin and Schneider 2012) for details. In Figure 4.22c, experimental UTS values are plotted against AHI and also failed to separate nominal, cold, and hot weld schedules. The AHI however, did not include plunge force; yet plunge force may make the difference between presence or absence of a defect.
Figure 4.22: Experimental ultimate tensile strength (UTS) values are plotted against (a) energy input (Pew, Nelson et al. 2007), (b) Pseudo heat index (Kandukuri, Arbogast et al. 2007), and c) Alternative heat index (Querin and Schneider 2012).

Now, with a view to determining parameters optimizing weld quality here a relation of weld quality to three principal weld parameters ($N$, $V$, and $F_z$) is obtained empirically. From a total 66 weld schedules, 34 schedules are classified as defect-free nominal welds. The nominal welds exhibited UTS and toughness values equal or more than 66% and 43% respectively of base metal values. In Figure 4.23, plunge force ($F_z$) vs. dimensionless speed ratio ($R$) has been plotted for nominal welds. The values of $F_z$ vs. $R$ constitute a field and not a linear relation. It is also observed that as the speed ratio increases, the plunge force required to achieve nominal welds decreases. Using a non-linear regression approach, a correlation between plunge force and speed...
ratio for producing defect free nominal welds can be written as equation (4.5). The goodness of fit ($R^2$) value is 0.92.

$$F_z = C_1(R)^{-C_2} \tag{4.5}$$

Where, $F_z$ is the plunge force measured in kN and $R$ is the dimensionless speed ratio. The Constant $C_1$ and exponent $C_2$ depend on welding material, pin tool design, and other welding conditions (e.g., clamping condition, chill bar, backing plate, environmental temperature conditions, etc.). These constants $C_1$ and exponent $C_2$ can be determined experimentally. For least square curve fitting, the coefficient $C_1$ and $C_2$ can be expressed as-

$$C_2 = \frac{n \sum_{i=1}^{n} (\ln R_i \times \ln F_{zi}) - \sum_{i=1}^{n} (\ln R_i) \times \sum_{i=1}^{n} (\ln F_{zi})}{n \sum_{i=1}^{n} (\ln R_i)^2 - (\sum_{i=1}^{n} \ln F_{zi})^2} \tag{4.6}$$

$$C_1 = \exp\left(\frac{\sum_{i=1}^{n} (\ln F_{zi}) - C_2 \sum_{i=1}^{n} (\ln R_i)}{n}\right) \tag{4.7}$$

In the current study, the values of $C_1$ and the exponent $C_2$ are 256.93 and 0.561, respectively, fitted from defect-free nominal weld data. In other words, equation (4.5) has been found to be valid for defect-free nominal welds. Once the constants in equation (4.5) are established, it is possible to correlate the types of defects to be anticipated (and hence weld quality) with an “empirical force index (EFI)”. The EFI can be written as seen in equation (4.8), which is a dimensionless ratio. When this non-dimensional EFI value deviates from unity, defect free welding conditions are lost.

$$EFI = \frac{F_z}{C_1(R)^{C_2}} \tag{4.8}$$

For nominal welds, the EFI is approximately 1.00. If the EFI is increased, the weld tends to be within the hot range with associated defect characteristics. Alternatively, as the EFI drops below 1.00, defect characteristics of cold welds are observed. The EFI value deviation from 1.00 causes
degradation of weld quality. The ranges of the EFI associated with weld quality (UTS and Toughness) are shown in Figure 4.24a and Figure 4.24b.

Figure 4.23: Plunge force vs. speed ratio plotted to obtain empirical correlation among three weld process parameters for nominal weld (goodness of fit = 0.92)

Figure 4.24: Variations of tensile properties with empirical force index (EFI): (a) Ultimate tensile strength vs. EFI, and (b) Toughness vs. EFI. These properties both decline on either side of an (EFI) of 1.00
For the defect classification, three ranges of force index values can be expressed:

\[
EFI \leq 0.90 \Rightarrow \text{Cold Weld (WH, TR, IP)} \quad (4.9)
\]

\[
0.90 < EFI \leq 1.14 \Rightarrow \text{Nominal Weld (No Defects)} \quad (4.10)
\]

\[
EFI > 1.14 \Rightarrow \text{Hot Weld (UF, Voids)} \quad (4.11)
\]

For validation of the developed empirical force index (EFI), six weld schedules were experimented having different welding parameters \((N, V, \text{and } F_z)\). The welded plates were inspected with PAUT and tensile tested to obtain joint properties and classification. Welding parameters along with EFI, tensile properties, and quality of the joint are listed in Table 4.3. The EFI predicted weld classification has exactly matched with the experimental result.

Table 4.3: New weld schedules along with weld quality for the validation of developed of empirical force index (EFI) in weld classification

<table>
<thead>
<tr>
<th>N (RPM)</th>
<th>V (mm/min)</th>
<th>Fz (kN)</th>
<th>UTS, MPa</th>
<th>Toughness, MJ/m³</th>
<th>EFI (kN)</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>228.60</td>
<td>36.48</td>
<td>336.69</td>
<td>48.33</td>
<td>1.04</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>228.60</td>
<td>40.03</td>
<td>346.47</td>
<td>49.43</td>
<td>1.14</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>203.20</td>
<td>28.91</td>
<td>285.38</td>
<td>15.19</td>
<td>0.88</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>203.20</td>
<td>20.91</td>
<td>314.92</td>
<td>18.75</td>
<td>0.83</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>203.20</td>
<td>23.58</td>
<td>357.46</td>
<td>35.11</td>
<td>0.94</td>
</tr>
<tr>
<td>6</td>
<td>400</td>
<td>203.20</td>
<td>26.69</td>
<td>348.17</td>
<td>32.65</td>
<td>1.06</td>
</tr>
</tbody>
</table>

4.9. Summary

The FSW process, if not correctly designed or the weld process is not controlled can generate defects. For a particular pin-tool and welding condition, the quality of a FS- weld greatly depends on three critical process parameters including plunge force, rotational speed, and travel speed. A known relationship between critical process parameters (e.g., spindle rotational speed \((N)\), welding speed \((V)\), and plunge force \((F_z)\)) with weld defects is necessary to design
defect-free weld schedules. An extensive study was conducted to determine the effects of varying the FSW principal process parameters \((N, V, F_z)\) for 8.13 mm thick panels of AA2219-T87 aluminum alloy.

- To understand the effects of varying welding process parameters, the weld schedules are classified into three categories (hot, nominal, and cold welds) based on three critical process parameters (spindle rotational speed, weld speed, and plunge force), non-destructively evaluated weld defects, and tensile test results. The presence of defects reduces mechanical properties, especially ultimate tensile strength and toughness values.

- For defect-free nominal-welds, the values of plunge force \((F_z)\) vs. dimensionless speed ratio \((R)\) constitute a field; and any schedule within the bounded field produces a defect-free weld. Weld schedules above the bounded line are considered hot-welds, and weld schedules below the bounded line produces cold-welds. Using experimental results obtained from various schedules, an empirical index (called “empirical force index- EFI”), which is a function of critical weld process parameters \((N, V, F_z)\), is proposed to identify hot, cold, and nominal- weld schedules.

- Empirical Force Index (EFI) values correlate well to optimum welding condition. If \(EFI\) values deviate from unity, the welding condition also deviates from the optimum condition and be responsible for welding defects. The \(EFI\) is associated with three critical process parameters and two materials and process dependent constants. The constant values can be obtained experimentally. The empirical correlations between critical process parameters can reduce huge amount of experimental works as well as save money to generate sound weld.
• Weld schedules within $0.90 < EFI \leq 1.14$ yielded zero defects and produced optimal mechanical properties. These schedules were labeled “nominal-weld”. Weld schedules with $EFI \leq 0.90$ were labeled “cold-weld”. Cold weld schedules produced defects such as: wormholes, trenching, and incomplete penetration. The UTS and more importantly, the toughness were reduced. Weld schedules with $EFI > 1.14$ were labeled “hot-weld”. Hot schedules produced underfill and micro-voids. The UTS and toughness were reduced with these defects.
CHAPTER 5 : PREDICTION OF TENSILE STRENGTH OF FSW JOINTS WITH ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM (ANFIS) AND ARTIFICIAL NEURAL NETWORK (ANN)

5. Introduction

In previous Chapter 4, the effect of weld process parameters on weld defects, microstructures, and tensile properties are discussed. From experimental investigations it was observed that all three critical process parameters i.e. spindle rotational speed ($N$), welding speed ($V$), and plunge force ($F_z$), have direct influence on tensile strength of friction- stir- welding (FSW) joint. But non-linear behavior of weld process parameters makes it complex to develop a model to predict UTS (Ultimate tensile strength) of FSW joint. In this chapter, an adaptive neuro-fuzzy inference system (ANFIS) model has been developed utilizing experimental data to predict ultimate tensile strength of FSW joint. ANFIS is a hybrid predictive model which uses both of neural network and fuzzy logic to generate mapping relationship between inputs and outputs. Efforts were made to determine the best model based on best combination of input variables, parameter optimization, and fuzzy inference architecture. The leave-one-out cross validation (LOO-CV) approach was applied to validate each ANFIS model built in terms of root-mean-square-error ($RMSE$) and mean-absolute- percentage-error ($MAPE$). A total of 1200 models were developed by varying the number of membership functions, the type of membership function, and the combination of four input variables ($N, V, F_z, EFI$) in MATLAB platform; where $EFI$ denotes an empirical force index derived from the three process parameters, which is discussed in Chapter 4. For comparison, artificial neural network (ANN) models were also developed to predict UTS from FSW process parameters. This newly developed ANFIS model could be utilized for the prediction of tensile strength of friction- stir- weld joints fabricated with different operating conditions, mentioned above.
5.1. Scope

Development of an appropriate physical model which can predict the main characteristics (i.e. weld defects and mechanical properties) of the FSW process is quite complex. Hence, researchers have focused on building predictive models based on numerical analysis such as finite element methods or empirical models derived from experimental observations (Record, Covington et al. 2007; Elangovan, Balasubramanian et al. 2008; Jayaraman, Sivasubramanian et al. 2008; Lakshminarayanan and Balasubramanian 2009; Rajakumar, Muralidharan et al. 2010; Tansel, Demetgul et al. 2010; Gopalakrishnan and Murugan 2011; Rajakumar, Muralidharan et al. 2011; Bilici 2012; Bozkurt 2012; Dinaharan and Murugan 2012; Rajakumar and Balasubramanian 2012; Pradeep and Muthukumaran 2013). Nontraditional optimization algorithm like genetic algorithm (GA)-Taguchi approach (Bilici 2012; Bozkurt 2012; Parida and Pal 2015), simulated annealing (SA) (Yang, Srinivas et al. 2009; Chen, Lin et al. 2010; Zain, Haron et al. 2011), and other metaheuristic algorithms (Liao and Daftardar 2009) have been used to determine optimal operating parameters for various processes. The response surface methodology (RSM) (Elangovan, Balasubramanian et al. 2008; Jayaraman, Sivasubramanian et al. 2008; Lakshminarayanan and Balasubramanian 2009; Rajakumar, Muralidharan et al. 2011; Dinaharan and Murugan 2012) has been extensively utilized to predict mechanical properties of FSW joint. RSM consists of a group of mathematical and statistical techniques that can be used to define the relationships between the response and the independent variables. The major drawback of RSM is to fit the data to a second order polynomial (Baş and Boyacı 2007). Highly nonlinear FSW process parameters and tensile properties might not be well accommodated by the second order polynomial. Some investigators applied artificial neural network (ANN) (Okuyucu, Kurt et al. 2007; Lakshminarayanan and Balasubramanian 2009; Tansel, Demetgul et al. 2010; Shojaeefard, Behnagh et al. 2013; Ghetiya and Patel 2014) to predict mechanical...
responses of FSW joint. Most of them utilized limited experimental data, and unfortunately, none of them are decisive.

Adaptive network-based fuzzy inference system (ANFIS) is a hybrid predictive model which uses both of neural network and fuzzy logic to generate mapping relationship between inputs and outputs (Jang 1993). Although ANFIS is a powerful modeling tool; but there has been only one study (Babajanzade Roshan, Behboodi Jooibari et al. 2013) utilized this technique in modeling FSW process. In that study pin-tool profile, tool rotational speed, welding speed, and axial force are utilized as input variables to predict ultimate tensile strength, yield strength, and micro-hardness of friction-stir-welded AA7075 aluminum alloy joints. The data set used in that study (Babajanzade Roshan, Behboodi Jooibari et al. 2013), however, seems low, especially when 5- different pin tools were used. They utilized 31- data sets to develop a predictive model and 10- data sets for testing the predictive model. Building and testing model based on simple data splitting is known to be not reliable. For a small data set the leave-one-out cross validation (LOO-CV) (Jalali-Heravi and Kyani 2007; Dong and Wang 2011; Shahbazikhah, Asadollahi-Baboli et al. 2011; Tsujitani and Tanaka 2011) technique is beneficial to train on as many examples as possible.

The current investigations entails experimental investigations and development an optimized ANFIS model utilizing leave-one-out cross validation (LOO-CV) approach to predict tensile properties of FSW joint of AA2219-T87 aluminum alloy. For comparison, an optimized artificial neural network (ANN) model has been also developed in this study.
5.2. Methodology

In this chapter optimized artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) were utilized to develop predictive models for FSW joints. Details of the methodology for ANN and ANFIS are discussed below.

5.2.1. Artificial Neural Network (ANN)

The first artificial neural network (ANN) was designed in 1958 by psychologist Frank Rosenblatt and he called this as ‘perceptron’. Artificial neural network (ANN) is a computational model, which replicates the function of a biological network composed of neurons. ANN is often used to model complex nonlinear functions in various applications. The basic unit in the ANN is neuron. Neurons are connected to each other by links known as synapses. Andersen et al. (1990) first applied ANN in welding area to predict weld bead shape during Gas Tungsten Arc welding (GTAW) process (Andersen, Cook et al. 1990). A multilayer perceptron ANN system has three layers which are input, hidden, and output layers. The input layer consists of all the input factors. Information from input layer is next processed in the hidden layers, and then by output layer (Figure 5.1). Details on the neural network modeling approach are given elsewhere (Zhang and Friedrich 2003).

![Schematic of artificial neural network (ANN) layers](image)

Figure 5.1: Schematic of artificial neural network (ANN) layers (two input variables, two hidden layers with 3 nodes each, and one output)
Multilayer perceptron ANN can be learned using various algorithms; well-known learning algorithms include back-propagation algorithm, counter-propagation algorithm, and genetic algorithm. Back-propagation neural network had been widely used to model the welding processes (Nagesh and Datta 2002); hence it is also adopted in this study. In building the model input variables, training functions, and number of nodes in hidden layer were varied to obtain the best model producing the lowest root- mean- square- error (RMSE) and mean- absolute- percentage- error (MAPE). The MATLAB (R2012a) platform was used to train and test the ANNs.

5.2.2. Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS constructs an input-output mapping based on human knowledge and generated input-output data pairs by using a hybrid algorithm. According to Jang (Jang 1993), the ANFIS is a neural network that is functionally the same as a Takagi-Sugeno-Kang (TSK) type inference model (Takagi and Sugeno 1985). The TSK rules can be described as equation (5.1).

\[
IF \ (x_1 = A_{i1}^1) \ and \ (x_2 = A_{i2}^2) \ and \ ... \ and \ (x_n = A_{in}^n) \ THEN \ y = f(x_j) \quad (5.1)
\]

Where, \( x_j \) is the \( j^{th} \) input \( (j = 1, 2, ... , n) \); \( A_{i1}^1 \) is the \( i^{th} \) linguistic term defined as a fuzzy membership function on \( x_j \); the mapping function \( f \) could be linear, nonlinear, or simply a real number (Liao 2003). Five distinct layers are used to explain the concept of ANFIS structure (Jang 1993). The first layer is the fuzzification layer. In this layer the crisp inputs are transformed into membership values by using the membership function at the node \( i \). The output can be stated as equation (5.2).

\[
O_i^1 = \mu_{\xi_i}(x) \quad (5.2)
\]

Where, \( \mu_{\xi_i} \) is the \( i^{th} \) membership function for the input \( x \).
The second layer is the rule base layer. It calculates the firing strength for the next layer by multiplying linguistic inputs (assuming “2”) to node $i$ of this layer (equation (5.3)).

$$O_i^2 = w_i = \mu_{x_i}(x) \times \mu_{y_i}(y) \quad (5.3)$$

The third layer performs the normalization of membership values. The normalized firing strength at node $i$ of this layer is obtained using equation (5.4).

$$O_i^3 = \bar{w}_i = w_i / \sum_{j=1}^{K} w_j; \ i = 1, 2, 3 \ ... \ K \quad (5.4)$$

$K$ denotes number of nodes in this layer, with each corresponding to a unique rule.

The fourth layer is the adaptive layer. The relation between inputs (assuming 2, i.e., $x$ and $y$) and output can be defined as equation (5.5).

$$O_i^4 = \bar{w}_i \times p_i = \bar{w}_i \times (s_i x + f_i y + n_i) \quad (5.5)$$

Where parameters $s_i, f_i, n_i$ of node $i$ in this layer are called as consequent parameters.

The fifth layer is the de-fuzzification layer and the output is the final result of all fuzzy rules. The results can be described as equation (5.6).

$$O^5 = \sum_{i=1}^{K} \bar{w}_i \times p_i; \ i = 1, 2, \ ... \ K \quad (5.6)$$

Where $p_i$ denotes the inferred output of the ANFIS rule $i$. Like neural network, in an ANFIS structure, the inputs of each layer are obtained from the nodes of the previous layer. Considering an ANFIS network with $n$ inputs ($x_1 \ldots x_n$) and each input having $m$ membership functions (MFs), the number of nodes ($N$) in first layer is equal to the product of $n$ (as number of inputs) and $m$ (as number MFs) ($N = m \cdot n$). The number of nodes in other layers (layer 2–4) relates to the number of fuzzy rules ($R$). Figure 5.2 illustrates a typical ANFIS structure showing 5 different layers.
Construction of an ANFIS model requires the partition of the input-output data into rule patches. This can be achieved by using three different clustering methods, i.e., grid partitioning, subtractive clustering method, and fuzzy c-means (FCM) (Guillaume 2001). In the Matlab Fuzzy Toolbox, it is named as GENFIS1, GENFIS2, and GENFIS3. GENFIS1 produces grid partitioning of the input space and GENFIS2 uses subtractive clustering to produce scattering partition to define the membership functions. GENFIS3 uses fuzzy c-means (FCM) as a mechanism to cluster the inputs. Apart from structure identification, a fuzzy interference system has many other parameters that can also be optimized, i.e., membership-function parameters and rule-consequent parameters (Guillaume 2001). Success in obtaining a reliable and robust model depends heavily on the choice of the domain used for construction and training purposes. Important factors that contribute to produce an accurate ANFIS model include type of fuzzy
based rule, number of MFs, and their MFs types. In this study, a first order TSK type fuzzy-based rule is used for the creation of predictive models. Then, different types of MFs (triangular, generalized bell, Gaussian, Gaussian combination (i.e. gauss2mf), and pi) with varying numbers of MFs are applied to obtain the best model that produces the minimum root mean square error (RMSE) and mean absolute percentage error (MAPE) by comparing experimental results.

5.2.3. Leave-One-Out Cross Validation (LOO-CV)

The *leave-one-out cross-validation* (LOO-CV) approach is a useful validation method for small data set and it has been widely applied for model selection (Sheng, Xia et al. 2005). In this technique one sample is left out and the remaining samples are utilized to build a model. If $n$ numbers of samples are available in a given data set, each model is trained with $n - 1$ samples and tested with the sample left out. This process repeated $n$ times until every sample in the data set have been utilized once as a cross-validation instance. Finally, the root-mean-square-error ($RMSE$) and mean-absolute-percentage-error ($MAPE$) are calculated using equations 5.7 and 5.8, respectively. The model with the minimum $RMSE$ and $MAPE$ is then selected (Dong and Wang 2011).

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (e_i - a_i)^2}
\]  
(5.7)

\[
MAPE = \frac{1}{n} \sum_{i=1}^{n} \frac{|e_i - a_i|}{e_i}
\]  
(5.8)

Where, $n$ total number of samples, $e_i$ is experimental output, and $a_i$ is ANFIS model predicted output.

5.2.4. Experimental Data

As discussed is Chapter 4, a total of 66 FSW schedules (various combinations of $N, V, and F_z$) are welded and tensile properties are obtained experimentally. From the
experimental analysis of weld process parameter and tensile strength of FSW joint, it was concluded that all three critical process parameters (i.e. spindle rotational speed, welding speed, and plunge force) act together to control the weld strength (See chapter 4). Weld process parameters and corresponding average ultimate tensile strength (UTS) of 66 different weld schedules are listed in Table 5.1.

Table 5.1: FSW process parameters and ultimate tensile strength of friction- stir- welded AA2219-T87 aluminum alloy

<table>
<thead>
<tr>
<th>SL #</th>
<th>N (rpm)</th>
<th>V (mm/min)</th>
<th>Fz (kN)</th>
<th>UTS (MPa)</th>
<th>SL #</th>
<th>N (rpm)</th>
<th>V (mm/min)</th>
<th>Fz (kN)</th>
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To obtain an optimized ANFIS model, a total of four input variables were utilized in the current investigation. The initial study started with the use of three critical process parameters ($N, V$, and $F_z$) as input variables and then another one input variable (i.e. empirical force index- EFI) is introduced to build a better ANFIS model. The empirical force index ($EFI$) is formulated from the three critical process parameters ($N, V$ and $F_z$), as shown in equations (5.9 and 5.10).

\[
Speed\ ratio, \ R = 2\pi rN/V
\]

\[
Empirical\ Force\ Index, \ EFI = \frac{F_z}{C_1(R)^{-C_2}}
\]

Where, $r$ is the pin-tool radius and $R$ is the dimensionless speed ratio. The Constant $C_1$ and the exponent $C_2$ depend on materials to be welded, type of pin tool used, and the welding conditions (e.g., clamping condition, chill bar, backing plate, environmental temperature conditions, etc.). These constants $C_1$ and $C_2$ can be determined experimentally. In the current study, the values of $C_1$ and the exponent $C_2$ are 256.93 and 0.56, respectively. Details relating to the significance of dimensionless speed ratio $R$ and empirical force index EFI are discussed in Chapter 4. The empirical force index vs. experimental UTS plot is shown in Figure 5.3. It indicates that for EFI values deviating from one there is a drop in UTS values observed. The drop is higher for lower EFI values. A range of EFI values exist where high UTS can be obtained. The non-linear behavior of process parameters and tensile strength makes it difficult to model the correlation between process parameters and UTS.
Now, the experimental investigation (see Chapter 4) indicates that all three critical process parameters ($N, V, F_z$) have direct influence on the UTS of FSW joints. It is desirable to obtain a model that is able to accurately predict tensile strength for given FSW process parameters. In the next section, details related to optimize adaptive neuro-fuzzy inference system (ANFIS) model development utilizing experimental data listed in Table 5.1 is discussed.

### 5.3. Building a Better ANFIS Model to Predict Tensile Strength

A preliminary study was first made using exhaustive search technique to obtain the best input parameters set. Before exhaustive search, all the 66- data instances were randomized and divided into 40- training instances and 26- testing data instances. The same procedure was repeated for four times utilizing the combination of two input variables out of 4- parameters. In
Figure 5.4, four plots are showing root-mean-square (RMS) error resulted from four different runs with the same data set and combinations of two input parameters. Same data with different runs resulted in different results. For example, in first run (Figure 5.4a) two input parameters \( (N, F_z) \) resulted in smallest difference between training and testing RMS error. In second, third, and fourth runs (Figure 5.4b, Figure 5.4c, and Figure 5.4d, respectively), resulted in better performances with the combination of \( (F_z, EFI) \), \( (V, EFI) \), and \( (N, EFI) \), respectively. The variation might be caused by randomization and the biasness in dividing training and testing data. To avoid this issue and to develop the best ANFIS model, all possible combinations of four input variables were tested with the leave-one-out cross validation (LOO-CV) technique. Details of developing the optimized ANFIS model are discussed below.

Figure 5.4: Variations of root-mean-square (RMS) error for different set of training and testing data
5.3.1. ANFIS Model Utilizing $N, V, and F_z$

Initial modeling began with the three input variables: rotational speed ($N$), welding speed ($V$), and plunge force ($F_z$). Utilizing grid partitioning fuzzy interference system (GENFIS1) with different combinations of three input variables ($N, V, F_z$) and varied number and type of membership functions (MFs) a total of 280 models were developed. Each model was related to a particular membership function and number of membership function for each input variable. Number of membership functions was varied from ‘1 to 3’ along with ‘5’ different types of membership functions (i.e. trimf, gbellmf, gaussmf, gauss2mf, and pimf). In the ANFIS model, at least one of the input variables ‘number of membership functions (# MFs)’ should be greater than one. Therefore, the number of models can be defined as in equation (5.11).

\[
Number \ of \ Models = [(n)^i \times m - m] \times c
\]

(5.11)

Where ‘n’ is the number of membership functions (n=3), ‘i’ denotes total number of input variable utilized to build model, ‘m’ is the different types of MFs (m=5), and ‘c’ is the number of combination of input variables. For example, 3 individual input variables ([N], or [V], or [F_z]) result in $(3^1 \times 5 - 5) \times 3 = 30$ models. Similarly, 3 different combinations of two input variables ([N, V], or [N, F_z], or [V, F_z]) has results in $(3^2 \times 5 - 5) \times 3 = 120$ models and 1 combination of three input variables ([N, V, F_z]) has results in $(3^3 \times 5 - 5) \times 1 = 130$ models. Selected models with different combinations of input variables, types and numbers of membership functions associated with input variables are listed in Table 5.2. The ANFIS model with (1, 1, 2) Gaussian membership functions for the three input variables ($N, V, F_z$) results in the lowest RMSE (36.87 MPa) and MAPE (10.92 %) values.
Table 5.2: Results from ANFIS model developed utilizing different combinations of three input variables \((N, V, F_z)\) along with types and numbers of membership functions associated with input variables

<table>
<thead>
<tr>
<th>Number of 'MF'</th>
<th>N</th>
<th>V</th>
<th>Fz</th>
<th>Type of 'MF'</th>
<th>RMSE (MPa)</th>
<th>MAPE (%)</th>
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<td>gaussmf</td>
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<td>10.92</td>
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</table>

Figure 5.5: Experimental and ANFIS model predicted UTS plotted for best the model developed utilizing three input variables \((N, V, F_z)\)

Based on the LOO-CV technique, a total of 66 data pairs of actual experimental outputs and ANFIS predicted outputs were obtained for each model. In Figure 5.5 shown below, the ANFIS
predicted and experimental UTS values are plotted for the best ANFIS model developed using three input variables. If the actual experimental and ANFIS predicted UTS values match perfectly, then all points should follow the diagonal line.

5.3.2. ANFIS Model Utilizing $N, V, F_z, \text{and} \ EF$I

Now, empirical force index (EFI) is added as an input variable along with the three process parameters ($N, V, F_z$). A total of 920 models were developed utilizing different combinations of the four input variables ($N, V, F_z, EFI$) taking EFI in common, along with varying number and type of membership functions. With different number and type of membership functions, 1 individual input variable ([EFI]) results in $(3^1 \times 5 - 5) \times 1 = 10$ models. Similarly 3 different combinations of two input variables ([N, EFI], [V, EFI], or [F$_z$, EFI]) results in $(3^2 \times 5 - 5) \times 3 = 120$ models, 3 different combination of three input variables ([N, V, EFI], [V, F$_z$, EFI], [V, F$_z$, EFI]) results in $(3^3 \times 5 - 5) \times 3 = 390$ models, and 1 combination of four input variables ([N, V, F$_z$, EFI]) results in $(3^4 \times 5 - 5) \times 1 = 400$ models. As mentioned earlier, each model is related to a particular membership function (i.e. trimf, gbellmf, gaussmf, gauss2mf, pimf) and number of membership function (i.e. 1 to 3) for each input variable. Selected models with low RMSE and MAPE values are listed in Table 5.3. It is interesting to observe that the ANFIS model developed utilizing only EFI as the input variable results in lower RMSE (36.51 MPa) and MAPE (9.90 %) values compared to the best model developed with 3 input variables without incorporating EFI (Table 5.2). In the current investigation, ANFIS models were developed based on first order TSK inference model. The highly nonlinear behavior between weld process parameters and UTS might result in higher RMSE and MAPE values in model developed without EFI. In EFI, weld process parameters are non-linearly related; this non-
linear relation might be the reason for lower RMSE and MAPE values in ANFIS model developed utilizing EFI.

Table 5.3: Results from ANFIS model developed utilizing four input variables ($N, V, F_z, E_FI$)

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<td>gauss2mf</td>
<td>34.76</td>
<td>9.34</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>pimf</td>
<td>30.84</td>
<td>8.28</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>pimf</td>
<td>31.02</td>
<td>7.96</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>pimf</td>
<td>31.86</td>
<td>7.87</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>pimf</td>
<td>29.70</td>
<td>7.75</td>
</tr>
</tbody>
</table>

Figure 5.6: Experimental and ANFIS model predicted UTS plotted for the best model developed utilizing three input variables ($V, F_z, E_FI$)
Nevertheless, EFI incorporated with other input variables was found to obtain the lowest RMSE and MAPE values. Specifically, the ANFIS model with (2, 1, 3) \( \pi \)-membership functions for \( V, F_z, \text{and} \ EFI \) results in lowest RMSE (29.7 MPa) and MAPE (7.7\%) values. Similarly, the experimental and ANFIS model predicted UTS values are plotted in Figure 5.6 where, a lesser amount of scattering is observed as compared to Figure 5.5. Lower scattering indicates a better model with lower RMSE and MAPE values; however, there are discrepancies observed between predicted and actual UTS data. The discrepancies might be related to the large variations in experimental UTS values produced by different weld schedules. Taking defect-free nominal welds as examples, UTS values vary from 310 to 360 MPa with a standard deviation of 13 MPa.

**5.3.3. Optimized ANFIS Model and Surface Plot**

In previous sections, GENFIS1 structure was applied and optimized by varying combinations of input variables, number, and type of membership functions. As mentioned before, GENFIS1 produces grid partitioning of the input space. To investigate performances, the other two partitioning methods for generating initial fuzzy inference system, namely GENFIS2 and GENFIS3, were utilized for modeling (also available in the MATLAB fuzzy toolbox). For both GENFIS2 and GENFIS3, the leave-one-out cross-validation (LOO-CV) technique was also applied as in GENFIS1. Using the GENFIS2 structure, optimized ANFIS model was developed by varying two parameters, namely ‘radii’, ‘epoch number’, and number of input variables \( (N, V, F_z, \text{and} \ EFI) \). The ANFIS model with \( V, F_z, \text{and} \ EFI \) as input variables and 'radii = 0.5' ‘epoch=20’ produces the lowest RMSE (38.40 MPa) and MAPE (10.06\%). In the case of GENFIS3, number of input variables, ‘number of a clusters’ and ‘epoch number’ were varied in the process to obtain the best ANFIS model. Using GENFIS3, the ANFIS model with \( V, F_z, \text{and} \ EFI \) as input variables and ‘number of clusters=4’ and ‘epoch numbers = 20’ has the
lowest RMSE (38.71 MPa) and MAPE (10.28%). In summary, the ANFIS model generated with
the GENFIS1 structure using three input variables \( (V, F_z, \text{and} \ EF\) \) results in the lowest RMSE
(29.7 MPa) and MAPE (7.7%) values.

For validation of the developed ANFIS model, 6 schedules were experimented having different
spindle speed (N), welding speed (V), and plunge force (F\(_z\)). Tensile strength for these tests were
obtained and compared to the ANFIS model. Welding process parameters along with
experimental and ANFIS predicted UTS are listed in Table 5.4. ANFIS predicted UTS values are
comparable with the experimental data. The details of the best ANFIS model are given in Table
5.5.

<table>
<thead>
<tr>
<th>Schedule</th>
<th>N (RPM)</th>
<th>V (mm/min)</th>
<th>F(_z) (kN)</th>
<th>EFI</th>
<th>Experimental UTS (MPa)</th>
<th>ANFIS predicted UTS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>228.60</td>
<td>36.48</td>
<td>1.04</td>
<td>336.69</td>
<td>341.08</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>228.60</td>
<td>40.03</td>
<td>1.14</td>
<td>346.47</td>
<td>344.09</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>203.20</td>
<td>28.91</td>
<td>0.88</td>
<td>285.38</td>
<td>286.29</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>203.20</td>
<td>20.91</td>
<td>0.83</td>
<td>314.92</td>
<td>317.86</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>203.20</td>
<td>23.58</td>
<td>0.94</td>
<td>357.46</td>
<td>349.02</td>
</tr>
<tr>
<td>6</td>
<td>400</td>
<td>203.20</td>
<td>26.69</td>
<td>1.06</td>
<td>348.17</td>
<td>340.16</td>
</tr>
</tbody>
</table>

Table 5.5: Basic details of the best ANFIS model to predict UTS from FSW process parameters

<table>
<thead>
<tr>
<th>Type of Inference:</th>
<th>Sugeno (If x is ( M_F^x ), y is ( M_F^y ), and z is ( M_F^z ), then output w=f(x,y,z))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of inputs</td>
<td>3 [(x, y, z)=(V, F(_z), EFI)] ; Number of output = 1 [w=UTS]</td>
</tr>
<tr>
<td>Number of input MFs</td>
<td>( [x, y, z]=[2,1,3] ); Consequent Output: 6 ( [w_1, w_2, w_3, w_4, w_5, w_6] )</td>
</tr>
<tr>
<td>Number of Rules</td>
<td>6</td>
</tr>
<tr>
<td>1. If (x is ( MF_1^x )) and (y is ( MF_1^y )) and (z is ( MF_1^z )) then (w is ( w_1 ))</td>
<td></td>
</tr>
<tr>
<td>2. If (x is ( MF_1^x )) and (y is ( MF_1^y )) and (z is ( MF_2^z )) then (w is ( w_2 ))</td>
<td></td>
</tr>
<tr>
<td>3. If (x is ( MF_1^x )) and (y is ( MF_1^y )) and (z is ( MF_3^z )) then (w is ( w_3 ))</td>
<td></td>
</tr>
<tr>
<td>4. If (x is ( MF_2^x )) and (y is ( MF_1^y )) and (z is ( MF_1^z )) then (w is ( w_4 ))</td>
<td></td>
</tr>
<tr>
<td>5. If (x is ( MF_2^x )) and (y is ( MF_1^y )) and (z is ( MF_2^z )) then (w is ( w_5 ))</td>
<td></td>
</tr>
<tr>
<td>6. If (x is ( MF_2^x )) and (y is ( MF_1^y )) and (z is ( MF_3^z )) then (w is ( w_6 ))</td>
<td></td>
</tr>
</tbody>
</table>

Input1 Range : V= [76.2 266.7]
Input2 Range : F\(_z\) = [12.46 37.81]
Finally, ANFIS predicted UTS values are plotted in a surface plot as shown in Figure 5.7 for the model generated utilizing two input variables (V and EFI). For a particular weld speed (V), a range of empirical force indexes (EFI) exist where higher UTS values can be obtained. Higher UTS values are related to defect-free nominal welds. Lower and higher EFI values, deviating more from one, result in lower UTS values, which are related to cold and hot welds containing weld defects as also shown in Figure 5.3. The surface plot is helpful to visualize required welding process parameters to achieve certain tensile strength.
5.4. ANN (Artificial Neural Network) Modeling and Validation

In ANN model construction a preliminary analysis was carried out by using all 4 input variables ($N, V, F_z, EFI$) and dividing the 66 data sets into training (40 data), testing (13 data), and validation (13 data) sets. Before partitioning, the data was randomized. For the same data set and same ANN structure (4-10-1), different runs resulted in different results. To avoid the variation, the LOO-CV approach was utilized to build ANN models, similar to building ANFIS models. Initially, all 4 data input variables ($N, V, F_z, EFI$) were utilized along with different network training functions (i.e. Levenberg-Marquardt back propagation, quasi-Newton back propagation, and gradient descent with adaptive back propagation) in a MATLAB (R2012a).
platform to obtain lowest RMSE and MAPE. It was found that Levenberg-Marquardt back propagation network training function produced best performance. Thereafter, different combinations of input variables were utilized with single hidden layer and 10 nodes in the hidden layer. For each case, the program was repeated for 6 times and average RMSE and MAPE values were calculated (Table 5.6).

Table 5.6: RMSE and MAPE values for different combination of input variables (Number of hidden layer=1; Number of nodes in hidden layer = 10; Training function= Levenberg-Marquardt back propagation)

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>RMSE (MPa)</th>
<th>MAPE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Similar to ANFIS model, the ANN model (i.e. ANN structure: 3-10-1) based on the following three input variables ($V, F_z$, and $E F I$) has resulted in lowest RMSE (38.28 MPa) and MAPE (10.64 %) values. For further optimization, the number of nodes in the hidden layer was varied from 3 to 15 to obtain the best model with three input variables ($V, F_z$, and $E F I$). For each case, the program was run 6 times to obtain average RMSE and MAPE values. It was found that 5
nodes in the hidden layer (i.e. ANN structure: 3-5-1) resulted in best performance (RMSE=36.70 MPa, MAPE = 10.09%). The basic details of the best ANN model is listed in Table 5.7.

Table 5.7: Basic details of the ANN model with lowest RMSE and MAPE

<table>
<thead>
<tr>
<th>ANN Model</th>
<th>3-5-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Configuration</td>
<td></td>
</tr>
<tr>
<td>Number of input nodes</td>
<td>3 (V, Fz, EFI)</td>
</tr>
<tr>
<td>Number of output nodes</td>
<td>1 (UTS)</td>
</tr>
<tr>
<td>Number of hidden layer</td>
<td>1</td>
</tr>
<tr>
<td>Number of hidden nodes</td>
<td>10</td>
</tr>
<tr>
<td>Number of epoch</td>
<td>100</td>
</tr>
<tr>
<td>Learning factor (Mu)</td>
<td>0.001</td>
</tr>
<tr>
<td>Training function</td>
<td>Levenberg-Marquardt back propagation</td>
</tr>
</tbody>
</table>

5.5. Summary

For a particular FSW condition, three critical process parameters (i.e. $N, V, F_z$) are considered as key factors in the determination of quality of FSW joints. From experimental investigations, it was observed that all three critical process parameters ($N, V, F_z$) have direct influence on ultimate tensile strength (UTS). But non-linear behavior of weld process parameters makes it complex to develop a model to predict UTS of FSW joint. Utilizing experimental data, an optimized adaptive neuro-fuzzy inference system (ANFIS) model has been developed to predict tensile strength of FSW joint. The optimization process involves testing different combination of four input variables (rotational speed, welding speed, plunge force, and empirical force index) and varying ANFIS parameters to obtain a model with minimum error (RMSE and MAPE). For comparison, the artificial neural network (ANN) approach was also utilized to develop a fairly optimal model using the same experimental data set. The following summaries and observations can be made:

- For the limited number of experimental data set (66 data points), the leave-one-out cross-validation (LOO-CV) approach was utilized for both ANFIS and ANN model generation.
and cross validation. Using the LOO-CV approach every experimental data point was cross validated and biasness aroused in dividing training and testing data set was avoided. LOO-CV also allows to obtain the predicted UTS value for every experimental data point and to calculate mean absolute percentage error (MAPE) easily.

- To develop the ANFIS and ANN models, four input variables ($N, V, F_z, and EFI$) were utilized and optimized. Among the four input variables, Empirical Force Index (EFI) was observed to have stronger correlation with UTS compared to other parameters. EFI was formulated from experimental investigations and found to be non-linearly correlated with the three critical process parameters ($N, V, F_z$).

- A total of 1200 different ANFIS models were developed by varying number of membership functions (MFs), type of membership function, and combination of four input variables ($N, V, F_z, EFI$). It was found that the ANFIS model with three input variables ($V, F_z, and EFI$) resulted in lowest RMSE and MAPE values of 29.7 MPa and 7.7%, respectively.

- The ANN model with the three input variables ($V, F_z, and EFI$) also resulted in minimum RMSE (36.7 MPa) and MAPE (10.09 %); however, error of the best ANN model is larger than those of the optimized ANFIS model.

- The developed best ANFIS model can be applied to select weld process parameters to achieve desirable joint strength.

The fixed pin configuration for pin-tool has been used throughout this study. In the future, the effect of pin-tool design can also be incorporated into the model to make the model more robust. To this end, far more data is needed.
CHAPTER 6 : EFFECTS OF POST- WELD HEAT TREATMENT (PWHT) ON FRICTION- STIR- WELDED AA2219-T87 JOINTS

6. Introduction

Effects of weld process parameters on the quality of friction-stir (FS) welded high strength aluminum alloy (AA2219-T87) joints are discussed in the last two chapters (Chapters 4 and 5). Friction-stir-welding (FSW) offers better performances on aluminum alloy joints compared to conventional fusion welding techniques. However plastic deformation, visco-plastic flow of metals, and complex heating cycles during FSW process (Nandan, Roy et al. 2007) results in dissolution of alloying elements, intrinsic microstructural changes, and post-weld residual stresses development in the weld joints. Therefore, precipitate strengthened aluminum alloys show lower mechanical properties in the weld and heat-affected-zone (Cabibbo, Meccia et al. 2003; Aydın, Bayram et al. 2009). In the current investigation, an average 30% reduction in the transverse ultimate tensile strength (UTS) and 60% reduction in yield strength (YS) were observed in as-welded (AW) specimen as compared to base metal specimens. Post-weld heat treatment (PWHT) is a common practice to refine grain-coarsened microstructures (Peng, Shen et al. 2013), remove or redistribute post-weld residual stresses (Cho, Lee et al. 2004), and improve mechanical properties of heat-treatable welded aluminum alloys by precipitation hardening. In this chapter, the effect of PWHT on the tensile properties along with micro-hardness, fracture, and microstructural behaviors of FS- welded AA2219-T87 joints are discussed.

6.1. Scope

Friction-stir-welding (FSW) is an innovative solid-state welding process in which the metal to be welded is not melt during the welding process. Thus the cracking and porosity often
associated with fusion arc welding of high strength aluminum alloys are eliminated by utilizing FSW process (Knipstrom and Pekkari 1997). However, some studies (Mahoney, Rhodes et al. 1998; Campbell and Stotler 1999; Liu, Fujii et al. 2003) on the microstructural characteristics and mechanical properties of the friction-stir-welded joints have indicated that FSW gives rise to softening of the heat-treatable high strength aluminum alloys joint because of the dissolution or segregation of strengthening precipitates during the welding thermal cycle. The softening might result in the degradation of mechanical properties of the weld joints. In literature, it is showed that the tensile strength of FS- welded heat treatable aluminum alloy joints varied from 60% to 70% of that of base metal (Elangovan and Balasubramanian 2007; Babu, Elangovan et al. 2009; Moreira, Santos et al. 2009). Yield strength (YS) reduction is even more severe (i.e. about 60% reduction in YS was observed for defect free FS- welded AA2219-T87 joints). Post-weld heat treatment is commonly utilized to remove residual stresses and improve strength of heat treatable aluminum alloy joints by precipitation hardening.

Liu and his research group (Liu, Chen et al. 2006) employed artificial age-hardening (165 °C for 18h) on FS- welded AA2219-T6 to determine the effects of PWHT on tensile properties. It was shown that the PWHT sample exhibits 89% tensile strength of the base material. In another study (Chen, Liu et al. 2006), they studied the effect of PWHT conducted on FS-welded AA2219. Their PWHT involves solution-treatment at 535 °C for 32 min, followed by quenching at 25 °C and artificial aging at 165 °C for 18h. They showed that the PWHT increases tensile strength of FS-weld joint. Few study reported on the effect of PWHT on fusion arc welded AA2219-T87 joints (Malarvizhi, Raghukandan et al. 2008; Zhu, Deng et al. 2015). In (Malarvizhi and Balasubramanian 2011), showed that the post weld heat treated (AH-175°C-
12h) specimens has contains more amount of precipitates than that of AW joints and results in higher tensile properties of different weld joints.

Different welding joints and different tempered materials require different PWHT condition. On the other hand, improved mechanical properties of weld joints are closely related to structural integrity of weld joints. High strength and light weight AA2219-T87 extensively utilized in aerospace industries. Although AA2219 aluminum alloy is demonstrated to have better weldability than other series of age- hardenable aluminum alloys; it suffers from a significant reducing of joint strength. No study reported on the comprehensive study of PWHT on FS-welded aerospace grade high strength AA2219-T87 joints. Thus, in the current study an optimized PWHT condition is obtained to improve mechanical properties of FSW AA2219-T87 joints.

6.2. Post-Weld Heat Treatment (PWHT) Process

There are different types of PWHT techniques are utilized for different aluminum alloys joint. Two common practices for welded aluminum alloys are artificial age-hardening (AH) and solution-treatment followed by age-hardening (STAH). In this study, FS-welded and defect free AA2219-T87 aluminum alloy plate was used for PWHT. For the base metal, T87 stands for solution treatment at 535°C followed by age-hardening at 163-191°C for 18 to 36 hours (ASM-International 1990). To study the effect of artificial age-hardening (AH), welded and defect-free tensile test specimens were placed into conventional oven at 170 °C and aging-time was varied from 5 to 18 hours followed by air cooling at room temperature. For Solution-Treatment (ST), as-welded specimens were placed into conventional oven at 540 °C for 1.0 hour followed by quenching into water (20 °C). Subsequently, the effect of artificial AH was investigated on ST-samples to obtain peak aging time. In current study, aging temperature was kept constant at 170
°C and aging time was varied from 5 hours to 18 hours. Solution-treatments followed by age-hardening specimens are named as “STAH”.

6.3. Results and Discussions

6.3.1. Effect of FSW on Tensile Properties

In Figure 6.1, tensile stress-strain curves are plotted for base and defect-free as-welded (AW) AA2219-T87 aluminum alloy joint. Base metal had an average 390 MPa yield strength (YS), 473 MPa ultimate tensile strength (UTS), and 68 MJ/m³ toughness values. Corresponding values for defect-free AW specimens are 159 MPa, 330 MPa, and 37 MJ/m³.

Figure 6.1: Effect of friction- stir- welding on tensile properties of AA2219-T87 aluminum alloy

It seems that the welded specimens has lost more than 50% yield strength and about 30% UTS as compared to base metal. The dissolution or segregation of strengthening precipitates and formation of large columnar grains (Malarvizhi, Raghukandan et al. 2008) around HAZ and
TMAZ areas during the welding thermal cycle are the main reasons for tensile properties reduction of FS- welded aluminum alloy joint.

Post-weld heat treatment (PWHT) techniques are commonly applied to improve tensile properties of FS-welded joints. Effects of PWHT techniques are discussed in sections below.

6.3.2. Effect of PWHT on Tensile Properties

Initially, the effect of only artificial age-hardening (AH) was analyzed. A tensile stress-strain plot with varying age-hardening period (5h, 10h, and 18h) is shown in Figure 6.2. Artificial age-hardening (AH) resulted in higher yield strength (YS) and ultimate tensile strength (UTS) values as compared to as-welded (AW) specimens. In an average 20% improvement in YS and 6% improvement in UTS was observed in specimens with age-hardening at 170 °C for 18 hours (AH-170°C-18h). However, about 12% reduction in toughness value was observed in AH-170°C-18h specimens. Artificial age-hardening helps in the precipitation of super-saturated alloying elements along the grain boundaries and results in higher tensile strength. But it cannot help in the microstructure rearrangements or residual stress removal (Dewan, Wahab et al. 2015). On the other hand, longer precipitation period results in lower ductility as well as toughness value of the heat treated specimens. In general, the tensile properties of FS-welded AA2219-T87 aluminum alloy joints can be recovered up to a certain limit utilizing only AH. To achieve full benefits PWHT, solution-treatment followed by artificial age-hardening (STAH) was performed. Effect of STAH heat treatments are discussed below.
Figure 6.2: Effect of artificial age-hardening (AH) on tensile properties of FSW AA2219-T87 joint

Tensile stress-strain curves for as-welded (AW) and STAH specimens are shown in Figure 6.3. Only solution-treated (ST) specimens showed lower YS, UTS, and toughness values as compared to as-welded (AW) specimens. The lower tensile properties might be related to the formation of super-saturated solid solution (SSSS) of alloying elements during ST process. AH after solution-treatment helps in the formation of precipitation around the grain boundaries and results in strengthening the welded specimens. STAH-170°C-18h treated specimens exhibited about 77% joint efficiency based on YS and 79% joint efficiency based on UTS of base metal specimens. Corresponding values for as-welded specimens were only 40% and 70% (Table 6.1). However, STAH-170 °C-18h treated specimens showed about 40% lower joint efficiency based
on tensile toughness value of as-welded (AW) specimens. Longer aging time usually results in over precipitation as well as precipitation-free zone (Krishnan 2002) which is related to reduced ductility of aluminum alloys joint. Therefore, optimum aging period is important to achieve better mechanical properties. For FS-welded AA2219-T87 peak aging time was 5 hours at 170°C. The STAH-170°C-5h treated specimens showed about 78% JE (joint efficiency) based on UTS, 61% JE based on yield strength, and 35% JE based on tensile toughness values of base metal. The summary of tensile test results with different post-weld heat treatments are listed in Table 6.1.

![Figure 6.3: Effect of solution-treatment followed by age-hardening (STAH) on tensile properties of FS-welded AA2219-T87 joint](image)

Figure 6.3: Effect of solution-treatment followed by age-hardening (STAH) on tensile properties of FS-welded AA2219-T87 joint
Table 6.1: The summary of tensile test results with different post-weld heat treatments for FS-welded AA2219-T87 joint

<table>
<thead>
<tr>
<th>Specimens</th>
<th>YS, MPa</th>
<th>UTS, MPa</th>
<th>Toughness MJ/m³</th>
<th>JE (%), YS</th>
<th>JE (%), UTS</th>
<th>JE (%), Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>390.7 ± 2.9</td>
<td>473.2 ± 0.9</td>
<td>67.7 ± 2.1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>AW</td>
<td>159 ± 3.6</td>
<td>330.1 ± 5.6</td>
<td>37.4 ± 1.6</td>
<td>40.6</td>
<td>69.7</td>
<td>55.2</td>
</tr>
<tr>
<td>AH-5h</td>
<td>188.3 ± 10</td>
<td>337.7 ± 6.8</td>
<td>28.2 ± 1.9</td>
<td>48.1</td>
<td>71.3</td>
<td>41.7</td>
</tr>
<tr>
<td>AH-10h</td>
<td>219.3 ± 11</td>
<td>337.2 ± 2.4</td>
<td>22.4 ± 2.7</td>
<td>56.1</td>
<td>71.2</td>
<td>33.1</td>
</tr>
<tr>
<td>AH-18h</td>
<td>231.5 ± 8.5</td>
<td>355.6 ± 5.2</td>
<td>22.7 ± 3.5</td>
<td>59.2</td>
<td>75.1</td>
<td>33.6</td>
</tr>
<tr>
<td>ST</td>
<td>151.6 ± 10</td>
<td>313.8 ± 8.3</td>
<td>25.4 ± 5.8</td>
<td>38.8</td>
<td>66.3</td>
<td>41.5</td>
</tr>
<tr>
<td>STAH-5h</td>
<td>239.1 ± 6.8</td>
<td>370.4 ± 12</td>
<td>23.9 ± 4.4</td>
<td>61.2</td>
<td>78.2</td>
<td>35.2</td>
</tr>
<tr>
<td>STAH-10h</td>
<td>285.5 ± 12</td>
<td>371.5 ± 12</td>
<td>13.9 ± 3.2</td>
<td>73.1</td>
<td>78.5</td>
<td>20.5</td>
</tr>
<tr>
<td>STAH-18h</td>
<td>301.2 ± 9.3</td>
<td>375.3 ± 8.9</td>
<td>10.3 ± 3.9</td>
<td>77.1</td>
<td>79.3</td>
<td>15.2</td>
</tr>
</tbody>
</table>

6.3.3. Effect of PWHT on Fracture Surfaces of Tensile Tested Specimens

Fractographs analysis is essential to understand the variations of tensile test results in welded and post-weld heat treated (PWHT) specimens. Fracture surfaces of the tensile tested specimens were examined under scanning electron microscope (SEM). SEM fractographs of as-welded (AW) and PWHT specimens (AH-18h and STAH-18h) are shown in Figure 6.4(a, b, c). The SEM images were taken at the center of the failure surface. The fractographs indicate that all the surfaces invariably consist of dimples, which is a typical indication that most of the failure occurred due to ductile fracture. This interpretation was in good agreement with the work reported by several earlier researchers (Malarvizhi and Balasubramanian 2012; Rajakumar and Balasubramanian 2012; Zhu, Deng et al. 2015). During tensile testing of ductile materials, voids are formed prior to necking. If the necking in the specimens is formed earlier, the void formation would be much more prominent; and as a result, coarse and elongated dimples can be seen. Typically larger and elongated dimples are related to higher ductility and lower tensile strength of tensile test specimens. Conversely, smaller dimples are related to lower ductility and higher
tensile strength. Defect-free as-welded (AW) and only age-hardened (AH-18h) specimens failed near TMAZ due to the presence of inhomogeneous and grain-coarsened structure. This is also related to lowest hardness values at TMAZ of AW and AH-18h specimens. On the other hand, STAH-18h specimens failed near the interface of weld nugget and TMAZ area. The STAH-18h sample contains a large number of fine dimples, which are related to higher tensile strength of STAH samples. The shiny and thick grain boundaries were also observed in STAH-18h sample. The thick grain boundary is associated with the formation of precipitate-free zone (Krishnan 2002) and generally responsible for lower ductility as well as lower tensile toughness value.

Figure 6.4: SEM fractographs of FS-welded and post-weld heat treated AA2219-T87 joints: (a) as-welded (AW), (b) age-hardened at 170°C for 18h (AH-18h), and (c) solution-treatment followed by age-hardened at 170°C for 18h (STAH-18h)
6.4. Effect of PWHT on Micro-hardness of FS-Welded AA2219-T87

For microhardness analysis, FSW welded plates were sectioned, polished, and measured along the mid-section as shown in Figure 6.5. Microhardness profile of FS-welded and PWHT samples are plotted in Figure 6.6 and Figure 6.7.

Figure 6.5: Cross section of FS- welded plate and schematic of points where HRB microhardness were measured

Figure 6.6: Effect of artificial age-hardening (AH) at 170 °C on micro-hardness of FS-welded AA2219-T87
Micro-hardness of aluminum alloys are related to tempering condition, precipitation of alloying elements, and microstructures. Complex heating cycles and deformation of plasticized material around weld zone results in microstructures refinements and decomposition of alloying elements during FSW of heat tempered aluminum alloys. As a consequence, as-welded (AW) specimen exhibited lower micro hardness values near the weld nugget and TMAZ regions (Figure 6.6).

For initial analysis, the effect of only artificial age-hardening (AH) on micro-hardness profile was studied (Figure 6.6). Age-hardening also known as precipitation hardening which usually helps in the precipitation of supersaturated alloying elements. It does not have effect on grain refinement and residual stresses. As a consequence, micro-hardness values can be improved up to certain extends around the weld nugget and TMAZ area. The higher hardness values are related to the precipitation of supersaturated alloying elements around grain boundaries, which is also true for the improvement of tensile properties in artificially age-hardened specimens.

Figure 6.7: Effect of solution-treatment followed by age-hardening (STAH) at 170 °C on micro-hardness of FS-welded AA2219-T87
To analyze the effect of solution-treatment (ST) and solution-treatment followed by artificial age-hardening (STAH) on micro-hardness, hardness profiles are drawn as shown in Figure 6.7. Solution-treatment results in the formation of supersaturated alloying element in aluminum matrix as well as grain refinement in heat treatable aluminum alloys. As a result, solution-treated specimens showed relatively lower microhardness values compared to base metal and hardness profile is uniform as compared to AW specimen. The lower hardness value is related to the formation of supersaturated precipitate element and uniform hardness is related to the grain refinement due to ST process. Now the age-hardening of ST specimens help in the formation of precipitation of alloying elements around grain boundaries and enhance hardness values. Thus, STAH-170°C-5h and STAH-170°C -18h specimens showed higher microhardness values as compared AW and ST specimens. This higher microhardness also related to the higher tensile strength of STAH specimens.

6.5. Effect of PWHT on Microstructures of FS-Welded AA2219-T87

To characterize the microstructures, the cross section of the FSW joint was cut, mounted onto epoxy, polished with diamond suspension (6µ to 0.25µ solution), and then etched with standard Keller’s reagent. Microstructural characterization and analysis were carried out utilizing optical microscope and scanning electron microscopy (SEM) equipped with X-ray energy dispersive spectroscopy (EDS).

6.5.1. Optical Macro and Micrographs Analysis

The optical macrograph of the as-welded AA2219-T87 aluminum alloy joint is shown in Figure 6.8. It can be clearly seen from Figure 6.8 that there are four distinct regions including weld nugget (WN), thermo-mechanically affected zone (TMAZ), heat-affected-zone (HAZ), and base metal are identified in a FSW joint. In Figure 6.9, optical micrographs of WN and TMAZ
are shown for as-welded (AW) AA2219-T87 joint. Weld nugget is composed of very fine and equiaxed grains. Then again, TMAZ and HAZ usually consist of elongated microstructures and heterogeneity in microstructure is observed. There is clear boundary and difference in grain orientation is observed between TMAZ and weld nugget (WN) area. The elongated and distorted grains in TMAZ are responsible for higher stress concentration and lower strength of FSW joint. As a result most of the defect-free tensile test specimens failed from TMAZ area.

Figure 6.8: Cross section of a friction-stir-welding (FSW) joint showing four different regions (WN, TMAZ, HAZ, and Base metal) in both advancing (AS) and retreating side (RS)

Figure 6.9: Optical micrographs of FS-welded AA2219-T87 joint (a) as-welded weld nugget (AW-WN) and (b) as-welded thermo-mechanically affected zone (AW-TMAZ)
Now, the effects of PWHT on microstructures are analyzed for FS-welded and post-weld heat treated (PWHT) AA2219-T87 joints. Optical macrographs of artificial age-hardened (AH-170°C-18h) and solution-treatment followed by age-hardened (STAH-170°C-18h) samples are shown in Figure 6.10. There is no significant difference in macrograph is observed between only age-hardened (AH-18h) and as-welded (AW) specimens (Figure 6.10a and Figure 6.8). This is also reported by other researchers (Priya, Subramanya Sarma et al. 2009). However, there is a significant difference is observed in solution-treated specimens (Figure 6.10b).

![Figure 6.10: Optical micrographs of FS-welded AA2219-T87 (a) AH-170°C-18h and (b) STAH-170°C-18h](image)

There is an abnormal grain growth occurred in the fine grain weld nugget, TMAZ, and HAZ areas due to solution-treatment and grain structure can be easily visualized from optical macrographs. This is also confirmed in other articles (Krishnan 2002; Hassan, Norman et al. 2003; Attallah and Salem 2005). Some studies concentrated on the heterogeneity of the FSW
The second phase particles and precipitates morphology within weld nugget, HAZ, TMAZ regions is one of the parameters leading to abnormal grain growth after solution-treatment (Attallah and Salem 2005). Due to solution-treatment, alloying elements form an instable solid solution in the aluminum matrix. As a consequence, only solution-treated specimens showed lower tensile strength and microhardness values. Now artificial age-hardening (AH) after solution-treatment results in the diffusion of the precipitates saturated solid solution into grain boundary and strengthens the parts (Krishnan 2002).

6.5.2. SEM and EDS Analysis

In Figure 6.11 shows backscattered electron (BSE) images of the weld nugget before and after PWHT. During FSW of AA2219-T87, welding temperature and plasticization of weld nugget area leading to the fine $\text{Al}_2\text{Cu}$ precipitates dissolve and segregate from grain boundaries (Malarvizhi and Balasubramanian 2011; Ni, Chen et al. 2013). Some un-dissolved second-phase precipitate particles are observed in SEM-BSE micrographs (Figure 6.11). The white dots in the micrograph represent precipitate element ($\text{Al}_2\text{Cu}$) in the weld nugget zone. The second phase particles are confirmed to be $\text{Al}_2\text{Cu}$ eutectic particles based on X-ray energy dispersive spectroscopy (EDS) analysis showing in Figure 6.12. The characteristic X-ray energy for $\alpha$-Al is 1.48 keV. Two peaks of Cu are related to $\beta$-Cu (0.95 keV) and $\alpha$-Cu (8.04 keV). The average composition of Al and Cu was measured using EDS. In base metal, average amount of Cu is 6.5% (wt.) and Al is 92% (wt.). The corresponding values for as-welded weld nugget (AW-WN) zone are 4.24% and 92 %. The lower amount of Cu in weld nugget zone is related the dissolution and decomposition of precipitates during welding process.
Figure 6.11: SEM-BSE micrograph showing grain structure and precipitates distribution in weld nugget (WN) of (a) as-weld (AW) and (b) age-hardened (AH-170°C-18h) specimens

Figure 6.12: Typical X-ray energy dispersive spectroscopy (EDS) spectrum of FS-welded AA2219-T87 joint

Similar to as-weld (AW) joint weldment analysis, the amount of precipitates present in PWHT specimens were also analyzed utilizing EDS (Energy dispersive spectroscopy). From EDS analysis, it is found that the PWHT specimen (AH-170°C-18h) specimen has an average 6.46% (wt.) Cu in the weld nugget zone. The higher percentage of precipitate element in heat treated
specimens is related to precipitation hardening during heat treatment process. The evidence can be also visualized from SEM-BSE micrographs shown in Figure 6.11b. In heat treated specimens, most of the alloying elements precipitated around the grain boundaries which are responsible for the higher strength and micro-hardness in heat treated specimens. The distribution of precipitates can be also seen from bright field transmission electron microscope (TEM) images of FS-welded AA2219 before and after PWHT (Figure 6.13). PWHT results in more in precipitations as compared to as-welded specimens (Malarvizhi and Balasubramanian 2011; Zhu, Deng et al. 2015).

![Figure 6.13: TEM bright field image of FS-welded AA2219 weld nugget (a) as-welded and (b) age-hardening at 175°C for 12h (Malarvizhi and Balasubramanian 2011). Heat-treated specimen has contains more amount of precipitates than that of AW joints](image)

**6.6. Summary**

The solid state nature of FSW leads to several benefits over fusion welding process and possible defects during cooling from liquid phase are avoided in FSW of high strength aluminum alloys. However, plastic deformation and complex heating cycles during FSW process results in the dissolution of alloying elements, intrinsic microstructural changes, and post-weld residual
stresses development in the heat treatable aluminum alloy joints. As a consequence, about 30% reduction in tensile strength and 60% reduction in yield strength were observed in defect-free as-welded AA2219-T87 joints. In this chapter, an extensive experimental investigation was accomplished on PWHT to improve tensile properties of FS-welded AA2219-T87 and obtain optimum PWHT condition. The results obtained can be summarized below:

- Artificial age-hardening (AH) helped in the precipitation of supersaturated alloying elements produced around weld nugget area during the welding process resulting an average 20% improvement in YS and 5% improvements in UTS were observed in AH-170°C-18h specimens as compared to AW specimens. However, about 12% reduction in toughness value was also observed in AH-170°C-18h specimens. The reduction is toughness values might be related due to the formation of precipitation-free zone and decrease ductility of age-hardened specimens.

- To achieve full benefit of PWHT, solution-treatment followed by age-hardening (STAH) was performed on FS-welded AA2219-T87 specimens. Solution-treatment (ST) helps in the grain refinement and formation of supersaturated precipitates in aluminum alloys. Age-hardening of ST specimens help in the precipitation of alloying elements around grain boundaries and strengthen the specimens. Longer aging time usually results in over precipitation as well as precipitation-free zone which are related to reduced ductility of aluminum alloy joints. Therefore, optimum aging period is important to achieve better mechanical properties. For FS-welded AA2219-T87 peak aging time was 5 hours at 170°C. STAH-170°C -5h treated specimens showed about 78% JE based on UTS, 61% JE based on yield strength, and 36% JE based on tensile toughness values of base metal.
• From microstructural study and EDS analysis, it can be concluded that the formation and distribution of Al$_2$Cu precipitates significantly changed after PWHT. In PWHT specimens, the Al$_2$Cu precipitated primarily distributed around the grain boundaries which led to higher tensile and microhardness properties compared to as-welded specimens.

• The results obtained from this study could be important for better design of FS-welded AA2219-T87 structures and in the forthcoming; the effect of PWHT on fatigue behavior can be analyzed as a future study.
7. Introduction

Effects of post-weld heat treatments and process parameters on the quality of friction-stir welded aluminum alloy (AA2219-T87) joint are discussed in last three Chapters (Chapters 4, 5, and 6). Friction-stir-welding (FSW) offers better performances on aluminum alloy joint compared to conventional fusion welding techniques. Due to higher initial cost and non-portability of FSW machine it is only utilized in some specific applications, but in general, fusion welding techniques are utilized in many structural applications to join aluminum alloys. Welding defects and the reduction in mechanical performances are the foremost problems for fusion welded aluminum alloys joints. The influences of weld defects and post-weld heat treatment (PWHT) on tensile properties of Gas Tungsten Arc (GTA) - welded aluminum alloy AA6061-T651 joints are investigated in this chapter. AA6061-T651 is chosen because this is one of the most commonly used general-purpose aluminium alloys and usually employed fusion welding techniques to join. The current investigations are divided into two sections: (1) influence of weld defects and (2) influence of post-weld heat treatment (PWHT) on tensile properties of GTA - welded AA6061-T651. The experimental investigations can be utilized to establish weld acceptance/rejection criteria and for the design of welded aluminum alloy structures. Details of the study are discussed below.

7.1. Scope

Weld defects and mechanical performances reduction are quite common in fusion arc weld joints of aluminum alloys. The weld defects can be in the form of surface or sub-surface
cracks, undercut, porosity, or sub-surface inclusions. The failures of welded structures generally start from preexisting weld defects (Greenberg 1966) which are intrinsic to the fusion arc welding processes. An important decision relating to its structural integrity must be made regarding weld defects and their effects on the strength of welded components. Only a limited number of studies have been reported in the open literatures on the effects of weld defects on mechanical performances (Rudy and Rupert 1970; Morton 1971; Lawrence Jr, Munse et al. 1975; Burk and Lawrence 1976). However, no conclusive study reported on weld defects and their effects on GTA- welded AA6xxx aluminum alloy. A relation between non-destructively evaluated weld defects and tensile properties can help in the designing of welded structures efficiently. Besides weld defects, residual stresses and microstructural changes are the two other key factors for performance reduction as well as failure of welded heat treatable aluminum alloy joints.

Post-weld heat treatment (PWHT) is a common practice to improve mechanical performances of weld joints. Heat treatment involves various heating and cooling procedures to change microstructures in a material. Although a number of research studies have investigated the application of post-weld heat treatment (PWHT) to different aluminum alloy welding joints using several welding processes (Akhter, Ivanchev et al. 2007; Bhanumurthy, Kumbhar et al. 2007; Elangovan and Balasubramanian 2008; Malarvizhi, Raghukandan et al. 2008; Aydin, Bayram et al. 2010; Ahmad and Bakar 2011; Maisonnette, Suery et al. 2011; El-Danaf and El-Rayes 2013; Peng, Shen et al. 2013; Damodaram, Ganesh Sundara Raman et al. 2014; Ding, Wang et al. 2014; Sivaraj, Kanagarajan et al. 2014) but only a few investigations showed the effect of PWHT on fusion arc welded AA6061 aluminum alloys (Ahmad and Bakar 2011; Maisonnette, Suery et al. 2011; Dewan, Liang et al. 2013; Peng, Shen et al. 2013).
From the critical reviews of the available literature, it is understood that few research efforts have been published on the effect of weld defects and PWHT on AA6061-T651 joints using Gas Tungsten Arc Welding (GTAW) method. The primary objective of this work is to obtain tensile test data for GTA welded joints AA6061-T651 aluminum alloy containing specific flaws and to correlate these data with the nondestructive phased array ultrasonic testing (PAUT) results. Tensile test data are also correlated with microscopic evaluation; and a comparison is made between these two inspection methods relative to the evaluation of weld discontinuities. The present investigation also included residual stress measurement and the influence of PWHT on mechanical properties of GTA - welded AA6061-T651 aluminum alloy joints.

7.2. Effect of Weld Defects on Tensile Properties

This section includes weld defects identification utilizing non-destructive evaluation (NDE) technique, welded specimens classification based on measured weld defects, verification of NDE measurement, defect size measurements and correlations with tensile strength and toughness.

7.2.1. Weld Defect Identification and Defect Size Measurement

Rolled plates of AA6061-T651 aluminum alloy with 300 mm × 76 mm × 6.35 mm dimensions were GTA-welded utilizing ER4043 filler rod. After welding, the plates were grinded and “dogbone” tensile test specimens were prepared according to ASTM standard (ASTM-International 2011). Each dogbone specimen was inspected with Olympus “Omniscan MX2.0” nondestructive phased array ultrasonic testing (PAUT) unit. Angle beam wedge (30° - 70°) with 5 MHz, 16- elements linear phased array ultrasonic probe was used for the PAUT inspection. Before inspections, the PAUT probe and wedge were calibrated with standard
calibration blocks made of the same material to be inspected. PAUT calibration included velocity, wedge delay, sensitivity, and sizing calibration.

Using PAUT one can find the A, B, C, and S scan views to find size, shape, and location of defects. The A-scan view represents waveforms which are the reflections from one sound beam position in a test piece. The B-scan is an image showing a cross-sectional profile through one vertical slice of the test piece, showing the depth of reflectors with respect to their linear position. The C-scan is a two dimensional presentation of data displayed as a top or planar view of a test piece. Lastly the S-scan or sectorial scan represents a two-dimensional cross-sectional view derived from a series of A-scans that are plotted with respect to time delay and refracted angles. Figure 7.1 shows the C-scan and S-scan views obtained from PAUT of dogbone specimens before they were tensile tested. The specimens were chosen to have different types of weld defects. The actual size, shape, and location of the defect can be detected utilizing C and S scan views. After conducting the nondestructive PAUT inspection, the specimens were classified into four categories according to the types of defects detected (no-defect, voids, lack- of - fusion (LOF), and lack- of- penetration (LOP)). The defects were formed due to the variations in welding conditions, welding process parameters, and control during manual fusion welding process. Lack- of- penetration (LOP) is usually caused by the use of too low welding current. Other causes can be the use of slow travel speed and narrow root gap. Lack - of - fusion (LOF) is generally caused due to low welding voltage and low welding speed. Multipass welding can also result in LOF and porosity, which are caused by entrapped gases in between the subsequent passes. The porosities are mostly formed due to inadequate shielding gases during the welding process.
Figure 7.1: The C and S-scan views of tensile test samples obtained with PAUT: a) no-defect, b) voids, c) LOF (Lack-of-Fusion), and d) LOP (Lack-of-Penetration)

Utilizing two dimensional representation of a defect, it is difficult to measure actual projected cross sectional area of an irregular shape weld defect. For simplicity in measurement, all defects were assumed to be rectangular in shape. The width and length of the defects were calculated utilizing S-scan view and C-scan view, respectively. For verification of PAUT
measurement, actual projected cross sectional area was measured utilizing Optical Microscope (OM) and compared to justify assumption made in PAUT measurement. A small discrepancy between the two measurements techniques is observed which is discussed in the following paragraph. Figure 7.2 shows the cross sectional view of the tensile tested samples with different types of weld defects obtained with OM. Using image processing software (Image- J), the projected cross sectional area of the defect was calculated.

Figure 7.2: Cross sectional view of tensile tested specimens with different weld defects obtained with Optical Microscope (OM)

7.2.2. Weld Defects Cross-Sectional Area Measurement utilizing PAUT and OM

The cross sectional area of the defect was measured from phased array ultrasonic testing (PAUT) and optical images, from which the cross sectional area-ratio was calculated by dividing the measured cross sectional area of the defect with original cross sectional area of the sample. PAUT measurements were performed before tensile test and OM measurements were performed after the tensile test. Figure 7.3 shows the relation between cross sectional area-ratio measured
with PAUT and OM. Only small difference is observed in the plotted data, which shows that PAUT can be confidently used to measure weld defects over a wide range of defect sizes as indicated by the linear relationship between two different measurement techniques. The small variation in the results may have occurred from measurement errors, assumption of a rectangular defect shape in PAUT measurements, and deformation of the specimen after tensile testing. In the current study, the tensile strains were below 5% for the defective samples and accordingly, the deformation effect was neglected during cross sectional area measurement of the defects using OM.

![Plot shows the relationship between the defect sizes measured with OM and PAUT](image)

Figure 7.3: Plot shows the relationship between the defect sizes measured with OM and PAUT

### 7.2.3. Effect of Different Types Defects on Tensile Properties

By controlling welding conditions (e.g. surface cleaning, jig and fixture positions, preheating, etc.) and welding process parameters weld defects can be controlled in automated
GTA welding. However, weld defects are common in manual GTA welding of aluminum alloys. Therefore, it is important to know the effect of weld defects on mechanical performances. In the current study the welded samples are classified into four different groups according to the defect location, size, and shape. The four groups are named as: (a) weld with no- defect, (a) weld with internal voids, (c) weld with lack- of- fusion, and (d) weld with incomplete penetration. Six samples were tensile tested from each group to obtain mechanical performances. Figure 7.4 shows the average tensile stress-strain curve with different weld defects. As expected, defect-free samples exhibited highest tensile strength and toughness values compared with the defective welded samples. The ultimate tensile strength (UTS) for the six defect-free tensile specimens ranged from 170 MPa to 182 MPa, averaging 177 MPa. The average toughness value was 14.1 MJ/m³. All defect-free tensile tested samples fractured near the heat-affected-zone (HAZ). The weld-defect type is found to be directly related with the tensile strength and specimen toughness. Specimens with voids had an average tensile strength of 162 MPa while their toughness was 8.3 MJ/m³. These tensile strength and toughness values were lower by 9% and 41% compared to defect-free specimens, respectively. Lack- of- fusion (LOF) has resulted in an 18% reduction in tensile strength and 65% reduction in toughness compared with defect-free welded samples. The corresponding reduction was 32% and 81% for lack- of- penetration (LOP). Table 7.1 shows the average tensile properties along with cross sectional area reduction ratio of four different groups with their standard deviations. In a defective sample, crack generally initiates from the defect sites. Defects on the surface (here, LOP) are more inclined to crack initiation sites as compared to internal defects (Tobe and Lawrenece 1977). As a results, sample with LOP defects provided lowest tensile properties. Internal defects (here, LOF and voids) are not so detrimental until the defect size turned into a critical value of the crack length. Sample with LOF has larger internal
defect as compared to the sample with internal voids and accordingly, specimen with LOF defect exhibited lower tensile properties as compared to the sample with internal voids.

![Tensile test curves of GTA-welded AA6061-T651 aluminum alloy with different types of weld defect](image)

Figure 7.4: Tensile test curves of GTA-welded AA6061-T651 aluminum alloy with different types of weld defect

<table>
<thead>
<tr>
<th>Defects</th>
<th>UTS (MPa)</th>
<th>Strain (mm/mm)</th>
<th>Toughness (MJ/m³)</th>
<th>Area-ratio (OM)</th>
<th>Area-ratio (PAUT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOP</td>
<td>119.1 ± 2.9</td>
<td>0.01 ± 0.005</td>
<td>2.6 ± 0.26</td>
<td>0.15 ± 0.02</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>LOF</td>
<td>146.5 ± 8.8</td>
<td>0.02 ± 0.007</td>
<td>4.8 ± 0.61</td>
<td>0.08 ± 0.02</td>
<td>0.08 ± 0.02</td>
</tr>
<tr>
<td>Voids</td>
<td>162.6 ± 10.1</td>
<td>0.04 ± 0.013</td>
<td>8.3 ± 2.12</td>
<td>0.05 ± 0.03</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>No-Defect</td>
<td>176.8 ± 5.9</td>
<td>0.06 ± 0.012</td>
<td>14.1 ± 1.35</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
</tbody>
</table>

Table 7.1: Average tensile test results with different weld defects
7.2.4. Effect of Weld Defect Size on Tensile Properties

Weld defects have direct influence on the reduction in tensile strength as well as in the tensile strain. To study the effect of welding defect size on the tensile strength, UTS vs. measured defect cross sectional area- ratio (i.e. ratio between defect cross sectional area and specimen cross sectional area) is plotted (Figure 7.5). The tensile strength decreases linearly with the increase of area reduction ratio (Morton 1971).

Figure 7.5: Tensile strength vs. defect cross sectional area ratio measured with PAUT and OM

Figure 7.6 shows the relation between toughness and measured cross sectional area ratio and it is found that, for small voids (defect area-ratio less than 0.05) in the fusion zone, the ultimate tensile strength decreased about 5%, whereas toughness decreased about 20%. A sudden drop in the tensile toughness is observed near area-ratio around 0.05. About 16% and 60% reduction are observed in tensile strength and toughness, respectively, when defect area-ratio reaches about
0.05. The sudden drop in toughness might be related to rapid decrease in tensile strain with defect size. If the defect size is higher than a critical value, crack propagation resistivity decreased, which results in sudden failure. After the threshold value, toughness value decreases linearly with the increasing projected defect area. In Figure 7.5 and Figure 7.6, a good agreement is observed between PAUT (red square marker) and OM (blue diamond marker) measured data.

![Graph showing tensile toughness vs. area-reduction ratio measured with PAUT and OM](image)

**Figure 7.6:** Tensile toughness vs. area-reduction ratio measured with PAUT and OM

After analyzing the effect of weld defects of tensile properties, fracture surfaces of the tensile tested specimens were analyzed utilizing scanning electron microscope. Fracture behavior is discussed in next section.

### 7.2.5. Effect of Weld Defects on Fracture Surfaces

In order to understand the fracture pattern, tensile tested specimens were examined under the scanning electron microscope (SEM). Micrographs were taken at weld zone and Heat-
Affected-Zone (HAZ) of As-Welded (AW) defect-free and base metal specimens (Figure 7.7). Defect-free as-welded specimens generally failed near the weld zone. The fracture surface of welded specimen shows ductile features, in addition to that, the size and the spacing between the grains produced at welded area are large, which is indicative of the ductility of the weld area. Based on Figure 7.7 it can be observed that the presence of dimples on fracture surface dominated the fracture surfaces, reflecting that most of the failure is the result of the ductile fracture; and this interpretation is in good agreement with the work reported by several earlier researchers (Hu and Richardson 2007; Rajakumar and Balasubramanian 2012; Peng, Shen et al. 2013). In the case of un-welded specimen, the grain size is small and the distance between different grains is also considerably small. The welded specimens with no-defects failed at the HAZ. It is obvious that at this zone, large grain particles are visible. Furthermore, the microstructure is inhomogeneous and coarse due to the welding process; therefore, a weak area was formed at the HAZ, causing the specimen to fail (Menzemer, Lam et al. 1999).

Figure 7.7: SEM fractographs of (a) base metal of un-welded specimen, (b) weld metal of as-welded (AW) specimen, and (c) HAZ metal of AW specimen
SEM fractographic analyses were also performed to understand the fracture behavior of the defective samples (Figure 7.8). In defective samples, the cracks are initiate from the defective region (e.g., LOP, LOF, and void) and then propagates through the weld metal. Brittle fracture surfaces are observed in the defective areas followed by ductile failure behavior in the non-defective regions. The LOP is a surface defect and results in higher stress concentration near the defective area. As a consequence, lowest tensile strength and strain has been experienced. Voids and LOF are sub-surface defects and are also a source of stress concentration but their effects are considerably lower than surface defects. But within the sub-surface defects, tensile samples with LOF indicated higher area reductions and lower strength, compared to tensile samples with voids.

![Fractographs of tensile tested welded specimens with various types of weld defects](image)

Figure 7.8: SEM fractographs of tensile tested welded specimens with various types of weld defects, (a) Lack- of- Penetration (LOP), (b) Lack- of- Fusion (LOF), and (c) Void

From above analysis it is observed that the defect free GTA-welded AA6061-T651 aluminum alloy joints have only 53% joint efficiency based on UTS and 33% joint efficiency based on yield strength. Post-weld heat treatment (PWHT) is a common practice to improve tensile properties of heat treatable aluminum alloy joints. Effects of PWHT are discussed in next sections.
7.3. Effect of Post-Weld Heat Treatment (PWHT)

For post-weld heat treatment analysis, only defect-free welded specimens are utilized for rational comparison. This section includes PWHT process, effect of different PWHT process on residual stresses, tensile properties, and micro-hardness on GTA-welded AA6061-T651.

7.3.1. PWHT Process

Post-weld heat treatment (PWHT) was performed to improve tensile properties of welded specimens. To study the effect of artificial age-hardening (AH), welded and naturally cooled specimens at room temperature were placed into conventional oven at 180 °C for 10 hours followed by air cooling at room temperature. For solution-treatment (ST), as-welded specimens were placed into conventional oven at 540 °C for 1.0 hour followed by quenching into cold water (20 °C).

Figure 7.9: Schematic of post-weld heat treatment (PWHT) process
Subsequently, artificial AH was investigated on ST- samples to obtain peak aging time. Aging temperature was 180 °C and aging-time was varied from 3 hours to 18 hours. Solution-treatments followed by age- hardening specimens are named as “STAH”. Schematic of post-weld heat treatment processes are shown in Figure 7.9. Horizontal axis represents time of heat treatment and vertical represents heat treatment temperatures for ST, STAH, and AH.

7.3.2. Effect of PWHT on Tensile Properties

Complex heating cycles during welding process results in dissolution of alloying elements, intrinsic microstructural changes, and post-weld residual stresses development in welded structures. Therefore, precipitate strengthened aluminum alloys show lower mechanical properties in the weld zone (Cabibbo, Meccia et al. 2003; Aydin, Bayram et al. 2009). In the current investigation, about 47% reductions in the ultimate tensile strength observed in as-welded (AW) specimens as compared to base metal specimens (Figure 7.10 and Table 7.2). Post-weld heat treatment (PWHT) is a common practice to refine grain-coarsened microstructures (Peng, Shen et al. 2013), remove or redistribute post-weld residual stresses (Cho, Lee et al. 2004), and improve mechanical properties of heat-treatable welded aluminum alloys. The effects of PWHT on tensile properties are illustrated in Figure 7.10 and Table 7.2.

Initially, only age-hardening (AH) was performed on defect-free welded specimens. Artificial age-hardening helps in supersaturated alloying element decomposes into precipitation hardening phase (Zakharov 2003; Peng, Shen et al. 2013). But it cannot help in the microstructure rearrangements or residual stress removal. Therefore, full benefit of PWHT cannot be achieved from only AH. In other words, utilizing only AH tensile properties of GTA-welded AA6061-T651 aluminum alloy joints can be recovered only up to a certain limit. About 7% improvements in ultimate tensile strength (UTS) and 16% improvement in yield strength (YS) observed in the age-hardened (AH-10h) specimens.
Then solution-treatment (ST) followed by quenching was applied on defect-free welded specimens to improve tensile properties. Closely packed atoms of the solute uniformly distribute into the solution due to solution-treatment (ST). After quenching, the solute atoms then form Guinier-Preston (GP) zones which are connected with the solvent matrix (Gao, Stiller et al. 2002). Conversely, solution treatment followed by quenching induces compressive stress fields near the weld joints and subsequently reduces tensile residual stresses. Only solution-treated (ST) specimens showed about 70% joint efficiency (JE) based on UTS and 51% JE based on YS. Artificial age-hardening (AH) was performed on ST -specimens to obtain optimum tensile strength. Age-hardening after the solution-treatment (STAH) helps in the precipitation hardening of the aluminum alloy. The alloying elements slowly precipitate into the grain boundary and impede the dislocations movement; thus higher strength can be obtained. However, longer aging time results in over precipitation as well as precipitation-free zone (Krishnan 2002). Therefore, optimum aging period is important to achieve better mechanical properties. For GTA- welded AA6061-T651, peak aging time was 5 hours at 180°C. STAH-5h treated specimens showed about 85% JE based on UTS and 71% JE based on yield strength. However toughness decreased about 29% in a STAH-5h treated tensile specimen.

Filler metal ER4043 containing lower alloying element behaves differently than base metal AA6061-T651 aluminum alloy with PWHT. Due to PWHT base and filler metal interface became strengthened due to grain refinement and precipitation hardening. Therefore failure occurred near fusion zone where weaker filler metal present. Aging time of 18 hours resulted lowest toughness (6.7% JE based on toughness values). From Figure 7.10, it can be concluded that the aluminum alloy weld joints results in about 50% reduction in UTS values as compared base metal UTS. By applying PWHT, the tensile strength can be recovered only up to a certain
extent. The percentage of tensile strength recovering usually depends upon PWHT time and temperature. For each material, there is a “peak artificial-aging time and temperature” is required to recover maximum tensile strength and toughness values. Over aging might results in lowering both tensile strength and toughness values.

Figure 7.10: Variations of tensile strength and toughness due to PWHT

Table 7.2: Effects of PWHT on Joint Efficiency (JE) of GTA- welded AA6061-T651 aluminum alloy

<table>
<thead>
<tr>
<th>Heat-treatments</th>
<th>UTS, MPa</th>
<th>JE (%), UTS</th>
<th>YS, MPa</th>
<th>JE (%), YS</th>
<th>Toughness, MJ/m²</th>
<th>JE (%), Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>334.08 ± 2.8</td>
<td>100.00</td>
<td>305.57 ± 3.5</td>
<td>100.00</td>
<td>31.07 ± 1.2</td>
<td>100.02</td>
</tr>
<tr>
<td>AW</td>
<td>176.87 ± 5.9</td>
<td>52.94</td>
<td>103.50 ± 3.6</td>
<td>33.87</td>
<td>16.91 ± 4.3</td>
<td>54.41</td>
</tr>
<tr>
<td>AH</td>
<td>197.27 ± 5.8</td>
<td>59.05</td>
<td>156.26 ± 13.4</td>
<td>51.14</td>
<td>13.04 ± 1.2</td>
<td>41.95</td>
</tr>
<tr>
<td>ST</td>
<td>234.53 ± 7.1</td>
<td>70.20</td>
<td>156.18 ± 6.3</td>
<td>51.11</td>
<td>18.04 ± 0.6</td>
<td>58.06</td>
</tr>
<tr>
<td>STAH-3h</td>
<td>273.32 ± 7.4</td>
<td>81.81</td>
<td>232.16 ± 14.2</td>
<td>75.98</td>
<td>7.38 ± 1.7</td>
<td>23.75</td>
</tr>
<tr>
<td>STAH-5h</td>
<td>283.83 ± 7.1</td>
<td>84.96</td>
<td>217.96 ± 7.4</td>
<td>71.33</td>
<td>8.00 ± 3.1</td>
<td>25.74</td>
</tr>
<tr>
<td>STAH-7h</td>
<td>248.01 ± 8.8</td>
<td>74.24</td>
<td>198.71 ± 16.4</td>
<td>65.03</td>
<td>4.58 ± 1.1</td>
<td>14.73</td>
</tr>
<tr>
<td>STAH-18h</td>
<td>227.23 ± 11</td>
<td>68.02</td>
<td>205.44 ± 10.9</td>
<td>67.23</td>
<td>2.09 ± 0.6</td>
<td>6.73</td>
</tr>
</tbody>
</table>
7.3.3. Effect of PWHT on Residual Stresses

Residual stresses are essentially “locked-in stress” to the material after production and extremely difficult to detect. In this study, non-destructive ultrasonic testing method was utilized to quantify transverse residual stresses in as-welded (AW) and post-weld heat treated specimens (STAH-5h). In case of transverse residual stress measurement, the overall variations of sound velocity in 50 mm long specimens were calculated. Average transverse residual stresses of the as-welded (AW) and post-weld heat treated (PWHT) specimens is shown in Figure 7.11. The PWHT results in about 45% removal of post-weld tensile residual stresses in GTA-welded AA6061-T651 aluminum alloy.

![Figure 7.11: Transverse residual stresses ($\sigma_t$) measured by ultrasonic testing](image)

To compare the post-weld residual stress measured using ultrasonic testing and hole-drilling methods were used for as-welded (AW) specimens. In this study, the residual stress is measured at heat-affected-zone (5 mm from center of the weld seam). The average tensile residual stress of about 44 MPa is found in the transverse welding direction. Both ultrasonic and hole-drilling tested results are comparable, but there are few differences observed. In the case of
ultrasonic testing, residual stresses are measured within the bulk materials, whereas, in hole-drill method, the hole was drilled up to a certain depth (equivalent to the diameter of the strain rosette) for the measurement of the relaxed residual stresses. This might be the reasons for the variations in the measured results. Steves in 2010 calculated 40 MPa transverse residual stresses in GTAW welded aluminum alloy utilizing hole-drilling technique (Steves 2010), which is quite close to our calculated values. Karunakaran and Balasubramanian in 2011 calculated residual stress of GTAW welded AA6351-T6 aluminum alloy using X-ray diffraction method. They obtained residual stress 74 MPa in transverse direction, which is also in the same order of magnitude of our results, although X-ray diffraction results are generally obtained in the near-surface condition.

7.3.4. Effect of PWHT on Microstructures

Tensile properties improvements of post-weld heat treated AA6061-T651 specimens are directly related to the changes in microstructures and precipitation hardening. Optical micrographs of weld zone of as-welded (AW), age-hardened (AH-10h), and solution-treatment followed by age-hardening (STAH-5h) specimens are shown in Figure 7.12. Due to complex thermal cycle during the welding process, the alloying elements usually dissolve into the aluminum matrix and results in lower tensile properties. Artificial age-hardening helps in precipitation of supersaturated alloying elements around the grain boundaries and does not respond to change in microstructures (Figure 7.12b). As discussed earlier, silicon rich filler metal ER4043 does not respond to only age-hardening. As a result, there is no significant difference noticed between AW and AH-10h samples microstructures. To obtain full benefit of PWHT, it is required to apply solution treatment then artificial hardening. There is clear difference in grain structure and precipitation at weld zone can be noticed between STAH (Figure 7.12c) and AW
specimens (Figure 7.12a). In STAH-5h specimens, precipitates (Mg$_2$Si and CuAl$_2$) accumulated around the grain boundaries and obstruct the dislocations movement during tensile test. Consequently, STAH-5h specimens showed higher tensile strength but lower tensile toughness value. This is also verified in other studies (Ravindra and Dwarakadasa 1992; Liu, Chen et al. 2006; Elangovan and Balasubramanian 2008; Dewan 2012). For further verification, SEM images are taken at weld zone of AW, AH-10h, and STAH-5h specimens and observed similar microstructures as observed in optical micrographs.

Figure 7.12: Optical micrographs of weld zone for (a) as welded (AW), (b) age hardened (AH-10h), and (c) solution treatment followed by hardened (STAH-5h) specimens showing precipitation (Mg$_2$Si and CuAl$_2$) of alloying elements

For the confirmation of precipitation elements, the average composition of precipitate elements (Si and Mg) was measured using EDS (Energy dispersive spectroscopy). The typical EDS plot along with SEM image for STAH-5h-weld zone is shown in Figure 7.14. Filler metal (ER4043)
contains about 4.5 wt.% Si. Weld zone of as welded (AW) specimens had about 1.5 wt.% Si. The lower amount of Si in weld nugget zone of AW specimen is related to the dissolution and decomposition of precipitates during the welding thermal cycles. The corresponding values for AH-10h and STAH-5h specimens were 1.7 wt.% and 2.03 wt.%, respectively. For further analysis, EDS analysis was also done on a spot of STAH-5h specimen and found about 4.9 wt.% Si and confirmed the precipitates composition. The higher percentage of precipitate element in STAH-5h specimens is related to precipitation hardening during PWHT process.

Figure 7.13: SEM micrographs of weld zone for (a) as welded (AW), (b) AH-10h, and (c) STAH-5h specimens showing precipitation of alloying elements

Precipitates (Mg₂Si and CuAl₂)
7.3.5. Effect of PWHT on Micro-Hardness

For better understanding of the effect of PWHT, hardness values were measured in the welded specimens (Figure 7.15). As expected, for the as-welded (AW) specimens, the major softened region is the weld-center area and the adjacent to HAZ area [21-23]. The lowest hardness values for AW- specimens are obtained in the fusion zone and HAZ areas and the hardness values are about 55 HR15T and 53 HR15T, respectively. Figure 7.15 also reveals that heat treatment processes are beneficial as the hardness values for all of the three zones (i.e. weld, HAZ, and base metal) are higher than the corresponding values of AW- specimens. Higher hardness values also related to higher tensile strength of PWHT specimens. Hardness values increased due to precipitation hardening and grain refinement during PWHT. However, only age-hardening (AH) does not have the full effect on grain refinement. As a result, the weakest zone of AW and AH-10h specimens are in the HAZ areas (about 10 mm away from weld-center). It is also determined that the solution -treatment followed by artificial age-hardening (STAH) helps in grain refinement (Figure 7.12) as well as precipitation hardening in welded specimens. For this reason, higher hardness values are observed near HAZ of STAH specimens. But, the weld-zone
showed the lowest hardness values due to lower precipitating elements present in the filler metal. Lowest hardness values in the welded zone are associated with the lower tensile properties of ER4043 filler metal (See Table 3.2). STAH-5h specimens observed to have lowest hardness values about 68 HR15T at the center of weld joint, which is about 25% higher than AW specimens.

![Figure 7.15: Effect of PWHT on hardness profile](image)

**7.3.6. Effect of PWHT on Fractographs**

The fracture surfaces of the heat-treated specimens were characterized using SEM to understand the failure patterns. The SEM images are taken at the center of the failure surface (Figure 7.16). The micrographs indicate that all the surfaces invariably consist of dimples, which is a typical indication that most of the failure occurred due to ductile fracture. During tensile testing of ductile materials voids are formed prior to necking. If the necking in the specimens is
formed earlier, the void formation would be much more prominent; and as result, coarse and elongated dimples can be seen. Defect-free, as-welded, and only age-hardened (AH) specimens failed at the HAZ due to the presence of inhomogeneous and grain-coarsened structure. This is also related to lowest hardness values at HAZ of AW and AH specimens. On the other hand, STAH specimens failed near weld zone for the lower hardness as well as lower tensile properties of the filler metal (Table 3.2). STAH-5h sample contains a large number of fine dimples and larger sized voids. Fine grain results in higher tensile strength and the larger voids might be related to isolated second phases on the dendrite boundaries between filler metal and base metal. Over-aging results in more voids and consequences lower tensile strength and lower toughness values. The shiny and thick grain boundaries are observed in STAH-18h sample. The thick grain boundary is associated with the formation of precipitate-free zone (Krishnan 2002) and generally responsible for brittle failure.

![Fractographs of PWHT samples: (a) AH-10h, (b) STAH-5h, (c) STAH-18h](image)

7.4. Summary

Welding defects and the reduction of mechanical performances are the foremost problems especially for fusion welded aluminum alloy joints. The influences of weld defects and
post-weld heat treatment (PWHT) on tensile properties of gas tungsten arc (GTA) - welded aluminum alloy AA6061-T651 joints are investigated in this Chapter. A brief summary from this study are as follows:

- Non-destructive phased array ultrasonic testing (PAUT) can be successfully applied to locate welding defects. The PAUT results are compared with destructively measured values for validation. The results showed that PAUT can be confidently used for estimating weld-defect size and location.

- Weld defects have direct effect on the tensile strength and toughness values of GTA-welded structures. The tensile strength decreased linearly with the increase of weld defect size. However, small voids (area-ratio < 0.05) do not have significant effect on toughness values. Once the defective area-ratio exceeds a certain critical threshold value (≥ 0.05) toughness value decline sharply. After the threshold value of the defect area-ratio achieved, toughness value decreases linearly with increasing projected defect-area.

- Solution-treatment followed by artificial age-hardening generally needed to enhance tensile properties of fusion arc welded aluminum alloys. The experimental results confirmed that the mechanical properties of the AA6061-T651 joints with PWHT are significantly improved in comparison to as-welded specimens. However, exposing the material to a temperature for longer time than optimally required aging time can create larger precipitation-free zone, impose brittleness, and consequently lower the tensile properties. And therefore, it is necessary to obtain optimum aging temperature and time for achieving better strength.
CHAPTER 8 : EFFECT OF POST-WELD TREATMENT ON GAS TUNGSTEN ARC WELDED AISI- 4140 ALLOY STEEL

8. Introduction

In the last four chapters (Chapters 4, 5, 6, and 7) structural integrity of two different aluminum alloys joint are discussed. But in many structural applications, alloy steels are utilized for its high strength and high stiffness properties. Therefore structural integrity analysis of alloy steel joints is also an important topic. And therefore, the effect of fusion arc welding on structural integrity of high strength AISI-4140 steel is investigated in this chapter. Unlike aluminum alloy joints, weld defects are not prime concern for steel joints. By controlling welding conditions and weld process parameters, defect- free weld joint can be obtained fairly easily; but residual stress development, microstructure changes, and unstable brittle fracture are unavoidable active problems for alloy steel joints that require special attention to address these types of problems. To improve mechanical performances of fusion welded alloy steel joint, two different post-weld treatment (PWT) techniques e.g. post-weld heat treatment (PWHT) and electrolytic-plasma-processing (EPP) are utilized in this current study. An EPP has been developed to improve corrosion behavior and wear resistance of structural materials; and can be employed in several other applications and surface modifications aspects as well (Dewan, Liang et al. 2014). In this study, surficial EPP employed on gas tungsten arc (GTA)-welded AISI-4140 alloy steel joint to improve mechanical performances and compared with commonly utilized PWHT. The post-weld residual stresses are measured using ultrasonic testing. Surficial microstructural and micro-hardness changes are examined by optical microscope and Rockwell hardness readings, respectively. Finally, tensile tests are carried out to identify the effect on the strength recovery and change of ductility of different heat treatment processes.
8.1. Scope

The wide applications of alloy steels call for reliable welding process and post-weld treatment process which has always been a great challenge for designers and technologists. Among different fusion welding techniques, gas tungsten arc welding (GTAW) technique is widely employed for joining high strength alloy steels for its higher joint efficiency and higher controllability properties. For a fusion weld joint, weldment especially the heat-affected-zone (HAZ), is a complex problem where variable microstructures formed from different thermal treatments and environmental conditions. This complexity involves inherent mechanical behavior such as strength, ductility, hardness, and fracture toughness. In addition, three-dimensional residual stress field can cause significant decrease of fracture toughness values in the HAZ area (Mac Henry and Potter 1990; Venkata Ramana, Madhusudhan Reddy et al. 2010). Post-weld heat treatment (PWHT) is a common practice to relieve undesirable post-weld tensile residual stresses and improve mechanical properties of welded low alloy and high strength steel structures by grain refinement. The degree of PWHT embrittlement is dependent upon heating rate, holding time or duration of treatment, applied stress, grain size of the weld, and HAZ microstructures (Zhang, Yang et al. 2013). Sometimes, PWHT is difficult to control and apply according to the recommendations, as well as it might be expensive and time-consuming. For this reason the authors have explored different surface processing technique such as, Electro-plasma- processing (EPP) which is an environmental friendly technique. During EPP treatment, Direct Current (DC) voltage is applied to the electrodes in the aqueous electrolyte, which produces plasma at the surface of the submerged workpiece. Thermal, chemical, electrical, and mechanical effects caused by EPP to the workpiece produce unique surface features (Meletis, Nie et al. 2002; Gupta, Tenhundfeld et al. 2005). EPP- treatment might result in sub-micro-grained surface structure and low martensite volume fraction at the top surface; which provides
the benefits of combination of high hardness and good corrosion resistance properties (Meletis, Nie et al. 2002; Liang, Wang et al. 2011). It is reported that welded metals are poor corrosion resistant when exposed to corrosive environment (Dadfar, Fathi et al. 2007). Therefore EPP might be an important processing for post-weld treatment process to improve both corrosion resistant and mechanical properties of welded structures. Only a handful of studies are reported in the open literature on the use of Plasma-Electrolytic-Oxidation (PEO) coating on welded structures, corrosion, and stress corrosion cracking related studies (Prasad Rao, Janaki Ram et al. 2008; Srinivasan, Blawert et al. 2008). But in the open literature, to the knowledge of the authors, currently no study is reported on the effect of EPP on mechanical properties of the welded alloy steel. This prompted the authors to conduct this current investigation on the welded structures and joints; since welding is the largest fabrication industry in the western world; and most marine structures fall into this category; and are susceptible to corrosion and failures due to stress-corrosion-cracking (SCC). The duration for EPP treatment is relatively short and the process could be used effectively in such environment.

8.2. Sample Preparation

In this study, rolled plates of AISI-4140 annealed multipurpose alloy steel with 300 mm × 76 mm × 6.35 mm dimensions were manually gas tungsten arc (GTA)-welded utilizing SAE-4130 chromoly filler rod. Welding was followed by natural air cooling at room temperature and then grinding. For rational comparison among different post-weld treatment techniques, only defect-free welded specimens were utilized. To ensure defect-free specimens, the welded and grinded plates were tested with Olympus “Omniscan MX2.0” nondestructive phased array ultrasonic testing (PAUT) unit. From the phased array ultrasonic testing A, B, C, and S scan views can be obtained to find actual size, shape, and position of weld defects. Typical B and C
scan views from welded plates are shown in Figure 8.1. In plate 1, two defects are detected: one defect is at the left side and another is at the right side of the plate (red color). Dog-bone specimens were prepared by hydro-cutting from defect-free locations of the welded plates. The specimens were again tested with PAUT. Only defect-free dogbone samples were utilized for post weld treatment and tested in tension.

![Figure 8.1: GTA- welded and grinded AISI-4140 plates and typical B and C-scan views showing defective and defect- free region](image)

8.3. Post-Weld Treatment (PWT) Process

Two different types of post-weld treatment (PWT) techniques (i.e. post-weld heat treatment and electrolytic-plasma-processing (EPP)) are utilized to improve mechanical performances of GTA-welded AISI-4140 steel. To study the influences of post-weld heat treatment (PWHT) on the level of residual stresses and mechanical properties of the specimens, the welded samples were subjected to two different stress-relieving heat treatment processes: i.e.,
(i) Annealing was done in a furnace at 650°C temperature for 1.0 hour and (ii) hardening at 500°C for 1.0 hour followed by air-cooling.

Figure 8.2: (a) Schematic and (b) experimental set-up of EPP-technique utilized on GTA-welded AISI-4140 alloy steel

Figure 8.3: Typical SEM micrographs of steel before and after EPP-treatment

Electrolytic-plasma-processing (EPP) was applied on weld metal and heat-affected-zones (HAZ) of the welded samples to study its ability to relieve post-weld residual stresses. Continuously NaHCO₃ electrolyte was delivered onto the sample surface through a tube connected with porous anodic plate. The electrical conductivity of the NaHCO₃ electrolyte is 43.1×10⁻³ S/cm. This connection ensures the plasma formation on the cathode side (the welded
samples). The applied voltage and current were (150 V) and (2 ± 0.2A), respectively; and EPP was applied for 5 minutes on each side of welded flat samples. The schematic and experimental set-up for EPP- treatment is illustrated in Figure 8.2. All EPP- tests were conducted at atmospheric pressure and initiated from room temperature. Figure 8.3 shows typical SEM micrographs before and after EPP- treatment (Liang, Wahab et al. 2011). Due to EPP- treatment, spheroids are generated on the specimen surfaces and results in higher corrosion resistance property (Liang, Wang et al. 2011).

Figure 8.4: Schematic illustrating different types of specimens utilized in current investigation

Five different types of specimens were tested in this study (Figure 8.4). All post weld treated and welded specimens were compared with un-welded base specimens. Some defect-free welded specimens were tested without applying post-weld treatment and named as as-welded (AW) specimen. Some defect-free welded specimens were heat treated at 650 °C temperature for 1.0 hour and named as W-HT-650 °C. Welded and heat treated at 500 °C temperature for 1.0
hour specimens are named as W-HT-500 °C. Welded and EPP treated specimens are named as W_EPP. Some welded and annealed (heat- treated at 650°C) specimens were treated with EPP to observe the combined effect. These specimens are named as HT-650 °C + EPP.

After acquiring different types of specimens, different experimental techniques including microstructure analysis, micro-hardness testing, and tensile testing techniques are utilized to characterize structural integrity. Obtained results are discussed from next section.

8.4. Results and Discussions

8.4.1. Effect of Fusion Arc Welding and PWT on Microstructures

Welded specimens were polished and etched with 2% Nital solution to analyze the effect of welding heat on microstructure changes. In GTA-welded 4140 steel joint, heat- affected- zone (HAZ) is considered as most critical section and all tensile test specimens failed near HAZ area. Accordingly, optical micrographs are analyzed at HAZ (i.e. surface) for as welded (AW) and EPP treated specimens and compared with base metal microstructure (Figure 8.5). The typical microstructure of the base plate is ferrite and pearlite (Figure 8.5a). The base metal adjacent to the weld metal is HAZ metal, which is subjected to a complex thermal cycle and rapid cooling during the welding process. As result, HAZ region of an AW joint is composed of bainite with small grains of pearlite (Figure 8.5b). The grains are extended compared to base metal. During EPP- treatment, melting of surface takes place due to high temperature plasma produced within small hydrogen bubbles. Quenching of the melted surface along with shock wave is created from collapsing bubbles. Localize intense heating and rapid cooling during EPP treatment has resulted in martensite or lenticular microstructure (lath) formation along with bainite and pearlite microstructure (Figure 8.5c). This type of martensite is found in plain carbon and high strength chromium-molybdenum alloy steels up to about 0.5 wt.% carbon. The martensite reaction is a
diffusionless shear transformation, highly crystallographic in character, which leads to a characteristic lath or lenticular microstructure. Martensite lath width decreases with increasing cooling rate (Ghazanfari, Naderi et al. 2012). Reduced lath or lenticular microstructure was observed in EPP-treated samples. Gupta and Tenhundfeld (2005) also indicated similar effect of EPP on un-welded steel (Gupta and Tenhundfeld 2005).

Figure 8.5: Optical micrographs of AISI-4140 alloy steel (Etchant: 2% Nital)

8.4.2. Effect of PWT on Micro-Hardness

Surface hardness mapping method is an easy way to observe the microstructure of whole weld zone and investigation of distribution of mechanical properties and microstructure (Ghazanfari, Naderi et al. 2012). Micro-hardness tests were performed to characterize the Brinell hardness (BHN) profile along the transverse direction of the welds. Figure 8.6 illustrates the
hardness profile of GTA-welded AISI-4140 steel. At the interface to HAZ and weld zone is known as fusion line, which is composed with large lath width martensite. The width of martensite lath decreases at location closer to the weld center. So, higher hardness value is observed in the weld center line compared to fusion line. Just after the fusion line, finer grain region with highest hardness value is observed. Further away from that region toward base metal, hardness value decreased for the grain coarsening effect during complex thermal cycle in the heat-affected-zone. PWHT has resulted in grain refinement and lower difference in hardness value between HAZ and base metal is observed. EPP-treatment does not have any significant effect on the grain refinement. Therefore, a substantial change in hardness values is not observed as compared with as-welded samples. Gupta and Tenhundfeld (2005) also showed that a passive surface generated after EPP treatment, which is good for corrosion resistant, but do have significant effect on microhardness (Gupta and Tenhundfeld 2005).

Figure 8.6: Change of Brinell micro-hardness in GTA-welded AISI-4140 steel (converted from Rockwell 30N)
8.4.3. Effect of PWT on Residual Stresses

Residual stresses are essentially “locked-in” stress and a key part in determining the overall strength of a welded component. In this study, non-destructive ultrasonic testing method was used to measure residual stresses as discussed in chapter 3. To plot the distribution, residual stresses were measured at five locations: 0, 5, 10, and 20 mm away from the weld centerline. Residual stresses profile of the as-welded (AW), PWHT (650°C and 500°C), EPP- treated, and PWHT (650°C) plus EPP- treated samples are plotted in Figure 8.7. Highest residual stresses are generally experienced in the heat-affected-zone (HAZ) followed by fusion zone (Mei-juan and Jin-he 2009). Away from the HAZ, the tensile residual stresses decreases and observed compressive residual stresses. Lower tensile residual stresses are experienced in PWHT samples for the grain refinement. As stated earlier, EPP was applied on the HAZ and fusion zone to investigate its ability to relieve residual stresses. During EPP-treatment, a compressive thermal shock is induced by the expansion of plasma bubbles on the surface (Gupta, Tenhundfeld et al. 2007), which helps to remove tensile residual stresses and induce compressive stresses. As a result, lesser tensile residual stresses are illustrated in HAZ and fusion zone in EPP- treated specimens compared to AW (As-welded) specimens. Application of EPP after PWHT did not exhibit significant change on residual stresses, which is attributed to the fact that residual stresses are already relieved by grain refinement during PWHT at 650°C. As stated earlier, acoustoelastic constant is applicable only in the elastic range of the material. If the residual stress is above the yield strength, acoustoelasticity may not be used to measure residual stresses. In his study, the measured residual stresses (highest value was about 600 MPa) are quite below than the actual yield strength (about 758 MPa) of AISI4140 steel. So, the use of acoustoelasticity to measure residual stress is justified.
Figure 8.7: Distribution of residual stresses in GTA- welded AISI-4140 alloy steel

Once microstructures, micro-hardness and residual stress analysis are done; uniaxial tensile tests are accomplished to understand the effect of post weld treatments on tensile properties. Tensile test results and fractographs analysis are discussed in next section.

8.4.4. Effect of PWT on Uniaxial Tensile Test Results

Uniaxial transverse tensile stress strain curves of base metal (Base), as-welded (AW), PWHT (W_HT_500°C and W_HT_650°C), and EPP- treated (W_EPP, W_HT_650°C_EPP) samples are shown in Figure 8.8. Tensile stress-strain curve is utilized to calculate yield strength, ultimate tensile strength and tensile toughness properties of different specimens. The average 0.2% offset yield stress and ultimate tensile strength of base materials are 758 MPa and 836 MPa, respectively. Corresponding values for as- welded specimen are 700 MPa and 839 MPa. As welded specimens resulted about 39% lower failure strain as compared to base metal. GTA-
welded samples failed by pure shear fracture mode, resulting from the dislocation slip (Arivazhagan, Singh et al. 2011; Kumar and Shahi 2011).

Figure 8.8: Tensile stress strain curves of GTA- welded AISI-4140 steel

The ability of a metal to deform plastically and to absorb energy in the process before fracture is termed toughness. Toughness, which is measured by calculating the area under the tensile stress strain curve, is a combination of stress levels and ductility. The key to improve toughness is a good combination of strength and ductility. Note that the ductility is the ratio between ultimate strain and yield strain. About 37% reduction in toughness value is observed due to welding. Reduction in strength and ductility of welded joints can be attributed to the prominent increase of grain size near the fusion zone (Mohandas, Banerjee et al. 1998; Kumar and Shahi 2011). Improvement in ductility and reduction in yield strength is observed after PWHT at 650 °C. This may be attributed to the decomposition of martensite and the grain coarsening of alpha phase, which makes easy inter-granular slip and dislocation movement. In
addition, the yield point might locally be reached earlier because of the decrease of residual tensile stress after PWHT, thus leading to an overall reduction in yield strength. About 88% higher toughness is achieved by PWHT at 650 °C compared to as welded samples. PWHT at 500 °C does not have any significant effect on the tensile strength and ductility of GTA- welded 4140 alloy steel.

EPP-treated samples showed 743 MPa and 912 MPa, yield strength and ultimate strength, respectively. The highest tensile strength of the welded joint after EPP- treatment is related with the presence of fine martensitic structure in weld and HAZ metal, and removal of residual stresses. Martensitic structures restricted the dislocation movement through the intragranular region and results in lower ductility as well as lower toughness. As a result, only 10% toughness improvement was perceived compared to as-welded samples. EPP was applied on welded annealed samples (PWHT at 650 °C) to observe the effect on tensile strength. The results show that EPP after PWHT do not exhibit any significant effect on the tensile strength and toughness, as EPP works on the surface, which limits its effect on the grain refinement. However, when EPP is applied on the as-welded samples, it relieved residual stress and resulted in higher tensile strength. The summary of the uniaxial test results is given in Table 8.1.

Table 8.1: Tensile test results of GTA- welded AISI- 4140 alloy steel

<table>
<thead>
<tr>
<th>Tensile properties</th>
<th>Base</th>
<th>AW</th>
<th>HT_500°C</th>
<th>HT_650°C</th>
<th>EPP</th>
<th>HT_650°C+ EPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (MPa)</td>
<td>758.3±20.1</td>
<td>700.5±14.5</td>
<td>698.9±5.7</td>
<td>618.2±20.4</td>
<td>743.7±12.5</td>
<td>627.6±11.2</td>
</tr>
<tr>
<td>Ultimate Strength (MPa)</td>
<td>836.3±6.0</td>
<td>839.2±22.8</td>
<td>837.7±7.3</td>
<td>774.5±14.4</td>
<td>912.2±5.9</td>
<td>805.6±12.2</td>
</tr>
<tr>
<td>Failure Strain (%)</td>
<td>9.54±0.7</td>
<td>5.80±0.3</td>
<td>7.11±0.2</td>
<td>11.52±0.5</td>
<td>6.33±0.3</td>
<td>8.70±0.7</td>
</tr>
<tr>
<td>Toughness (MJ/m³)</td>
<td>65.98±4.9</td>
<td>41.44±4.6</td>
<td>46.51±3.8</td>
<td>78.09±3.9</td>
<td>46.76±4.1</td>
<td>58.25±4.8</td>
</tr>
<tr>
<td>Ductility</td>
<td>3.77±0.22</td>
<td>2.71±0.16</td>
<td>3.41±0.10</td>
<td>5.90±0.23</td>
<td>3.08±0.15</td>
<td>4.34±0.30</td>
</tr>
</tbody>
</table>
8.4.5. SEM Fractographs

The fracture surfaces of the specimens are characterized using SEM to understand the modes of failure pattern. The SEM images (Figure 8.9 (a, b, c, d)) are taken at the center of the failure surface of base, as-welded, PWHT 650°C, and EPP-treated samples.

Figure 8.9: Fracture surface of tensile tested 4140 steel- a. base metal, b. as- welded, c. heat-treated (650°C), d. EPP treated (middle), and e. EPP- treated (near surface) specimens
The micrographs indicate that all the surfaces invariably consist of dimples, which is of typical indication of ductile fracture. During tensile testing of ductile materials, voids are formed prior to necking. If the neck is formed earlier, the void formation would be much more prominent; and as a result, coarse and elongated dimples can be seen. Cleavage, which is the separation along particular crystallographic planes is the foremost fracture mechanism shown by base metal (Rubio-Gonzalez, Gallardo-Gonzalez et al. 2008). The as-welded tensile specimens fail by shear in the heat-affected-zone and have resulted in finer dimples. Grain refinement occurred due to PWHT at 650°C and turns into more ductile. As a consequence, cup and cone fracture surface with coarse and elongated dimples are detected. Figure 8.9(e) is taken near surface of EPP-treated sample. By comparing, Figure 8.9(d) and (e), it can be concluded that the EPP works only on surface and have no significant effect on the bulk materials. As a result, core of the EPP-treated specimens seems similar to AW specimens, but subsurface fracture seems finer dimples with brittle fracture. The specimens after EPP- treatment has failed by quasi-cleavage fracture. The petal-like cleavage faces and the tearing edges are observed in the rupture surface (Lin, Starke et al. 1984).

8.5. Summary

Post-weld treatment (PWT) is commonly adopted on welded steel joints and structures to relieve post-weld residual stresses; and restore the mechanical properties and structural integrity. An electrolytic-plasma-processing (EPP) has been studied to improve corrosion behavior and wear resistance of structural materials; and can be employed in other applications and surface modifications aspects. In this study, the effects of PWHT and EPP-treatment on the residual stresses, micro-hardness, microstructures, and uniaxial tensile properties are explored on gas
tungsten arc welded AISI-4140 alloy steel with SAE-4130 chromium-molybdenum alloy welding filler rod. The following general conclusions can be drawn from this study:

- The reduction in ductility and toughness is common in GTA- welded low alloy steel for the development of tensile residual stresses and martensitic microstructures in HAZ and weld zone. Consequently, as-welded (AW) samples showed about 39% and 37% reduction in failure- strain and toughness values, respectively, compared to the base metal.

- Post-weld heat treatment (PWHT) is a general practice to relieve post-weld tensile residual stresses and improve mechanical properties of welded AISI- 4140 alloy steel. About 88% increase in toughness values and 12% lower yield strength was achieved by PWHT at 650 °C compared to as-welded samples. This might be related to the decomposition of martensite, grain refinement, and removal of tensile residual stresses due to PWHT.

- The electrolytic-plasma-processing (EPP) is developed to improve different materials surface properties, especially the corrosion resistance property. EPP was applied on HAZ and weld zone of GTA-welded AISI-4140 steel to improve tensile properties. EPP-treated samples showed 743 MPa and 912 MPa yield and ultimate strength, respectively. Corresponding values for the AW samples were 700 MPa and 839 MPa. The highest tensile strength of EPP- treated sample is related with the presence of fine martensitic structure in weld and HAZ metal; and removal of residual stresses by shock wave generation from collapsing hydrogen bubbles. Due to the presence of fine martensitic microstructures, surficial EPP-treatment has resulted in about 10% improvement in toughness as compared to AW samples.
• EPP-treatment might be a good candidate technology to improve tensile strength by relieving of post-weld tensile residual stresses, as well as imparting corrosion resistant property of GTA- welded low alloy and high strength steel structures.

• EPP treatment takes very short time as compared to PWHT. For this particular study, EPP was applied for only 5 minutes on each side of the dogbone specimens. So, it took only 10 minutes to apply EPP on weld and HAZ area of each dogbone specimen. Whereas, PWHT requires very high temperature and longer time which is time consuming, expensive, and sometime difficult to apply for large welded structures. Instead, EPP could be easily applied to a targeted area such as weld and HAZ area of large welded structures to improve mechanical and corrosion performances.
CHAPTER 9: EFFECTS OF ROTATING, BENDING, AND TORSIONAL FATIGUE LOADS ON WELDED STEEL JOINT

9. Introduction

In the last five chapters (Chapters 4, 5, 6, 7, and 8) structural integrity and post-weld treatment of two different aluminum alloys and alloy steel joints are discussed. For structural integrity analysis of weld joints non-destructive test, uniaxial tensile test, micro-hardness test, and microscopic analysis were performed. But many welded structures are subjected to multiaxial fatigue load in real life situations and majority of the fatigue failure initiated from weld joints. Therefore, it is important to evaluate multiaxial fatigue behavior of commonly utilized welded materials, although, in general fatigue test results are reported for uniaxial fatigue test (i.e. tensile-compression or rotating-bending). In the current investigations, the influence of rotating-bending fatigue load along with pulsed torsional load was evaluated on commonly used welded steel. A rotating-bending-torsional (RBT) fatigue testing unit was specifically designed and fabricated for biaxial fatigue test of welded and non-welded R.R. Moore specimens. For welded specimens, gas tungsten arc welding (GTAW) was carried out on 19.05 mm diameter round bar of AISI 1018 steel with ER-70S2 filler metal (Electrode). For rational comparison, only defects-free specimens were carefully chosen and tested. After welding, uniaxial tensile test was conducted to understand the fatigue loading criteria during rotating-bending fatigue test. Rotating-bending (RB) and rotating-bending-torsional (RBT) fatigue tests were conducted to obtain a systematic understanding of biaxial fatigue behavior. Moreover microstructural characterization and fracture surface analysis were performed to understand the fracture behavior of the tested specimens.
9.1. Scope

Multiaxial stress is a state of stress where two or more stress components act on a critical plane of the structure. Railroad and vehicular bridges are known for sustaining static and cyclic loads that might vary according to the service conditions such as, traffic loads, temperature changes, or wind gusts. Welded pressure vessel components, gas turbines, power plants are also subjected to cyclic loading (Wei and Dong 2010). Therefore, the fatigue behavior of the structural materials is an important factor that needs to be taken into consideration during designing. The vast majority of component fatigue failures go on at the weld joints (Rolfe and Barsom 1977; Bokesjö, Al-Emrani et al. 2012). Uniaxial fatigue and rotating-bending fatigue analysis is common for welded structures (Gurney 1979; Mac Henry and Potter 1990; Schütz 1996; G.M. Almaraz, M. Tapia et al. 2010). But many welded engineering structures are subjected to multiaxial or biaxial stresses e.g. vehicle frames and bogies (Bäckström and Marquis 2001). A handful studies reported on the effect of biaxial loading (e.g. bending and torsion) on different welded structures (Yung, Lawrence et al. 1985; Sonsino 1995; Sonsino and Kueppers 2001; Takahashi, Takada et al. 2003; Pelton, Fino-Decker et al. 2013). Current experimental investigations executed to obtain multiaxial fatigue data of weld joint and help engineering community to design more reliable welded structures. Among different engineering materials, AISI 1080 steel is commonly used structural materials in different industrial applications for its easy weldable and surface hardenable quality (G.M. Almaraz, M. Tapia et al. 2010). It is especially suitable for carburized parts requiring soft core and high surface hardness, such as: gears, pinions, worms, ratchets, etc. In the current investigations, rotating-bending-torsional fatigue tests are conducted on cold-drawn GTA-welded AISI-1018 low carbon steel specimens. The influences of a torsional pulsed load are emphasized for both non-welded and welded specimens.
9.2. Sample Preparation

General purpose cold-drawn AISI-1018 low carbon steel rod with 19.05 mm diameter were gas tungsten arc (GTA)-welded using ER70-S2 filler rod according to AWS welding codes for steel (AWSD1.1/D1.1M 2010). Before welding, a 254 mm long rod was cut into half and 33° bevel groove was machined on both pieces. For alignment during welding process, the specimens were placed in horizontal position using a three jaw chuck and rotated at 5 RPM while multi-pass welding was completed. Welding was followed by natural air cooling at room temperature. Once welding is done, specimens were machined according to ASTM standard ASTM E466-07 (ASTM-International 2007) and R.R. Moore fatigue test specimens are prepared. In Figure 9.1, welded AISI-1018 steel specimens are shown- (a) before machining, (b) after machining.

Figure 9.1: Picture of welded rods and R.R. Moore fatigue test specimens
9.3. Results and Discussions

9.3.1. Effect of Welding on Uniaxial Tensile Test and Fracture Morphology

Uniaxial tensile test was performed to estimate the fatigue stress and observe the effect of GTAW on tensile behavior. Figure 9.2 shows tensile stress-strain curve of non-welded (NW) and welded (W) AISI 1018 low carbon steel. Tensile stress-strain curve is utilized to calculate tensile strength, elongation and energy required (i.e. toughness) to break specimens. About 18% decrease in ultimate tensile strength (UTS) and 5% increase in toughness are observed in GTA-welded AISI-1018 carbon steel as compared to base metal (Table 9.1). Lower tensile strength in welded specimens might be related to microstructure changes and residual stress development during welding process. Then again, higher toughness in welded specimen is related to the use of low carbon in filler metal (i.e. 0.04% carbon in filler metal and 0.18% carbon in base metal).

![Figure 9.2: Effect of welding on uniaxial tensile stress strain curve](image-url)
Table 9.1: Tensile test results and joint efficiency (JE) of GTA-welded AISI-1018 steel

<table>
<thead>
<tr>
<th></th>
<th>UTS, MPa</th>
<th>Toughness, MJ/mm$^3$</th>
<th>JE (%), UTS</th>
<th>JE (%), Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1018-NW</td>
<td>676.22 ± 7</td>
<td>83.55 ± 3.4</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>AISI 1018-W</td>
<td>563.52 ± 14</td>
<td>87.74 ± 7.1</td>
<td>83.33</td>
<td>105.02</td>
</tr>
</tbody>
</table>

For further investigations, scanning electron microscopic (SEM) fractographs and optical micrographs are analyzed. Fractographs are used to understand fracture behavior and tensile properties of weld joints. Optical micrograph provides information about fracture initiation sites and mechanical behavior. Figure 9.3 shows the SEM fractographs of non-welded (NW) and welded (W) AISI-1018 low carbon steel. Smaller dimples in un-welded specimens are related to higher tensile strength of base metal. Elongated and larger dimples in welded specimens are related to lower tensile strength and higher ductility of welded specimens.

Figure 9.3: Scanning electron microscopic (SEM) fractographs of tensile tested specimens

Tensile tested welded specimen failed from weld and heat-affected-zone (HAZ). Optical micrographs are analyzed to understand the fracture initiation sites in tensile test specimens. Figure 9.4 shows optical micrographs of base, HAZ, and weld metal of AISI 1018 steel. Base
metal composed of ferrite-pearlite microstructure where pearlite is dispersed on the ferrite matrix. HAZ is known as grain refinement region where peak temperature reaches just above austenitic critical temperature. At that temperature, austenite grains nucleate and later decomposed into small pearlites and ferrite grains during subsequent cooling. The distribution of pearlite and ferrite are not uniform because of limited diffusion time for carbon under high heating rate during welding (Kou 2003). Weld metal microstructure has a ferrite-pearlite microstructure as well; but since the carbon content of the filler metal is lower compared to the base metal, the white ferrite matrix is larger with less two-phase pearlite structure. Less carbon also related to higher toughness and lower tensile strength in welded specimens. On the other hand, acicular ferrite structures developed in the weld zone due to welding heat. Acicular ferrite is desirable because it improves toughness of the weld metal in association with fine grain size.

![Figure 9.4: Optical micrographs of AISI 1018 steel- (a) base metal, (b) HAZ metal and (c) weld metal](image-url)
Once tensile and fracture behaviors are identified a systematic biaxial fatigue tests are performed. Biaxial fatigue analysis starts with the rotating-bending (RB) fatigue test followed by rotating-bending-torsional (RBT) fatigue test.

9.3.2. Rotating-Bending-Torsional Fatigue Test Results

Initially rotating-bending (RB) fatigue test was performed on base metal and compared with literature to evaluate designed rotating-bending-torsional fatigue testing unit. Rotating-bending fatigue test S-N curve for AISI-1018 steel is shown in Figure 9.5. Fatigue life decreases with the increase of bending stress, which is understandable. Rotating-bending (AISI 1018-NW-RB) fatigue life obtained from current investigations is compared with literature results (Perovic 2007; G.M. Almaraz, M. Tapia et al. 2010) and the experimental results correlate well with literature results. For non-welded specimens, $10^3$ cycle bending fatigue strength ($\sigma_f$) is about 628 MPa and ultimate tensile strength ($\sigma_u$) is 676 MPa. The ratio between $\sigma_f$ and $\sigma_u$ is 0.93 which is close to value mentioned for R.R. Moore fatigue test (Juvinall and Marshek 2011).

Now, rotating-bending fatigue life of welded (W) and non-welded (NW) specimens is compared. For welded specimen, $10^3$ cycle bending fatigue strength ($\sigma_f$) is about 512 MPa and ultimate tensile strength ($\sigma_u$) is 563 MPa. So, the ratio between $\sigma_f$ and $\sigma_u$ is 0.91 for welded specimens. Whereas, at $10^5$ rotating bending fatigue life, the ratio between fatigue strength and ultimate tensile strength is 0.55 and 0.48, respectively for non-welded (NW) and welded (W) specimens. Welded specimens showed lower RB fatigue strength as compared to non-welded specimens. About 29% reductions in rotating-bending fatigue strength are observed in welded specimens as compared to NW specimens (at $10^5$ cycles). This can be attributed to reduction on tensile and development of residual stresses due to welding. Similar behavior also showed for laser welded NiTi alloy wire in (Yan, Yang et al. 2006).
Now, the effects of torsional load are investigated for welded (W) and non-welded (NW) specimens separately. The comparative S-N curves on Figure 9.6 and Figure 9.7, illustrate results obtained from rotating-bending (RB) and rotating-bending-torsion (RBT) fatigue tests. As observed, for base metals, the application of the torsional load has no major effects on the fatigue strength at higher bending strength level. Trend-lines for both RB and RBT loading conditions overlap. Tendency that derived from two different causes: First, when comparing the maximum bending stresses and the first principal stresses (calculated from Mohr circle considering torsional load); maximum difference between bending and first principal stress is in the order of 1.0 MPa. The amount of applied torque is only 2.7 percent of the ultimate tensile strength (UTS) of base metal. Secondly, the pulse-torque application at every 2000 cycles might not reflect on the final results. However, at lower bending stress level, torsional stress has an effect on fatigue strength and RBT fatigue life reduces as compared to RB test (Figure 9.6). At $10^5$ cycles, the
ratio between fatigue strength and ultimate tensile strength is 0.55 and 0.47, respectively for rotating-bending (RB) and rotating-bending-torsional (RBT) fatigue testing of non-welded (NW) specimens. The non-welded RBT test specimens showed an average 15% reduction in fatigue strength at $10^5$ cycles as compared to non-welded RB test specimens. Previous work done experimentally by Stoychev applying 20 and 30 percent shear stress of the maximum bending stress, resulted on an increment of the fatigue life for a 90 degree phase (Stefanov and Stoychev 2004). However, this amount of torque cannot be reached for the electric motor restrictions in our designed testing unit. Further work by (Sonsino 2009), showed that for shear stresses greater than 50 per cent than the axial bending resulted in allocation of the points between a percentage of 10 and 90 percent due to the interdependence of the local equivalent stress amplitude and the cycles to failure for the carried out test for pure bending.

Figure 9.6: Effect of torsional load on rotating-bending fatigue life of non-welded (NW) AISI-1018 steel
Similar trends are also observed for welded specimens and reported by other researchers as well (Wahab and Sakano 2003). However, for the welded specimens there is a noticeable difference observed at higher cycles when the pulsating torsional load is applied. At $10^5$ cycles, the ratio between fatigue strength and ultimate tensile strength (i.e. welded specimen) is 0.48 and 0.37, respectively for rotating - bending (RB) and rotating-bending-torsional (RBT) fatigue testing of welded (W) specimens. The welded RBT test specimens showed an average 22% reduction in fatigue strength at $10^5$ cycles as compared to welded RB test specimens. The effect of torsion at lower stress level is more notable (Figure 9.7).

![Figure 9.7: Effect of torsional load on rotating bending fatigue life of welded (W) AISI 1018 Steel](image)

As it is observed from tensile test, the welded specimen exhibits lower UTS as compared to non-welded specimen. But the magnitude of applied torsional stress is same. So, the amount of
applied torque is higher in proportion as compared to base metal case. That might be one of the causes of higher reduction in fatigue strength in RBT fatigue testing case of welded specimens. Another reason might be the difference in microstructure at the core and surface of the weld joints. During multi-pass welding, dissolution of δ occurs in weld core due to reheating below γ-solvus temperature. Lower ferrite causes reduced ductility and consequence to faster crack propagation during RBT test.

Now, the effect of welding on rotation-bending-torsion (RBT) fatigue life is investigated for AISI-1018 low carbon steel (Figure 9.8). Similar to rotating-bending (RB) loading conditions, welded specimens showed lower fatigue life as compared to non-welded specimens. This might be related to the effect of torsional load on fatigue life. Torsional stress remained fixed throughout the experiment. Therefore, at lower bending stress, effect of torsional stress is significant. But at higher bending stress the effect of small proportion torsional stress (percentage of bending stress) is also small.

![Graph showing effect of welding on RBT fatigue life](image)

Figure 9.8: Effect of welding on rotating-bending-torsional (RBT) fatigue life
The biaxial fatigue behavior of GTA-welded and non-welded AISI-1018 steel specimens is discussed above. Welded specimens exhibited lower rotating-bending fatigue strength as compared to base metal. Effect of pulsating torsional load is also analyzed on rotating-bending fatigue life of welded and non-welded specimens. Pulsating torsional load has stronger effect on welded specimens. It is also important to analyze fracture behavior of fatigue tested specimens to understand the reasons of failure and fatigue strength variations in different specimens. Fracture morphology of fatigue tested specimens is analyzed in next sanction.

9.3.3. Fracture Morphology of Fatigue Tested Specimens

Fatigue crack generally initiated from the surface and then propagate through the cross sections of the critical section. For all specimens, shear failure mode observed due to rotating-bending-torsion (RBT) fatigue loading (Figure 9.9). Figure 9.10 shows optical image and SEM fractographs near surface and core of the specimen. A clear difference is observed between core and surface fractographs. More fracture dimples are observed near the core as compared to near the surface fractographs. This may have happened due to tension-compression loading nature of RBT fatigue test.

Figure 9.9: Photograph of rotating-bending-torsional (RBT) fatigue tested welded specimen
Figure 9.10: Fracture morphology variation from center to surface of the rotating-bending-torsional (RBT) fatigue tested AISI-1018 Steel

Figure 9.11 shows the SEM fractographs of non-welded (NW) and welded (W) AISI-1018 steel after rotating-bending (RB) and rotating-bending-torsion (RBT) tests. Trans-granular fracture, featuring cleavage facets and secondary cracks are observed in all fractographs (Wang, Duan et al. 2014). There is no significant difference is observed un-welded specimens. The fracture surface of un-welded metal is still in the ductile mode and it is evident from the presence of dimples. Welded specimens also showed ductile fracture behavior, but the shape and size of the dimples are different and it is influenced by the microstructure of the weld metal region. Due to torsional loading, welded RBT specimens observed to have larger trans-granular fracture as compared to welded RB specimens.
9.4. Summary

Most welded structures are subjected to multiaxial fatigue load and majority of the fatigue failure initiated from weld joints. Therefore, it is important to evaluate multiaxial fatigue behavior of commonly used welded materials. In the current investigations, the influence of rotating -bending fatigue load along with torsional pulsed load was appraised for most commonly used AISI-1018 low carbon steel. A multi-axial rotating-bending-torsion fatigue testing unit was successfully designed and manufactured to evaluate the effect of biaxial load on...
welded specimens. The effects of rotating-bending and pulsating torsional load was studied on welded (W) and non-welded (NW) AISI-1018 low carbon steel rods. Additionally, an attempt to evaluate the failure mechanisms was studied by evaluating characteristic microstructure and surface fractographs. After evaluating all the retrieved data, the following general conclusions can be drawn:

- Due to welding, rotating-bending (RB) fatigue strength of AISI 1018 carbon steel reduced by about 29% when compared to the base metal (at $10^5$ cycles). It was also observed that crack initiation and final failure occurs at the HAZ and weld metal of welded specimens due to grain refinement and residual stresses.

- Under combined loading condition (RBT), welded specimens fatigue strength was reduced by about 22% as compared RB fatigue strength of welded specimens (at $10^5$ cycles)

- All fracture surfaces invariably comprised of fracture dimples indicating ductile failure during fatigue tests. Fatigue failure initiated from surface of the specimens and propagated towards the critical section of the specimens.
CHAPTE R 10 : CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

10. Overview

Various welding techniques are extensively utilized within manufacturing sectors for various structures ranging from bridges and machinery to all kinds of automobiles, marines, nuclear reactors, and space vehicle, etc. But the welding process involves different types of complications such as weld defect, microstructure changes, distortion, and post-weld residual stresses, which are responsible for performance reduction as well as, failure of welded structures. Hence, structural integrity analysis and performance improvements of weld joints are extremely important issues which need to be addressed. In this PhD research, an extensive analysis was accomplished on the challenges towards structural integrity analysis and performance improvement of different weld joints. Two different types of welding techniques (friction-stir-welding and gas tungsten arc welding) were employed on widely utilized aluminum alloys of two different types and two different structural steels joints. Different destructive and non-destructive testing techniques were utilized for structural integrity analysis of different welded joints. Different post-weld treatment techniques were also employed to improve mechanical performances of different weld joints. Conclusions and future works of this current research are discussed below.

10.1. Conclusions

In this PhD research, an extensive analysis on structural integrity and performance improvement of different weld joints are addressed. The work herein is divided into six different sections including: (i) FSW defects linked to weld process parameters; (ii) FSW joint strength estimation from weld process parameters; (iii) Effects of PWHT on friction-stir (FS) - welded
aluminum alloys; (iv) Influence of weld-defects and PWHT on fusion arc welded aluminum alloys; (v) Influence of PWHT on welded steel joint; and finally, (vi) Biaxial fatigue behavior of welded steel joints. Detail conclusions related to each section are discussed at the end of each chapter. A comprehensive summary of the complete work is discussed below.

10.1.1. FSW Process Parameters Correlated to Weld Defects

The solid-state FSW technique involves several critical process variables that affect the overall quality of the weld produced; consequently, it is difficult to accurately predict the most favorable process parameters to acquire high quality defect-free welds. This is one of the most important challenges the FSW research is facing now-a-days and considerable international efforts are ongoing throughout the world into this new research challenges. Defects arising in FSW welding in 8.13 mm thick high strength aluminum alloy AA2219-T87 were correlated with FSW weld process parameters from an assortment of different weld schedules generating considerably large amount of experimental data (i.e. 66 data). The welds were classified into three major categories (hot, nominal, and cold welds based on the three critical process parameters (spindle rotational speed, weld speed, and plunge force), non-destructively evaluated weld defects, and the results from tensile tests. Hot-welds (refer to higher plunge force or higher spindle rotational speed or lower welding speed in comparison to optimal parameters) were found to have Small-Voids and underfills; cold- welds (refer to lower plunge force or lower rotational speed in comparison to optimal parameters) were observed to have Wormholes (WH), Trenching (TR) and incomplete penetration (IP); and on the other hand, nominal- welds (refers to local optimum process parameters) had no weld defects. From the point of view of experimental investigations, an FSW process parameter window and a new empirical correlation (i.e., “empirical force index-EFI”) were established for effective joining of AA2219-T87. This
novel empirical correlation relates the three critical process parameters and was found to successfully distinguish among hot, nominal, and cold weld schedules. Weld schedules within $0.90 < EFI \leq 1.14$ yielded zero defects and produced optimal mechanical properties. These schedules were labeled “nominal” weld. Weld schedules with $EFI \leq 0.90$ were labeled “cold” welds. Weld schedules with $EFI > 1.14$ were labeled “hot” welds.

### 10.1.2. ANFIS Model to Predict Tensile Strength of FSW Joint

From experimental analysis it was observed that the FSW joint properties are very much dependent on the weld parameters. For this reason, it is important to obtain a correlation between these weld parameters and mechanical properties of weld joints. Utilizing experimental data, an optimized “adaptive neuro-fuzzy inference system (ANFIS)” model was developed to predict ultimate tensile strength (UTS) of FSW joints. Efforts were made to determine the best model based on the best combination of input variables, parameter optimization, and fuzzy inference architecture. Tensile strength obtained from the ANFIS model was thereafter compared with the experimental results, by calculating “root-mean-square-error (RMSE)” and “mean-absolute-percentage-error (MAPE)” values. For comparison, optimized artificial neural network (ANN) model was also developed to predict UTS from FSW process parameters. A total of 1200 different ANFIS models were developed by varying number of membership functions (MFs), type of membership function, and combination of four input variables $(N, V, F_z, EFI)$. It was found that the ANFIS model with three input variables $(V, F_z, and EFI)$ has resulted in the lowest RMSE and MAPE values of 29.7 MPa and 7.7%, respectively. The ANN model with the similar three input variables $(V, F_z, and EFI)$ also has resulted in minimum RMSE (36.7 MPa) and MAPE (10.09 %); however, error of the best ANN model is larger than those of the
optimized ANFIS model. The developed best ANFIS model can be applied to select weld process parameters to achieve desirable joint strength.

10.1.3. Effects of PWHT on FS- Welded Aluminum Alloys Joints

FSW offers significantly better performance on aluminum alloy joints compared to the conventional fusion arc welding techniques; however, plastic deformation, visco-plastic flow of metals, and complex non-uniform heating cycles during FSW processes, result in dissolution of alloying elements, intrinsic microstructural changes, and post-weld residual stress development. As a consequence, about 30% reduction in UTS and 60% reduction in yield strength (YS) were observed in defect-free, as-welded AA2219-T87 joints. PWHT is a common practice to refine grain-coarsened microstructures which removes or redistributes post-weld residual stresses; and improves mechanical properties of heat-treatable welded aluminum alloys by precipitation hardening. An extensive experimental program was undertaken on PWHT of FS- welded AA2219-T87 to obtain optimum PWHT conditions and improvement of the tensile properties. Artificial age-hardening (AH) helped in the precipitation of supersaturated alloying elements produced around weld nugget area during the welding process. As a result, an average 20% improvement in YS and 5% improvements in UTS was observed in age- hardened (AH-170°C-18h) specimens as compared to AW specimens. To achieve full benefit of PWHT, solution-treatment followed by age-hardening (STAH) was performed on FS-welded AA2219-T87 specimens. Solution-treatment (ST) helps in the grain refinement and formation of supersaturated precipitates in aluminum alloys. Age-hardening of ST specimens help in the precipitation of alloying elements around grain boundaries and strengthen the specimens. Longer aging time usually results in over precipitation as well as precipitation-free zone which are related to reduce ductility of aluminum alloy joints. Therefore, optimum aging period is important to achieve
better mechanical properties. For FS-welded AA2219-T87 peak aging time was 5 hours at 170°C. STA1-170°C -5h treated specimens showed about 78% JE based on UTS, 61% JE based on yield strength, and 36% JE based on tensile toughness values of base metal.

10.1.4. Effects of Weld Defects and PWHT on Fusion Arc Welded (GTAW) Aluminum Alloys Joints

In many applications fusion arc welding techniques are employed to join various aluminum alloys. Weld defects and the reduction of mechanical performances are the foremost problems for fusion arc welded aluminum alloy joints. The influence of weld defects and PWHT on tensile properties of GTAW, employing AA6061-T651 was investigated. All welded specimens were non-destructively inspected with “phased array ultrasonic testing (PAUT)” to classify weld- defects and to measure the projected weld-defect’s “area-ratio”. It was found that UTS value decreased linearly with the increase of the size of the weld-defects but tensile toughness behaved non-linearly with the change of defect sizes. Defect-free, as-welded specimens observed to have 53% joint efficiency based on UTS and 34% joint efficiency based on YS of base metal. Furthermore, PWHT was applied on defect-free welded specimens to improve tensile properties by precipitation hardening, microstructure refinement, and removal of post-weld residual stress. Optimum PWHT specimens showed roughly 85% joint efficiency based on UTS and up to 71% joint efficiency based on YS of base metal.

10.1.5. Effect of Post-Weld Treatment (PWT) on Fusion Arc Welded Steel

In many structural applications, alloy steels are utilized for their high strength and high stiffness properties. The effect of fusion arc welding on structural integrity of high strength AISI-4140 steel was thereby investigated. Unlike aluminum alloy joints, weld-defects are not generally a prime concern for steel joints. Post-weld residual stresses, microstructure changes,
and unstable brittle fracture are few of the unavoidable problems for alloy steel joints. Consequently, as-welded (AW) samples showed about 39% and 37% reduction in failure-strain and toughness values, respectively, compared to the base metal. The PWHT is a common practice to relieve undesirable post-weld (locked-in) residual stresses and improves mechanical properties of welded steel joints by grain refinement. Due to the nature of the control mechanisms sometimes, PWHT is difficult to control and apply effectively according to the recommendations; and this procedure can be expensive and time-consuming. For this reason the author has explored different surface modification processing technique including an “electrolytic-plasma-processing (EPP),” a novel technique for surface modification and strength improvement. The effects of PWHT and EPP on the residual stresses, micro-hardness, microstructures, and tensile properties are explored on Gas Tungsten Arc- welded AISI-4140 alloy steel. The PWHT resulted in relief of undesired tensile residual stresses due to grain refinement. As a consequence higher ductility but slightly lower strength existed in PWHT samples. In comparison, EPP- treated samples revealed lower residual stresses but no significant variation on grain refinement. Consequently, EPP- treated specimens exhibited higher tensile strength but lower ductility and toughness values for the martensitic formation, which was due to the rapid heating and quenching effects of the EPP.

10.1.6. Effects of Multiaxial Loads on Fatigue Behavior of Fusion Arc Welded Steel

Most welded structures are subjected to multiaxial fatigue loading in actual service conditions, and the majority of the fatigue failure initiates from the grain-coarsened weld joints. Therefore, it is important to evaluate multiaxial fatigue behavior of commonly utilized welded joints. In this study, the influence of “rotating-bending (RB)” fatigue load along with the pulsed torsional loading was evaluated on commonly used GTA-welded steel (i.e., AISI-1018). A
“rotating-bending-torsional (RBT)” fatigue testing unit was specifically designed for this purpose and fabricated for biaxial fatigue testing of welded and non-welded R.R. Moore specimens. Both RB and RBT fatigue tests were conducted to obtain a systematic understanding of the biaxial fatigue behavior. The RB fatigue life of welded specimens reduced considerably (i.e. about 29% lower fatigue strength at $10^5$ cycles), compared to base material specimens in welded specimens as a result of the complex thermal cycle and microstructural changes during the welding process. Under the combined loading conditions of RBT, the average fatigue strength (at $10^5$ cycles) of the welded specimens was reduced considerably by 22%.

10.2. Recommendations for Future Works

The following recommendations are made based on experimental study performed on the structural integrity analysis and performance improvements of different weld joints.

10.2.1. Recommendations on FS-Welded Aluminum Alloy Joints

During FSW of aluminum alloy, effects of three critical process parameters (i.e. spindle rotational speed, plunge force, and welding speed) are analyzed and an empirical correlation has been developed for a particular pin-tool, lead angle, welded material, and clamping conditions. In practice, the value FSW process parameters $(N, V, F_z)$ largely depend on pin-tool design, materials need to be welded, and lead angle utilized during the welding process. In the developed empirical model, two constants were introduced to compensate the effect of pin-tool design, materials, and clamping conditions. A robust model needs to take consideration all these factors along with three critical process parameters. In a preliminary study, a different pin-tool was employed to join AA2195-T8 aluminum alloy utilizing three different lead angles ($0^\circ$, $1.5^\circ$, and $3^\circ$) while other welding parameters were kept constant. From tensile stress-stain plot shown in Figure 10.1 can be seen that the higher lead angles ($1.5^\circ$ and $3^\circ$) provide better tensile properties
as compared to 0° lead angle. But there might be an optimum lead angle where tensile properties will be maximized for this particular pin-tool design. In future, along with three critical process parameters an optimized lead angle can be obtained for different pin-tool design and materials. Then a generalized empirical correlation can be obtained for FSW of different materials at different conditions.

Figure 10.1: Tensile stress-strain curve of FS-welded AA2195-T8 plates at three different lead angles (0°, 1.5° and 3°) while other process parameters are kept constant (N=325 rpm, V=7 ipm, and $F_z=8000$ lbf)

10.2.1. Recommendations on Post-Weld EPP-treatment of Welded Joints

Electrolytic-plasma-processing (EPP) is commonly utilized for surface treatment of different materials to improve corrosion behaviors. In chapter 8, the effect of novel post-weld
EPP-treatment was analyzed on fusion arc welded high strength steel joints and improved tensile properties were obtained after EPP-treatment. A preliminary study was also done on the effect of post-weld EPP-treatment on corrosion behavior of welded alloy steel. For the corrosion test, 5 mm x 20 mm x 5 mm specimens were prepared from welded and EPP- treated specimens containing weld, HAZ, and bulk metal as shown in Figure 10.2. Utilized corrosion medium was aerated 3.5% NaCl and corrosion test was done utilizing potentiodynamic polarization from -0.8 to -0.1V at 1.0 mV/sec. From initial analysis, measured corrosion potential and corrosion current density are plotted for different sections (Figure 10.3). Usually lower current density indicates lower corrosion rate and higher corrosion potential indicates better corrosion resistance of the specimen. From Figure 10.3, it can be found that the weld metal has higher corrosion rate as compared to other specimens. Typically AISI-4140 is categorized as better corrosion resistance steel as compared to other high carbon steels. Therefore no significant difference was observed between as-welded (AW) and EPP- treated samples in terms on corrosion current density and potential. In future, EPP can be applied to other carbon steels joints and analyze the effect of post- weld EPP-treatment mechanical as well as corrosion behaviors.
Figure 10.2: Sample preparation for corrosion test of GTA-welded and EPP-treated AISI-4140 steel

Figure 10.3: Effect of post-weld EPP-treatment on corrosion potential and corrosion current density of GTA-welded AISI-4140 alloy steel
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APPENDIX

A1. Pin-Tool Design for FSW of Aluminum Alloys

Figure A1: Design of FSW pin-tool shoulder
Figure A2: Design of FSW pin-tool nib
VITA

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