2017

Friction Stir Welding Between Similar and Dissimilar Materials

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FRICTION STIR WELDING BETWEEN SIMILAR AND DISSIMILAR MATERIALS

A thesis submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Materials Science Engineering

By

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2017

Wright State University

WRIGHT STATE UNIVERSITY

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December 7, 2017

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Khaled Yousif Ali ENTITLED Friction Stir Welding between Similar and Dissimilar Materials BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Materials Science Engineering.

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ABSTRACT

Ali, Khaled Yousif. M.S.M.S.E., Department of Mechanical and Materials Engineering, Wright State University, 2017. Friction Stir Welding Between Similar and Dissimilar Materials.

This thesis focuses on the friction stir welding (FSW) between similar and dissimilar alloys. FSW is a solid state joining process that welds the work-pieces through a combination of heat generated by friction and mechanical stirring of the metals in the region of the joint. Being a solid state process, FSW can be used to weld alloys with significantly different melting points. This provides a significant benefit over traditional fusion welding process in a variety of applications in automotive, biomedical, aerospace, nuclear and petroleum industries.

Two materials - an aluminum alloy (6061-T6, m.p. 582 - 652ºC) and a steel (SAE 1018, m.p. 1480ºC) are the primary focus of this research. An end mill was modified to perform friction stir welding, and several tool designs made from H13 steel, A2 steel and tungsten carbide were investigated. The tool tilt angle, rotation speed, and travel speed were the primary welding parameters which considered. Rockwell hardness, tension, and 4- point bending tests were conducted to evaluate the mechanical properties of the welded samples as well as the microstructure test.

Results show that in the as-welded condition there is a considerable decrease in the strength and hardness of the aluminum alloy in the joint region. This can be attributed to

over-aging of the aluminum alloy due to the heat generated by the joining process. However, standard T6 heat treatment restores the mechanical properties of the aluminum -aluminum joint, and improves the mechanical properties of the aluminum-steel joint. This demonstrated the feasibility of FSW for joining both similar and dissimilar metals.

TABLE OF CONTENTS

Title **Page**

LIST OF FIGURES

Title **Page**

LIST OF TABLES

Title **Page**

LIST OF NOMENCLATURE

Q0	Net power, Watt or joule/min
μ	Friction coefficient, dimensionless
P	Pressure, MPa
ω	Rotation speed, rpm
$R_{shoulder,\ pin}$	Shoulder radius or pin radius, mm
V	Tool travel speed, mm/min
HI	Pseudo heat index, joule
W	The work, joule
Q	The energy or heat generation rate, joule
h	Thread pitch or step height, mm
d	Threaded tool or width for stepped spiral tool, mm
R	Outer radius, mm
r	Inner radius, mm
H	The pin height, mm

LIST OF ACRONYMS

FSW	Friction Stir Welding
NZ	Nugget Zone
SZ	Stir Zone
TWI	The Welding Institute
PCBN	Polycrystalline Cubic Boron Nitride
WC-Co	Tungsten Carbide-Cobalt
WC	Tungsten Carbide
BM	Base Metal
TMAZ	Thermo-Mechanically Affected Zone
SS	Stainless Steel
VHN	Vickers Hardness Number
HRF	Rockwell Hardness scale
HAZ	Heat Affected Zone
EDS	Energy Dispersive Spectroscopy
SEM	Scanning Electron Microscopy
UTS	Ultimate Tensile Strength
R	Rotational Speed
T	Travel Speed
A	Tilt Angel
EPMA	Electron Probe Microscopic Analyzer
XRD	X-Ray Diffraction

TEM	Transmission Electron Microscopy

ACKNOWLEDGEMENTS

The great experience I have gained through the master's program in material engineering was the most important accomplishment of my life. In these two years, I have learned more than what I had learned from my first day of college to my graduation with a bachelor's degree. This is because many of the research requirements available here in the United States, such as the laboratories and materials like titanium, which are difficult to obtain in Iraq. During my pursuit of a master's degree, I have lived the academic life for what it should be, and have gained knowledge in materials engineering, which most world countries deal with, especially the United States.

I would like to thank all the people, without any exception, who supported me while I got the results that are described in this research. Also, I would like to thank my academic advisor, Professor Raghavan Srinivasan, for accepting me into his group as the master's student. Dr. Srinivasan is a very knowledgeable professor who specializes in materials science. Additionally, I appreciate all of the time and advice he gave me while I worked under his supervision. Working with him as my advisor made me realize that a thesis is an interesting work which adds many experiences to the student, such as how to write academically and the right way to search.

I would like to thank all my committee members for their interest in my work, giving me the enough time to explain and defend my thesis, and for putting their important comments. I would like to thank all of my friends who supported me while I was working on my thesis. Most importantly, I would like to thank my family for their support of me during my time studying here in the United States. Lastly, I would like to thank Mom, Dad, my wife, and all my brothers and sisters for their constant love, support, and care.

Dedicated to my family

CHAPTER 1 : INTRODUCTION

1.1 Overview

This chapter discusses the friction stir welding process and its importance in many applications. Moreover, the chapter explains many of the other concepts that are related to this process, such as the advantages, limitations, welding parameters, joint design, distinguished zone, material flow, and tool geometry. Friction stir welding between similar and dissimilar materials with a butt joint are covered in the entirely of this chapter. This is because the welded zone has excellent mechanical properties compared with the conventional welding, making it more commonly used in many welding applications.

1.2 Introduction

The friction stir welding process is solid-state joining that uses a non-consumable tool (i.e., harder than the material being welded) to join two facings of materials without melting [1]. The friction stir welding process was patented by Wayne Thomas at The Welding Institute Ltd (TWI _ Cambridge, UK) in December 1991 as shown in Figure (1.1). This method can improve the joint mechanical properties, such as the strength, because the brittle compounds at the interface are minimized. Localized heating will generate because friction and plastic deformation between the tool (i.e., pin and shoulder) and the workpieces occurs.

That friction and plastic deformation results in mixing and stirring the materials around the pin from the front to the back. The heat generated by friction leads to the softening of the metals, especially near the friction stir welding tool [3]. That means mechanical energy is converted into thermal energy at the contact areas, without needing heat from other sources. The primary role of the friction stir welding tool is to heat the workpieces, and then induce the materials to flow and constraint beneath the shoulder [2] [3]. The materials that move around the pin can be very complicated and different from one tool to another, because of the various geometrical features of the tools. Simply, the friction stir welding concept is a particular design of a tool which consists of shank, shoulder, and pin. The pin can be inserted into a butt joint or even lap joint and then rotating forward along the joint line. There are some advantages of friction stir welding tool, these advantages include heating the surfaces of the workpieces, creating plastic deformation, stirring and mixing the materials around the pin to produce the joint, flow the material, and restricting the heat beneath the shoulder [4]. Some of the two phase alloys cannot be joined successfully using friction stir welding because of poor joint strength and metallurgical changes. Friction stir welding has many more characteristics than traditional welding; these characteristics include energy-efficiency, no waste of the materials, environmentally-friendliness, good mechanical properties, little pollution, and versatile joining techniques between similar and dissimilar materials that are difficult to fusion weld.

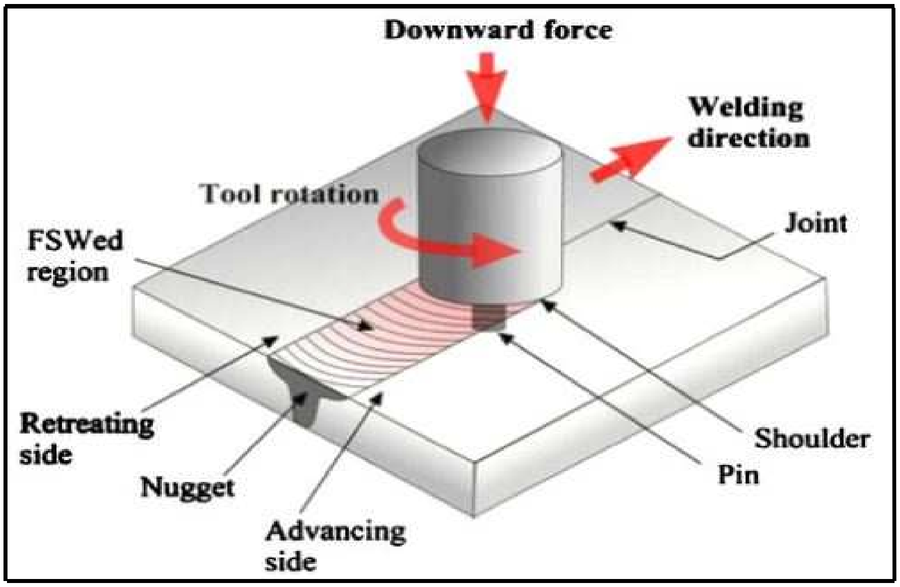


Figure (1.1) Schematic drawing shows the principle of friction stir welding process [6].

1.3 Friction Stir Welding

Friction stir welding occurs by rotating a tool with different speeds, and the quality of the weld joint and maximum possible welding speed is improved by choosing the suitable material of the tool [5]. Welding two sheets of metals with specific dimensions, such as square mating edges, require clamps to prevent movement apart or lift during the welding process, as shown below in Figure (1.2). There are different designs and shapes of the tool, but that does not effect on the working principle of the friction stir welding process.

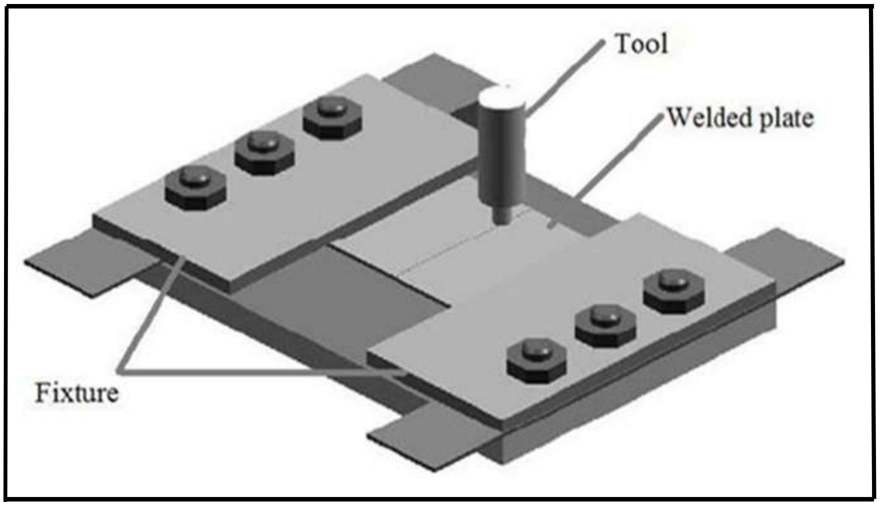


Figure (1.2) Schematic drawing shows the friction stir welding clamping [5].

Friction stir welding has five important steps: plunging, dwelling, welding, dwelling, and pulling, as shown in Figure (1.3). The tool is inserted into the butt joint slowly, until the shoulder makes contact with the upper surface of the workpieces. Then, the tool is forced by the machine to maintain contact between the shoulder and the sheets surface. This down force creates frictional heat between the shoulder, the pin, and the workpieces, which almost reaches 80% of the melting point. Also, a lateral force is applied by the machine along the direction of the welding, until the tool reaches the end of the joint. That lateral force is called travel speed.

In some friction stir welding conditions, there is no free area at the end of the joint, so the pin can be withdrawn while it is still rotating. Pulling the tool in this way will create a keyhole, which is regarded as a defect in friction stir welding applications, Figure (1.4) [5]. During friction stir welding, the maximum temperature reaches 0.8 of the melting temperature; this process called “Solid states.” Because the temperatures during friction stir welding remain below the melting point, the mechanical properties, such as reduction residual stress, and reducing shrinkage phenomenon, can be improved. The temperature generated by the friction between the tool and the workpieces depends on the type of material being welded. Also, tool geometry affects the heat generation rate through torque, traverse force, and thermodynamics environment experienced by the tool. In general, tool materials of friction stir welding should meet all of the following properties: fracture toughness, strength, thermal conductivity, thermal expansion coefficient, and reactivity of tool material with oxygen from the atmosphere and with workpieces [6].

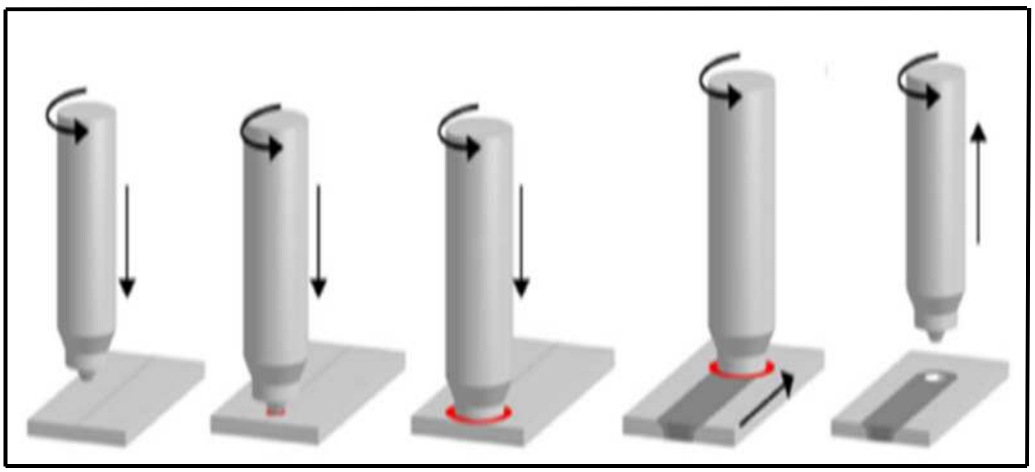


Figure (1.3) The friction stir welding process steps [6].

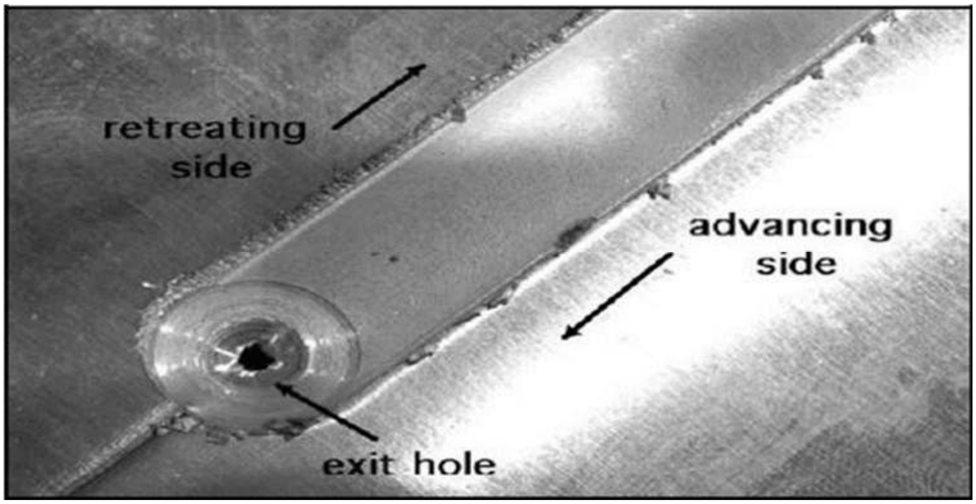


Figure (1.4) Friction stir welding process shows the exit hole. [9] [10] [11].

When the rotation tool direction is the same as the welding direction, it is called the advancing side, while the other side is called retreating side. As the tool moves forward with specific rotation speed and travel speed, the pin is tilted at a specific angle, which controls the weld appearance and makes it thin. The material is moved from the front edge of the tool to the rear edge, and is stirred by the mixing of the pin. Some researcher's said that the stirring process results from pin rotation, and that breaks up the oxide layer. [7]. It is most important that the pin length should be less than the workpiece's thickness to provide full closure to the bottom part of the joint.

1.3.1 Friction Stir Welding Limitations and Defects

1- Clamping the workpieces to prevent the joint from moving away and force are very necessary for this process. These two requirements limit the applications of the friction stir welding process to weld joints with certain geometries.

2- When the tool is lifted at the end of the welding process, a hole will be present, which is undesired in most applications of friction stir welding process.

3- High traverse speeds or low rotation speeds create insufficient weld temperatures, and that makes the material unable to accommodate extensive deformation during the welding process [8].

4- The welding parameters affect the properties of the joint; low forging pressure, short friction time, and low friction pressure makes the welded joint weak and voids will take place [9] [10].

5- When the two workpieces are lightly contacted together it is called a “kissing bond.” Those two sheets will be close to each other, but not close enough, causing defects that are difficult to be detected using non-destructive methods such as X-ray testing.

6- The interface at the bottom of the weld joint may not be disrupted if the pin is not long enough. The consequences of this problem is a lack of penetration defect.

7- Increasing the travel speed leads to hole initiation, near the bottom of the weld joint. Because of the insufficient material flow against the lower part of the weld joint, the size of the hole will increase with the increasing travel speed. Moreover, the wormhole formation mainly depends on the ratio of the rotational speed to the travel speed. The heat generated at the interface between the tool shoulder and the workpieces is higher than between the pin and the workpieces.

8- The processing temperature for the friction stir welding of titanium and its alloys can reach between 700 to 950 ºC, while for steel it's 600 to 875 ºC. Therefore, tool materials should be harder than titanium alloys, such as tungsten carbide with cobalt [9].

9- Studying the stability of both the formability and the microstructure of FSW joints is very rare. In other words, forming FSW welds is challenging because of the limited formability [11].

1.3.2 Friction Stir Welding Advantages

1- Friction stir welding improves the microstructure by creating fine grains and provides excellent mechanical properties to the welding zone such as strength, bending, tensile, and fatigue compared to other welding processes. The efficiency of the joint can reach (70-96%), depending on the materials. Sometimes, the efficiency reaches (100%) if the length of the joint zone is shorter[12].

2- The similar or dissimilar materials are joined together by friction stir welding process without melting; the joint that results is produced in a solid state. Therefore, friction stir welding minimizes/avoids some typical defects encountered in traditional welding, such as porosity, cracking, shrinkage, and solidification.

3- There are no shielding gases, porosity, spatter, arcs or fumes, and no filler materials are required during the friction stir welding process [13].

4- Solidification defects and weld distortion can be eliminated completely.

5- During friction stir welding, high power is not necessary, only an amount of energy to rotate the tool and apply the force that creates the friction heat is required.

6- Friction stir welding has many more characteristics than conventional welding: it saves time and money, it is environmentally-friendly, there is no wasting of materials, it is energy-efficient, has good properties, is pollution free, and its able to weld similar and dissimilar materials that are difficult to fusion weld [14][15][16].

1.3.3 Friction Stir Welding Tool

The friction stir welding tool is the most important part in this type of welding. The quality of welding zone is improved if the tool has excellent properties. The friction stir welding tool consists of three parts: shank, shoulder, and pin (i.e., probe). The shoulder has many functions, including applying pressure on the workpieces and restricting the plasticized material around the pin. The shoulder generates heat because of the friction with the upper workpiece's surface, causing plastic deformation. The main role of the pin is softening, plasticizing, and stirring the materials in the stir zone (SZ). Friction stir welding with special tool designs, shapes, dimensions, and materials improves many mechanical and physical properties including creep, ductility, strength, fatigue, eliminating casting defects, grain microstructure, corrosion resistance and formability [17] [6].

1.3.3.1 Tool Types of the Friction Stir Welding Process

The main roles of friction stir welding tool are heating the workpieces, created by the friction between the pin and shoulder and the workpieces, creating plastic deformation of the workpiece metal, and flow the material and restricting the heat beneath the shoulder. There are three different types of friction stir welding tools: fixed, adjustable, and self-reacting, or bobbin tool. The fixed pin tool is a single piece that includes both the shoulder and the pin. This type of tool can only weld a metal with a specific thickness because the pin length is fixed, and requires a backing anvil to hold the workpieces. The entire tool should be replaced when the pin breaks or wears completely. The second type of tool is the adjustable tool, which has two independent pieces, the shoulder and the pin. Changing the pin length during friction stir welding process is allowed using this tool. When the pin has been damaged, it is very easy to be replaced. Also, pin and shoulder can be manufactured from different materials, but the tool will be weaker than when manufactured using the same type of material for both pin and shoulder. Because the pin length is changeable, this tool can be used for different thicknesses of workpieces. A backing anvil is also required for this type of tool. The self-reacting tool or bobbin tool is manufactured from three different pieces: top shoulder, bottom shoulder, and pin. This tool can be used for joints with different gauges of thickness because the pin length is changeable between these two shoulders. The bobbin tool can work perpendicular to the surfaces, so backing anvil is not needed. However, The bobbin tool cannot be tilted at a specific angle, fixed and adjustable tools can be tilted at a specific angle longitudinally and laterally, which controls the welding zone appearance [4] [18] [19] [20]. Figure (1.5) below illustrates the three types of tools.

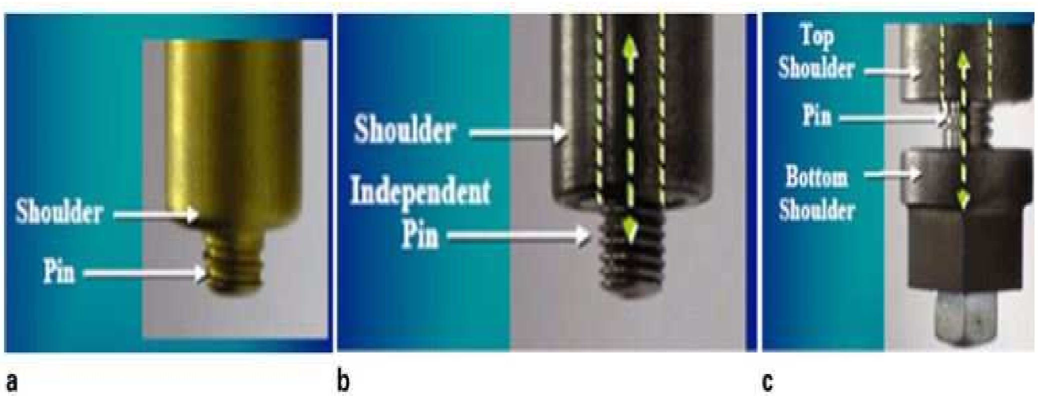


Figure (1.5) Shows tool types (a) fixed, (b) adjustable and (c) bobbin [6].

1.3.3.2 Shoulder Shapes of Friction Stir Welding

Tool shoulders should have a specific design to heat the upper surface of the workpieces, as a result of the friction force. The shoulder provides a downward forging pressure, which is important for welding integration and restricting heated material under the bottom surface. The common shape of the outer surface of the shoulder is a cylindrical shape, but sometimes a conical shape is used. There is no big effect of the outer surface of the shoulder on the welding quality if it's cylindrical or conical, because the plunge depth of shoulder is very small, around 1-5% of the sheet's thickness. The simple design of the shoulder's surface is called flat design. This design is not effective for trapping the flow materials under the shoulder, and provides too much material flash because the end shoulder surfaces are flat. The tool shoulder's other end surface is a concave design, which is very common in the friction stir welding process because it restricts the flow of materials from both sides of the shoulder, is easy to machine, and produces high quality welding. The concave angle is small and reaches between 6 – 10º, this angle goes from the flat shoulder end surface to the pin root. At the rotating tool, the pin feeds the stirring material into the shoulder cavity. The concave shoulder serves as the reservoir for the flow material that comes from the pin. Since the shoulder applies a downward force on the upper surface of the workpieces, the material that is stored in the shoulder concave causes forging pressure behind the tool. The tool movement forces the material to move into the shoulder cavity and pushes the old materials behind the pin. The perfect usage for this type of shoulder design is by tilting the tool during the friction stir welding process between 1-3º against the direction of the tool's travel. There are many of advantages of tilting the tool: it applies a compressive forging force on the welding zone, there is continuity in material storage under the shoulder, hydrostatic pressures, improve nugget zone (NZ) integrity and stirring material around the pin.

Another design of the shoulder is a convex design. It's a successful design because it pushes the material far away from the pin. The smooth surface does not have the ability to prevent the displacement of materials away from the pin, and that causes issues concerning the weld integrity. However, the advantage of convex shoulder design is that shoulder remains in contact with the workpieces' surfaces along the shoulder's end surface. As a result, the differences in thickness between the two joining will be controlled. Other important characteristics of shoulder end surfaces are shear and plastic deformation, which increase the mixing materials and weld quality, as well as the friction. There are different shoulder end styles that are used during the friction stir welding process. These styles include scrolls, concentric circles, ridges, knurling, grooves, and flat that divides into smooth or featureless. The scroll shoulder type consists of a flat surface, so the special spiral channel can cut from the edge to the center. The main advantage of the spiral channel is to allow the material to flow from the end of the shoulder towards the pin. The above characteristics can apply to the concave, flat or convex shoulder ends. Tool lifting can be reduced when the concave design is joined with a scrolled feature. The main advantages of the scrolled shoulder are removing the undercut defect, reducing the flash because of the coupling between the shoulder and the workpiece by the plasticized material, and increasing frictional heat with the surface. Moreover, combining the convex shoulder with the scroll results in many more advantages like greater flexibility between the end shoulder surface and the workpieces. Thus, getting better mismatch tolerance of the welding zone prohibits the material from moving away from the pin, from welding complex curvatures, and from welding metals with different thicknesses [4][20][18][6][19][21]. The figure (1.6) below illustrates the different types of the shoulder.

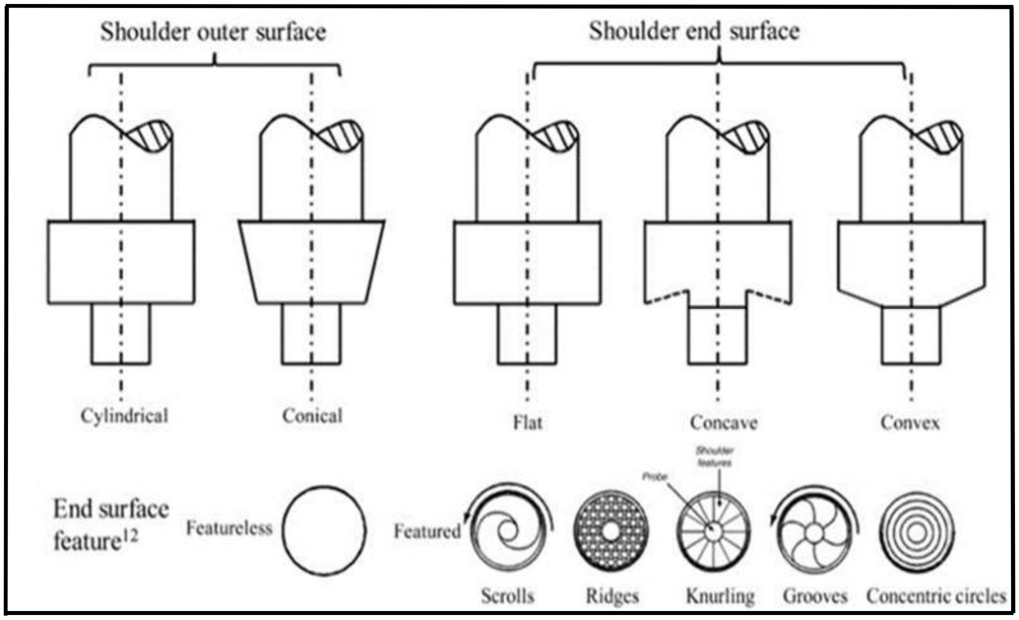


Figure (1.6) Shows shoulder outer surfaces, the bottom end surfaces, and the end features [6].

1.3.3.3 Pin Shapes of Friction Stir Welding

The main functions of the pin in the friction stir welding process include frictional heating and deformational, cutting the materials in front the tool, damaging the edges of the workpieces, and stirring and mixing the materials behind the tool. There are two different end shapes of the pin flat and domed, figure (1.7). The flat design is very easy to manufacture, and is the most commonly used in the friction stir welding process. The flat design can provide high forge force at plunging step, and can reduce forge force and tool wear. On the other hand, the domed design can improve the joint root at the bottom of the pin and improve the tool life by reducing the stress concentration in the joint zone. All the above domed advantages will be maximized when the dome radius at the pin end is equal to 75% of the pin diameter. The velocity of the cylindrical pin can be increased from zero to the maximum from the center to the edge, respectively. When the pin edge has high velocity and stirring power, the flow material will increase at the pin end. The lowest velocity of the pin and stirring action have been found at the lowest point of the bottom pin. Friction stir welding pin has two very common outer surface shapes, cylindrical and tapered. For cylindrical pin design, it is very useful for joining different metals, until the thickness reaches 12 mm. Thicker metals require the operating welding process to have high rotational and low travel speeds to provide high weld integrity. The frictional heat that results by using a tapered pin increases the plastic deformation because a tapered pin has a good contact area with the workpieces. Also, it provides high hydrostatic pressure in the joint region, and this is important for increasing the nugget integrity and materials stirring. However, these features of the tapered pin can lead to sharp tool wear. There are different shapes and features for the outer surface of the pin; these shapes include threads, flat or flutes. Even though the materials used to manufacture the pin have high strength and high corrosion resistance, threaded can be easily corrosive. However, threaded pins are the most frequently used in the friction stir welding process. Void closure, materials stirring, and oxide layer breakdown can be improved by two factors: the material circulating two times around the pin before depositing, and the threaded pin rotating the materials clockwise to be drawn down along the pin surface as shown in Figure (1.7) [22][20][4][23][24].

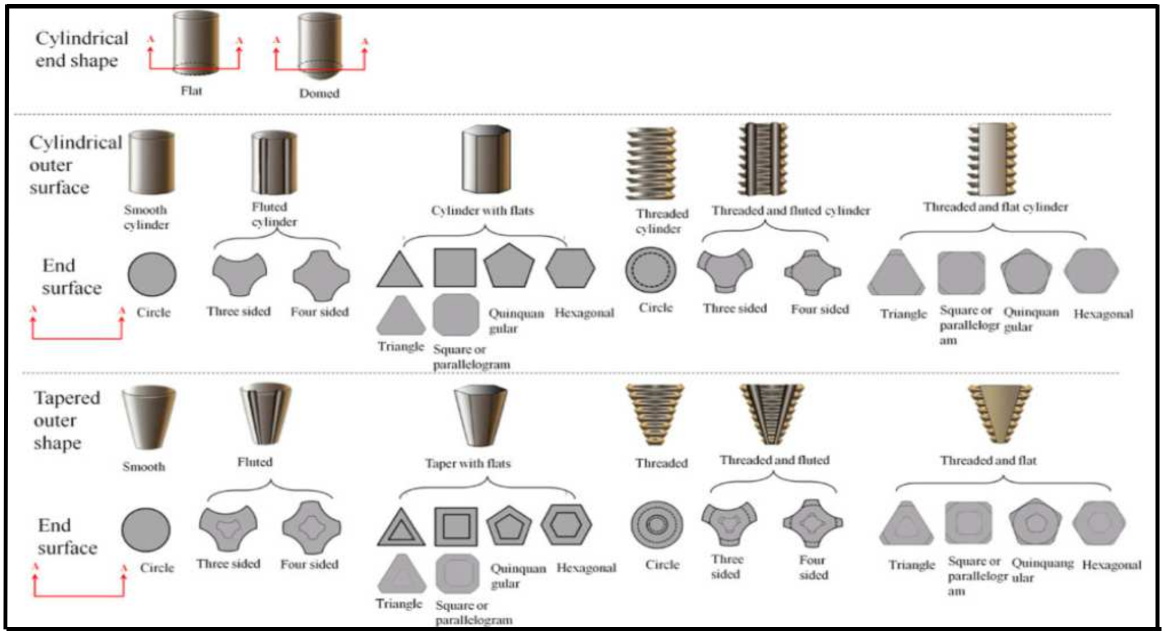
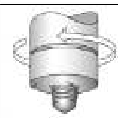
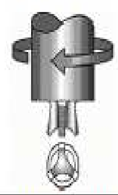
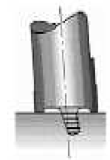
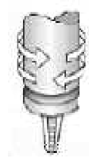


Figure (1.7) Shows the pin shapes and their main features [6].

There are three different types of tapered pin designs: non-threaded, threaded, and threaded with flats. Threaded and threaded with flats pins provide completely unified welds, whereas the non-threaded design produces voids in the welding zone. The material is restricted in the flat, then can be released, which improves the mixing. Also, the temperature and NZ width can increase if there is an increase in the flats. Pins with flat shapes can behave as the cutting edge. In general, the cylindrical threaded pin has been used for aluminum alloys of thicknesses of over 12 mm with a butt joint. However, for thicker workpieces, some of the features should be added to improve the flow and mixing of materials as well as to reduce the friction stir welding loads. The most important parameter in friction stir welding is the tool design. Tool designs with high swept rates can reduce the voids, increase the stirring and the mixing of materials, and scatter the oxide layer in the nugget zone. Much of the tool’s design was developed by welding institutes such as Whorl and MX Triflute. These types of tools can reduce the volume about 60-70% as shown in Table (1.1). These types include straight cylindrical, threaded cylindrical, tapered cylindrical, and triangular. The tool geometry plays an important role in the friction stir welding process, especially in the material flow, and in turn governs the travel rate.

Table (1.1) A selection of tools designed at TWI [23] [6].

Tool	Cylindrical	Whorl™	MX triflute™	Flared triflute™	A-skew™	Re-stir™
Schematics						
Tool pin shape	Cylindrical with threads	Tapered with threads	Threaded, tapered with three flutes	Tri-flute with flute ends flared out	Inclined cylindrical with threads	Tapered with threads
Ratio of pin volume to cylindrical pin volume	1	0.4	0.3	0.3	1	0.4
Swept volume to pin volume ratio	1.1	1.8	2.6	2.6	depends on pin angle	1.8
Rotary reversal	No	No	No	No	No	Yes
Application	Butt welding; fails in lap welding	Butt welding with lower welding torque	Butt welding with further lower welding torque	Lap welding with lower thinning of upper plate	Lap welding with lower thinning of upper plate	When minimum asymmetry in weld property is desired

1.3.4 Joint Design of the Friction Stir Welding Process

The most suitable joints which used during the friction stir welding process are butt and lap joints. The lap joint is harder than the butt joint during the friction stir welding process for many reasons: wider welds are required to move the loads, hooking defects should be avoided to get maximum fatigue strength, and the oxides that are found at the workpiece interface are difficult to disrupt the lap order. Butt joints consist of two plates clamped together firmly to prohibit the joint from moving away. These plates have the same thickness and are placed on the backing plate. When the tool is inserted into the butt joint between these two plates, take care and ensure that plates will not move because the forces are higher. The tool pin plunges and rotates in the butt join and then travels along the joint line. Because the shoulder is in direct contact with the upper surface of the plates, a welded long butt joint is produced. For lap joints, two plates are clamped on the backing plate, then the tool is rotated vertically and travels along the proper direction. For the friction stir welding process, there is no special preparation of the surfaces necessary for each butt and lap joint. In other words, the metals can be joined without any concern about the condition of the surfaces. Figure (1.8) illustrates the different types of joints[21].

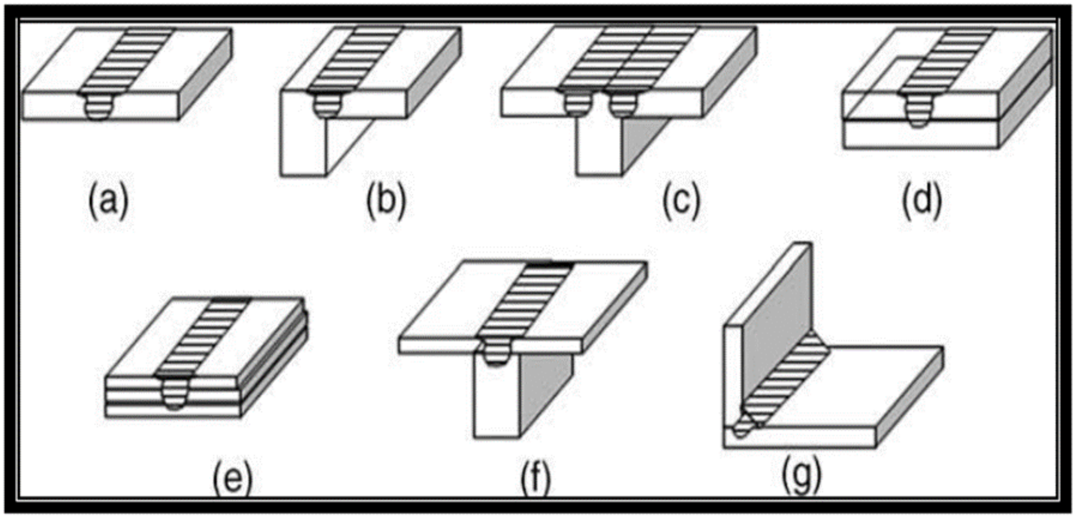


Figure (1.8) Joint configurations for FSW: (a) square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint and (g) fillet joint [11][17][22][43].

1.3.3.4 Tool Dimensions of Friction Stir Welding

The tool dimensions are a critical issue in the friction stir welding process. The manipulation of these dimensions can change the results of the process, and even the mechanical properties. In general, the diameter of the tool pin should be same the thickness of the workpiece, while the height of the pin should be a little bit less than the thickness. Further, the shoulder diameter should be between 3-5 times the pin's diameter. The shoulder radius to the third power can determine the heat input during the friction stir welding process. This heat linearly depends on the rotational speed as well as the downward forge force. That means the energy input in the friction stir welding process depends on the shoulder dimensions. The equation below illustrates all of these points, and also shows that the Z axis of the downward force is a function of the shoulder radius.

$$Q_0 = 4/3\pi^2\mu_k P\omega R^3 \quad \dots\dots\dots \quad (1.1)$$

$$F_f = \mu_k Fn \quad \dots\dots\dots \quad (1.2)$$

Where the symbol Q_0 means the net power, $4/3\pi^2$ is a constant, μ refers to the friction coefficient between the pin and shoulder and the workpieces, which are dimensionless, P means pressure and is measured in (MPa), R is the shoulder radius (mm), ω refers to the rotational speed (rev/min), F_f is the frictional force (Newton), and F_n represents the normal force (Newton). The shoulder diameter is regarded as the function of the plate's thickness or the pin diameter. This relationship means that with an increase in the sheet thickness, an increase in energy is required. Thus, the shoulder diameter required to generate heat must be large.

1.3.3.5 Tool Materials of Friction Stir Welding

Choosing the tool material used for friction stir welding process is very important issue because it determines the quality of the welding joint. The characteristics for these materials are critical. Selection of the tool material for the FSW process depends on many of factors, including the workpiece material, the user's own experience and performance, and the tool life. Therefore, the suitable tool material used in the friction stir welding must meet the following properties. First, the materials must have high strength, creep resistance and dimensional stability. Second, the compressive yield strength at the operating temperature should be higher than the stresses due to forces applied on the tool by the machine. Third, the thermal fatigue strength should be resistant to the repeating of heating and cooling cycles. Fourth, a harmful reaction of the workpiece material with the tool material should not take place. Fifth, the fracture toughness should be high to resist the damage that happens during the plunging and dwelling process. Sixth, the thermal expansion coefficient between the pin and the shoulder material should be low to reduce the thermal stresses. Seventh, a thermal barrier coating should be used to stop heat from moving into the shank part of the tungsten carbide tool. Eighth, the machinability must be good to ease the manufacture of different shapes for each shoulder and pin. Finally, the tool material should be affordable.

There are many materials that can be used to manufacture friction stir welding tools. Each material has good and non-good properties, depending on the type of material being welded. These materials include steels, carbide particle reinforced composites, tungsten carbide with cobalt, titanium carbide, tungsten carbide, nickel alloys and cobalt base alloys, refractory metals, ceramic materials, and polycrystalline cubic boron nitride (PCBN). Soft materials, such as aluminum, are welded using steel tools such as H13. Tungsten carbide with cobalt based material and polycrystalline cubic boron nitride (PCBN) are used for hard materials such as titanium and its alloys.

Carbide materials, such as tungsten carbide, are widely used as a tool material in the friction stir welding process. This type of tool offers many mechanical properties. First, it has excellent toughness and wear resistance at ambient temperature. Second, it has excellent fracture toughness for the pin and shoulder at ambient temperature. Third, it has hardness that reaches 1650 HV. Fourth, it is insensitive to sudden changes in temperature and loading. Finally, there is little deformation regarding the chemical inertness of the materials.

To date, tools for welding and processing have been well developed for specific materials that have low strength like aluminum alloys. These tools are relatively low cost and have a long life. However, a tool with low cost and a long life used during the friction stir welding process is still unavailable for many materials; these materials include abrasive materials and high strength and hardness materials such as titanium, nickel, and steels[4]. Tool materials affect many properties of the welded joint; these properties include the microstructure of the joint, heat generation, thermal conductivity, and thermal stresses of workpieces [20][21][4][18][19][25][24][21].

Table (1.2) Tool materials and suitable weld metals [19].

Tool Material	Suitable weld material
Tool steels	Al alloys, aluminum metal matrix composites (AMCs) and copper alloys
WC –Co	Aluminum alloys, mild steel
Ni-Alloys	Copper alloys
WC composite	Aluminum alloys, low alloy steel and magnesium alloys, Ti-alloys
W-alloys	Titanium alloys, stainless steel and copper alloys
PCBN	Copper alloys, stainless steels and nickel alloys

Table (1.3) Materials joined by friction stir welding using WC tool material [19].

No	Materials used
1	A3003-H112 Al alloy 15 mm thick & SUS304 (SS) 12 mm thick.
2	Al. alloy 1060 and titanium alloy Ti–6Al–4V plates 3 mm thick
3	Plates of SK4 high carbon steel alloy (0.95% C). 2 mm thick
4	Hyper-eutectoid steel (0.85mass% C, AISI-1080), 1.6 mm thick
5	SAF 2205 duplex stainless steel. 2mm thick
6	High carbon steel S70C (0.72 wt. % C). 1.6 mm thick
7	Carbon steels IF steel, S12C and S35C 1.6 mm thick plates

1.3.5 Friction Stir Welding Parameters

The parameters that are very important for friction stir welding process include the rotational speed (ω, rpm), where the direction can be either clockwise or counterclockwise. Second parameter is travel speed, which is mesared along the line of the welding joint. Travel speed symbol and unit are v and mm/min, respectively. Third parameter is a tilt angle. A suitable tilt direction will guarantee that the tool shoulder holds the material by the threaded pin from the front to the back. Moreover, tilting the tool influences the weld appearance and thinning. A suitable tilting angle for the friction stir welding tool is between 1-3°. The last welding parameter is the downward axial force of the tool shoulder on the workpiece that is applied by the machine.

Some of the researchers showed that perfect welding by friction stir welding is very difficult because the heat generated by the friction depends on controlling the above four factors. [13]. Applying low rotational speeds and high axial pressure during friction stir welding produces a high rate of deformation, and this results in a short weld time. On the other hand, high rotational speed and low axial pressure produces a relatively low rate of deformation. The optimum friction time for welding two sheets during friction stir welding depends on many factors. These factors include dimensions, material composition, rotational speed and friction pressure. If the friction time is too short, the heating distribution will become irregular, and the bond strength will be weak in some regions. Moreover, when the heating time exceeds the optimum time, productivity will decrease while increasing the material consumption. Material consumption leads to coarse grain structure [8].

Table (1.4) Main process parameters in friction stir welding [18] [13].

Parameters	Effects
Rotational speed	Friction heat, “stirring,” oxide layer breaking and mixing of materials
Tilting angle	The appearance of the weld, thinning
Welding speed	Appearance, heat control
Down force	Friction heat, maintaining contact conditions.

1.3.6 Zones in Friction Stir Welding Joint

Many complex interactions can happen between sorts of simultaneous thermos mechanical processes during the friction stir welding process. These interactions can affect many parameters; the mechanical integrity of the joint, dynamic recrystallization phenomena, and plastic deformation and material flow. The joint cross section of the friction stir welding process typically consists of a specific number of zones, these zones are (a) stirred weld zone SZ, or nugget zone NZ, which is in the center of the joint where the pin has passed (b) Thermo-mechanically affected zones TMAZ, this zone is intermediate on each side of the stirred zone (c) heat affected zones HAZ, this zone is adjacent to the TMAZ, and faces a thermal cycle but not a mechanical shearing (d) and the unaffected parent material or base metal BM. All these zones are illustrated below in Figures (1.10) and (1.11). In the stir zone, the refine grains are equiaxed and are attributed to dynamic recrystallization, and happen because of the heat and mechanical work. These fine equiaxed grains are less in magnitude than that of the base metal. The base metal in the friction stir welding cross section consists of elongated grains that go in the rolling direction. The heat affected zone in the friction stir welding process usually contains a large amount of coarsened grains with relatively low yield strength compared to that of the thermo-mechanically affected zone and the stir zone. As a result, the heat affected zone will be the weakest zone during the crack initiation in different tests such as fatigue and tensile strength. Since the shoulder contacts the upper surfaces of workpieces, this leads to a series of concentric semicircular rings in the center of the nugget zone. These rings, sometimes called “onion rings”, disappear when the rotation speed is increased. In addition, the rings will not take place if the tools are not threaded. Also, the ring feature is not visible for some alloys such as an aluminum alloy. The ring feature occurs for more than one reason. These reasons include either periodic variations in the crystallographic orientation of grains or the relative orientation of adjacent grains. However, differences in grain size will not result in the rings [26][27][24][21][28][29][30][31][32].

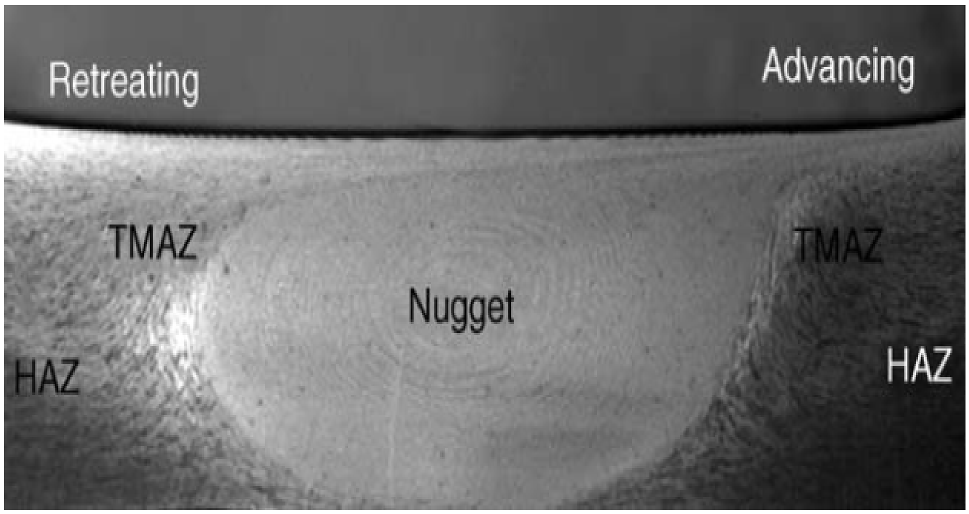


Figure (1.9) The microstructural zones in a friction stir weld [34][21][60].

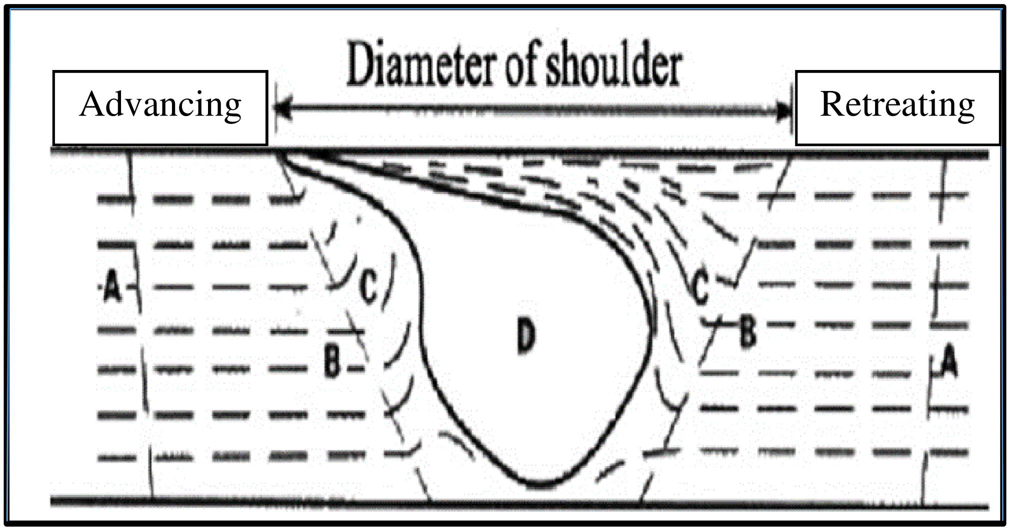


Figure (1.10) Schematic cross-section of a typical FSW weld showing four distinct zones: (A) base metal, (B) heat-affected, (C) thermos mechanically affected and (D) stirred (nugget) zone [26][33].

1.3.7 Material Flow and Mechanism of Joining during Friction Stir Welding.

Many of the experimental and computational work conducted recently on different materials using the friction stir welding method provided important features and joining methods. During friction stir welding, the plasticized material near the tool forms in the stir zone. However, most of the material flow happens on the retreating side. There are three important types of flow that affect the plasticized material transferring behind the tool. The first flow is near the tool, so a slug of plasticized material rotates around the tool. The result of this type of flow will be friction between the tool and the workpiece. The second type is the rotational motion of the threaded pin pushing the mixing material downward. The pushing is close to the pin, which drives an equivalent amount of material in the upward motion. The third type illustrates a motion between the tool and the workpiece, and this motion is relative. The simultaneous interaction of the above three types of flow and their effects results in the formation of the welded joint as well as the total motion of the softened materials [33]. The materials' velocities around the pin can be predicted by plastic flow models for friction stir welding [33].

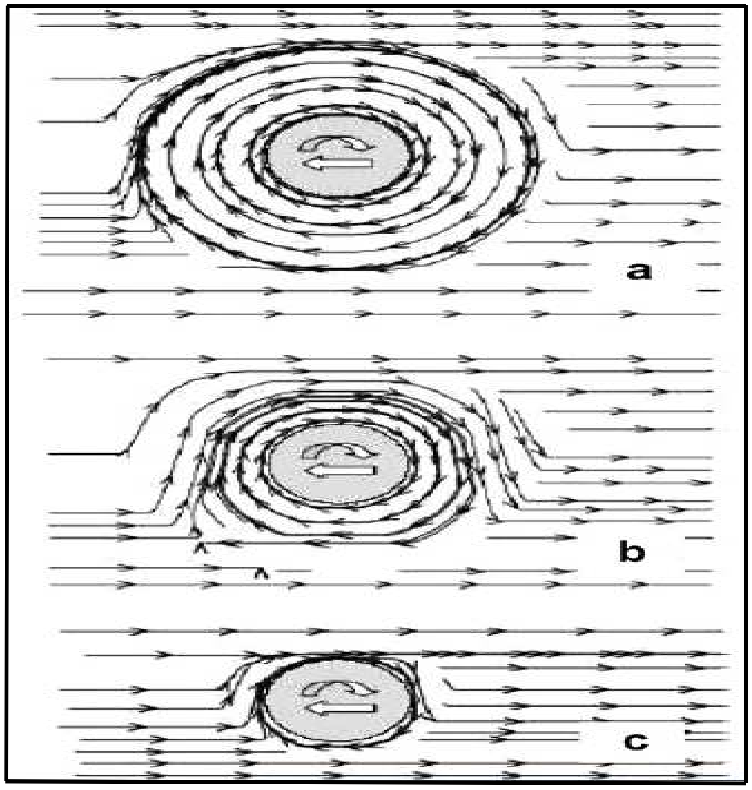


Figure (1.11) Stream traces on different horizontal planes (a) 0.35 mm, (b) 1.59 mm and (c) 2.28 mm below the top surface for a 304 stainless steel plate of thickness 3.18 mm. Welding speed 4 mm/s with tool rotation at 300 rpm [26][33].

Friction stir welding can be considered as a metalworking process with five conventional zones. These zones involve preheat, initial deformation, extrusion, forging, and post heat/cool down, figure (1.12). The temperature will rise at the head of the pin in the preheat zone for two reasons. These reasons are adiabatic heating due to the deformation of material and the frictional heating due to the rotation of the tool. The heating rate and extent of preheat zone are governed by the travel speed of the tool and the thermal properties of the workpiece. The initial deformation zone forms as the tool moves forward.

This formation happens when the workpiece is heated above the critical temperature, and the stress exceeds the critical flow stress of the material. These two reasons of forming the deformation zone leads to the material flow. The material in the initial deformation zone is forced downwards into the extrusion zone and upwards into the shoulder area, as illustrated in Figure (1.12). The extrusion zone location is around and at the end of the pin. In this region, where vortex flow patterns exist, a small amount of material is captured in the swirl pin specifically under the pin tip. Moreover, material flows around the pin from the front to the back because there is a finite width in the extrusion zone. The width of this zone is defined by the critical isotherm on both sides of the welding tool, where the temperature and the stress in this region are not be adequate to allow metal flow. When the material is in front of the welding tool and then is forced into the shoulder reservoir, it is called the forging zone. This process occurs when the pin moves under hydrostatic pressure. The tool shoulder has two very important functions; applying a downward forging force and restricting the material in the cavity. The material beneath the tool shoulder is dragged into the joint zone; this dragged material starts from the retreating side and moves across the advancing side. The final zone is post heat/cool down zone which is located behind the forging zone. In this zone, the material can cool under either forced cooling or passive conditions. Finally, material flow can be influenced by the material type, and material temperature [19] [30].

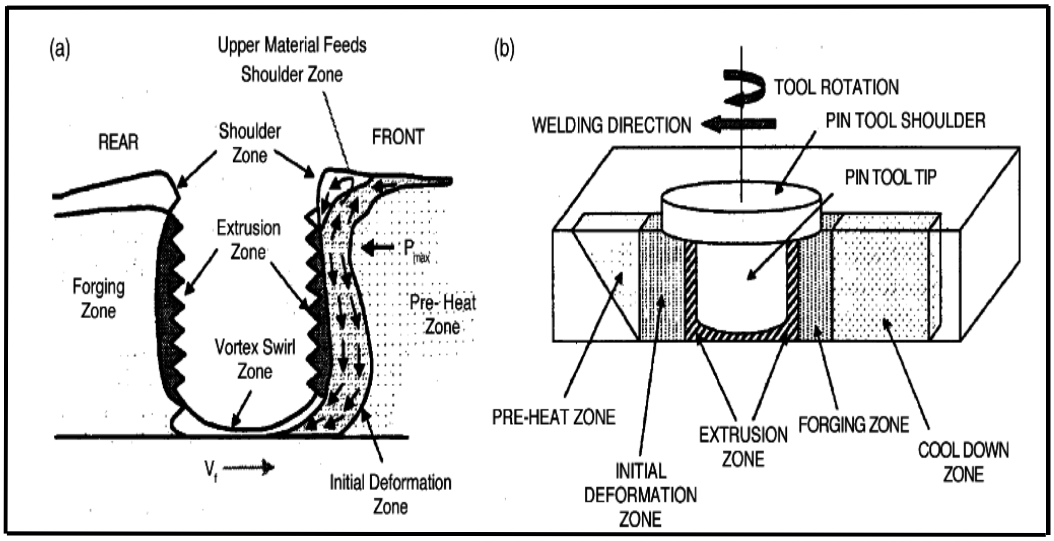


Figure (1.12) (a) Metal flow patterns and (b) metallurgical processing zones developed during friction stir welding [17].

1.3.8 Friction Stir Welding Applications

There are several applications for materials that are welded by using the friction stir welding process as this process has many characteristics such as low cost and weight saving. For example, aluminum alloys such as 2XXX and 7XXX series that have high strength and are widely used in aerospace industries. These alloys are difficult to weld together using traditional welding because of the hot cracking that occurs during welding. Also, some of the precise applications require different properties, and these properties cannot be attained by solitary materials. Today, friction stir welding between dissimilar materials plays an important role in advanced manufacturing technology, especially in aircraft manufacturing. Dissimilar joints of aluminum and aluminum to steel are widely used in petrochemical, cryogenic, and aerospace industries. Joining magnesium to aluminum and its alloys can be used in many of industries because of they are lightweight.

Therefore, they achieved high efficiency and excellent performance [10]. Generally, the most important applications of the friction stir welding process are: -

1- Friction stir welding can be used in aerospace industry on many parts such as fuselages, wings, empennages, and fuel tanks for space vehicles.

2- Shipbuilding and marine industries can use the friction stir welding method to join parts such as sides and panels for decks, bulkheads, and floors.

3- Friction stir welding can be used in railway industries for rolling stock of railways, high speed trains, underground carriages, and building of container bodies.

4- Friction stir welding can be used in the electrical industry for electrical connectors and electric motor housings.

5- Some alloys that are welded by this type of welding can be used in the construction industry and the chemical industry and for aluminum reactors for power plants.

6- Friction stir welding can be used for alloys that have high strength, which can be used as armor [21].

7- Friction stir welding joints can be used in land transportation for automotive engine chassis, truck bodies, and wheel rims.

CHAPTER 2 : LITERATURE REVIEW

2.1 Overview

This chapter illustrates that friction stir welding is a joining process is used to weld similar and dissimilar materials under the melting point of the base metal. This process is widely used for different alloys like aluminum, copper, magnesium, and steel, but it is hard to conduct on very tough materials with high thicknesses, like titanium and stainless steel. This chapter discusses some research of the friction stir welding process on titanium, aluminum, stainless steel, 1018 steel, and copper done by researchers in recent years [1] [2].

2.2 Friction stir welding between (Ti-6Al-4V) and (304 SS)

Muralimohan. [10] studied the friction welding process between two dissimilar materials, like titanium and stainless steel, using friction stir welding. The reason this was studied is because titanium and its alloys have unique properties that other metals do not have. These properties are high toughness and strength, good resistance to corrosion, a high melting point, and low density. During this study, important tests, like the tensile test, bending test, and hardness test, were conducted on the friction stir welding joint, after comparing them with the HAZ, TMAZ, and BM zones. In addition, the heat distribution and the microstructure of the friction stir welding joints were investigated. Gao Yefei et al. [14] showed in their research that the strength of the welding joint resulting from friction stir welding between titanium and 304 stainless steel depends completely on the brittle intermetallic compounds. This study illustrates that reducing these compounds will increase the strength of the joint. In addition to the brittle intermetallic compounds phases, such as FeTi, Fe2Ti, which make using conventional welding methods impossible, the direct welding of titanium and stainless steel is also limited because of high expenses. Moreover, this research showed that there are still some problems with the parameters of friction stir welding which affect the microstructure of the joint.

Ameth Fall et al. [34] aimed their work on checking the microstructure as well as the tool wear using Energy-dispersive spectroscopy(EDS) and optical and scanning electron microscopies (SEM) methods. This work showed that the radial tool wear of the pin part is not regular. Titanium alloy (Ti-6Al-4V) with 100 mm length, 50 mm width and 2mm thickness were welded using the friction stir welding method with a tungsten carbide tool (WC). The titanium alloy was annealed, and its mechanical properties were: hardness 344 VHN, yield strength 910 MPa, tensile strength 994 MPa, and elongation 17.2 %. The friction stir welding parameters used five times in this investigation are rotational speed (500, 700, 1000, 1250, and 1500 rpm) and travel speed (100, 100,100, 100, and100 mm/min). The tool material was tungsten carbide because it is harder than what was welded. Tungsten carbide particles were 3 and 200µm, so as to not affect the crystallization. The examination of all conditions showed that there are three zones; stirred zone (SZ), heat affected zone (HAZ), and base metal (BM).

Y. Zhang et al. [26] studied the friction stir welding joint of (Ti-6Al-4V) alloy at different rotational speeds, between 300 to 600 rpm, to clarify the relationship between the mechanical properties, the welding parameters, and the microstructure. In this work, the plate thickness was 3mm, the travel speed was 1 mm/s, and the plunged depth was 2 mm of the welding tool. An increasing in rotational speed increases the size of the phases α and β grains while the hardness value of stir zone decreases. The stir zone had a higher hardness than the base metal and the heat affected zone. The tensile test showed that all the joint's fracture was in the heat affected zone because it has lower strength and elongation than the base metal. The same analysis revealed that the stir zone exhibits better elongation and strength than the base metal. Moreover, this research proved that the microstructure for titanium in the stir zone is fine lamellar (α + β), while it is bimodal in the heat affected zone. M. Balasubramanian. [35] illustrated that titanium is chemically active, so it is very difficult to join titanium using traditional welding (e.g., arc welding). This is due to cast structure, deformation, and residual stress, as well as the existence of intermetallic compounds. In this investigation, the researcher used a titanium alloy, 304 stainless steel, and a silver interlayer. The dimensions were 50 mm x 50 mm x 5mm. The bonding did not occur over 825 Cº, but was very successful between the temperatures 750 Cº and 800 Cº for the dissimilar materials. Bonding pressure was 5 MPa at 90 min, and that provides ultimate shear strength.

Cheepu et al. [36] showed that solubility is limited between the elements Ti and Fe, and Ti and Cr because intermetallic compound phases form at the interface joint, and these compounds are brittle. The tool geometry, plunge depth, and rate of heating are a function of the travel speed, while the maximum temperature is a function of the rotation rate. The equation below illustrates the relationship between the temperature and friction stir welding parameters.

$$W = \frac{HI}{\nu} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (2.1)$$

Where ν is the tool travel speed (mm/min), HI is the pseudo heat index, and W is the work. Further, this research showed that the tapered tool design should be used during friction stir welding because titanium has low conductivity. The friction welding energy includes the heat generated either by the friction or by the work that allows the material flow. The total friction welding heat is equal to the heat created either by the plastic dissipation or by the friction between both the pin and shoulder with the workpieces. The heat generated by the plastic dissipation is produced by the heat of the stirred material minus the heat lost by conduction. The equations below show the amount of the heat generated during the friction stir welding process.

$$Q = Q_{friction\ heat} + W_{material\ flow} \quad \ldots\ldots\ldots\ldots \quad (2.2)$$

$$Q_{heat} = Q_{friction\ heat} + Q_{plastic\ dissipation} - Q_{conduction\ losses} \quad \ldots\ldots\ldots \ (2.3)$$

$$Q_{heat} = Q - W_{material\ flow} + Q_{plastic\ dissipation} - Q_{conduction\ losses} \quad \ldots\ldots\ldots\ldots \ (2.3)$$

Where Q is the energy or heat generation rate term, and W is the work.

Dey et al. [37], Fazel et al.[38], Kimura et al. [39] Kumar et al. [40], Lee et al. [2], Secietyt et al. [41], Nallappan. [42], and Mishra et al. [43] all studied the friction stir welding process between titanium and stainless steel. They showed the composite carbides, which consist from particle reinforced, can be used as a tool material. These materials are tungsten carbide and tungsten carbide with cobalt. Important properties for this tool material are plausible toughness and excellent wear resistance. The strength of the WC-CO tool is higher than Ti-6Al-4V alloys at all temperatures. Also, the displaced volume could result in the pin features. These features include both the threaded tool and stepped spiral tool, figure (2.1). An effective radius is required to estimate the displaced volume. The pin depth is used for both the outer and inner radius to provide the strict calculations. The equations below illustrate the pin volume with R and r for the outer and inner radius, respectively.

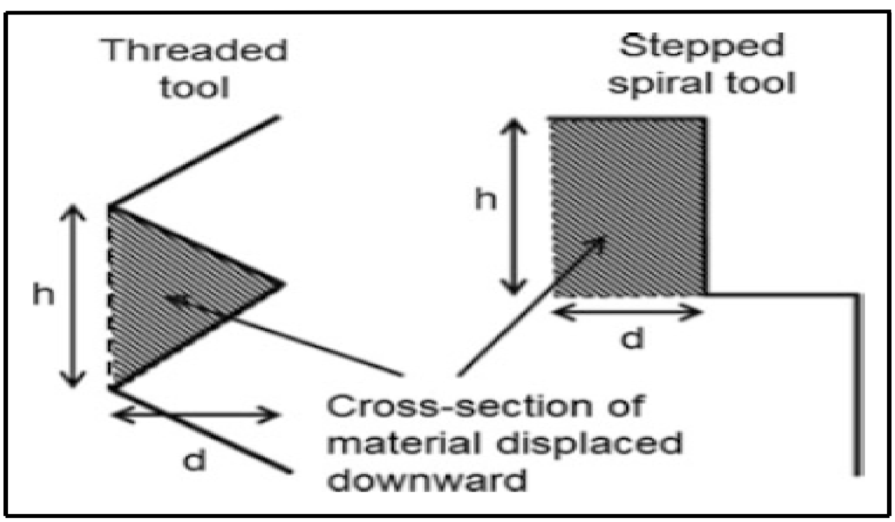


Figure (2.1) Illustration of displacement of volume by pin feature for a threaded tool and stepped spiral tool

$$\frac{1}{2}\text{h x d x } \left(2\pi\left(\frac{R+r}{2}\right)\right) \text{ For threaded tool………… (2.4)}$$

$$\text{h x d x } \left(2\pi\left(\frac{R+r}{2}\right)\right) \text{ For stepped spiral tool……… (2.5)}$$

The symbols in the above equations represent; $d = (\frac{h2}{4} + (R - r)^2)^{1/2}$ for the threaded or even the width of the spiral tool, h is the thread pitch. The spiral tool has a larger downward of the material than the threaded tool. There was a good comparison between the downward of material and the horizontally displaced volume. Horizontally displaced volume can be roughly estimated for one cycle of the tool as shown below [52] [51] [53].

$$\text{H x } \frac{\text{tool traverse rate in mm/min}}{\text{tool rotation rate in rpm}} \text{ x } \left(2\pi\left(\frac{R+r}{2}\right)\right) \text{ For both types of tools……. (2.6)}$$

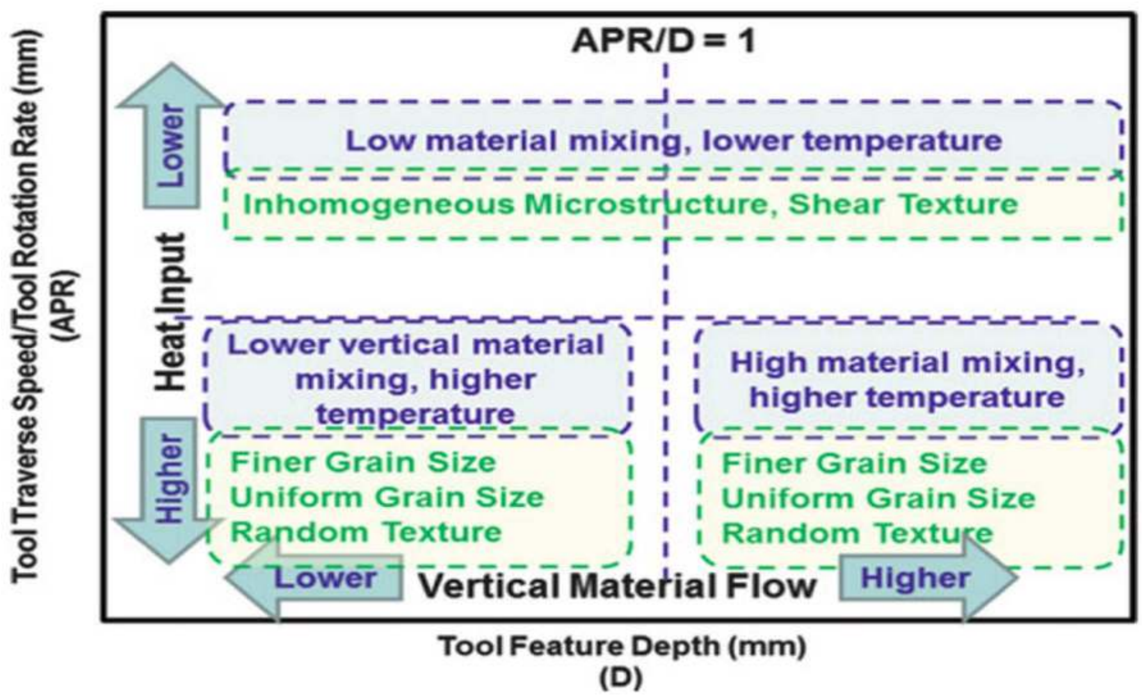


Figure (2.2) An example of conceptual map showing various domains as a function of process parameter and tool feature [51].

2.3 Friction Stir Welding between Al (6061-T6) and Copper 110

Jiahu et al.[44] studied the temperature distribution and the microstructure of the friction stir welding process between Al (6061-T6) to 99.9 % copper joint. Intermetallic compounds existed in the joint area. Those compounds included $CuAl_2$, CuAl, and Cu_9Al_4. The temperature distribution at the bottom of the nugget zone was numerous and the solid-solubility was high. The problem in friction stir welding of copper with other metals is conductivity. The high conductivity of copper dissipates the heat generated into the backing anvil, so the temperature in the joint area insufficient for welding. He discovered that the maximum temperature of the aluminum side was 580 Cº, and this is higher than the Al–Cu melting points. The welding parameters used in this research were rotation speed of 914 rpm and travel speed of 95 mm/min. The friction stir welding tool for this work was manufactured from steel material. Xue et al. [45] studied the friction stir welding process between Al (1060) and 99.9 % copper. The metallurgical bonding between these two different materials was excellent. However, a thin uniform layer of the intermetallic compounds at the nugget zone occurred. The tensile test fracture occurred on the aluminum side in the heat affected zone, which means that zone was weaker one. The welding parameters used during this process were 600 rpm, 100 mm/min for rotation speed and travel speed, respectively. Many tests were investigated, including (EPMA), (XRD), (SEM), (TEM), (EDS), and (XRD). XRD is a test which is conducted on the specimen surface before and after dissolving.

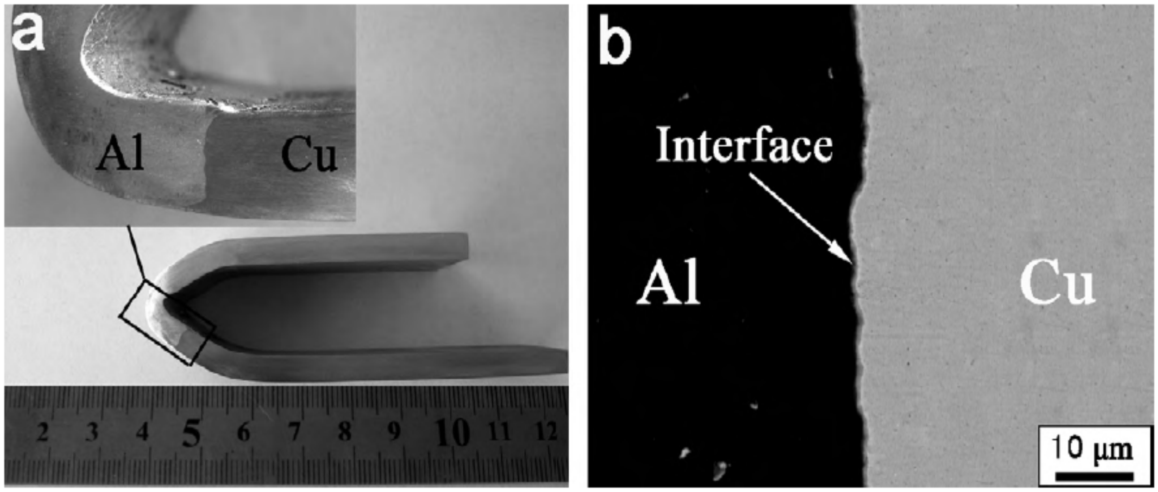


Figure (2.3) (a) Macrograph of the joint after bending test, (b) magnified SEM backscattered electron image of the interface region [45].

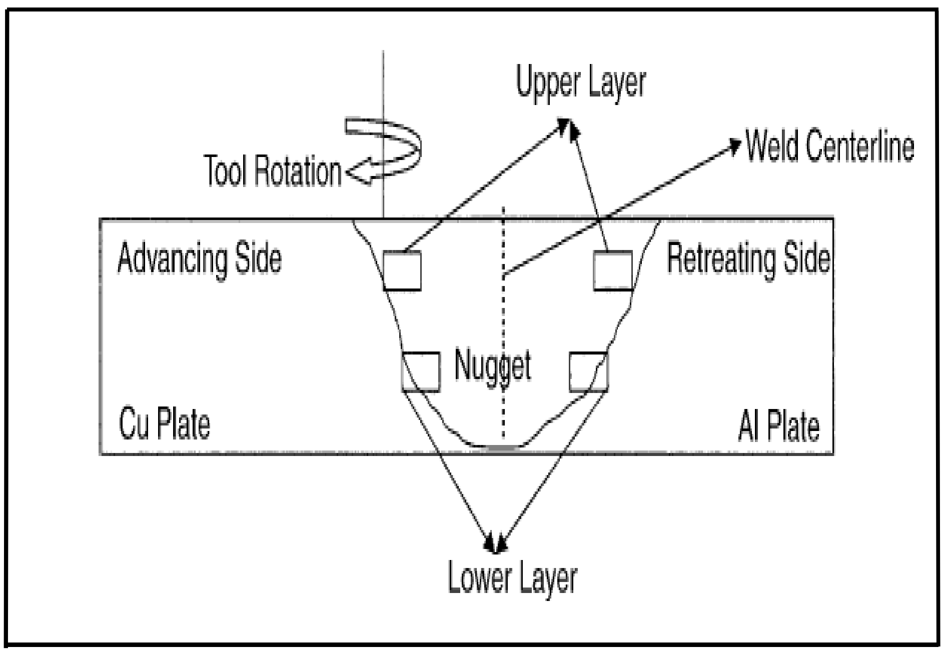


Figure (2.4) The cross sectional view representation of friction stir welded (6061) aluminum alloy and copper plate showing the positions upper layer, lower layer and the weld nugget [44].

Galvão et al. [46] examined the effect of the shoulder design on the formation and distribution of the intermetallic compounds between aluminum and copper. Two different designs of the shoulder were used, scroll and conical. The welding parameters were the same while the shoulder geometry was different. The scrolled shoulder design provided a mixing zone, composed of $CuAl_2$. However, the conical design provided some heterogeneous mixing compounds including CuAl2 and Cu9Al4. LI Xia et al. [47] used pure copper and 1350 aluminum sheets with 3mm thickness for the friction stir welding process. Most of the pin diameter was on the aluminum side with a rotation speed of 1000 rpm and a travel speed of 80 mm/min. There was no formation of intermetallic compounds in the nugget zone, and the microstructure was more complicated in this zone in that it had lamella structure. The hardness of the nugget zone on the copper side, especially at the bottom region, was higher than the aluminum side. The tension test showed that the ultimate tensile strength is 152 Map, while the elongation is 6.3%. Balram et al. [48] used three different welding parameters in their research: rotation speed, travel speed, and shoulder diameter. The ultimate tensile strength value was 140 MPs. This research showed that the tool geometry affects the butt joint properties, like the microstructure, because parameters were variable.

2.4 Friction Stir Welding between Al (6061-T6) and (1018 steel)

Many researchers have performed friction stir welding between Al (6061-T6) and (1018 steel) to study the mechanical properties and metallurgical analysis, such as the hardness, tension test, bending test, micro hardness, and the microstructure. Emel et al. [49] studied the properties of the welded zone between the aluminum and steel materials; those properties included the micro hardness, tension, and bending tests, rather than the microstructure. Tensile test strength was 170 MPs for low upset pressure and 250 MPs for high upset pressure. The tensile strength fracture occurred on the aluminum side in the plasticized region. A thin layer of the intermetallic compounds occurred in the joint area with 250 nm thickness; those compounds were FeAl and Fe2Al5 phases. Chen et al. [50] worked on joining the Al (6061-T6) and (1018 steel) sheets using the friction stir welding method with 6 mm thick layer of each material. The tool used for this welding was manufactured from steel material and was then inserted into the butt joint. The tool dimensions were 24 mm and 5.5 mm for the shoulder and pin diameters, respectively. In this research, the aluminum sheet was on the advancing side while the steel was on the retreating side. An optical microscope was used to find the metallographic analyses. The intermetallic compounds were explored and existed in the joint area, specifically in the nugget zone; those compounds included $Al_{13}Fe_4$ and Al_5Fe_2. At rotation speed of 917 rpm and after 100 mm distance, the tool broke. Also, the microstructure analyses showed that the welded zone between aluminum and steel was a heterogeneous zone. Other research, such as by Emel et al. [51] has shown that the welded zone has other intermetallic compounds. Those compounds include FeAl, Fe_2Al_5, $FeAl_3$, and $FeAl_6$ which follow the thermo-mechanical region while FeAl and Fe_2Al_5 phases belong to the welded conditions. Dehghani et al. [52] studied the effect of the friction stir welding parameters, such as pin design, tilt angle, travel speed, and plunge depth, on the tunnel formation, ultimate tensile strength, and the formation of intermetallic compounds. A low rotation speed, a thin layer of intermetallic compounds and tunnel defect take place, and due to this, the tensile strength was low. However, increasing the welding speed decreases the formation of intermetallic compounds, while increasing the tensile strength. He discovered that the tunnel defect could not be removed because the pin diameter could be changed. On the other hand, a threaded tool pin could remove the tunnel defect and formed a nugget zone with a bell shape. At a lower plunge depth of the pin and a higher rotation speed, the joint strength between aluminum and steel was poor due to the lack of bonding between those two materials.

2.5 Friction Stir Welding between of Al (6061-T6)

Friction stir welding of aluminum alloys is very common, especially in the aircraft industry. Many researchers study the welded zone for the most popular aluminum alloy, 6xxx. Sergey et al. [1] studied the friction stir welding of an Al (6061-T6) sheet at 3 mm thickness. A heat-treating process, which includes solid solution and aging, was done. For a solid solution, the specimens were held in the furnace at 550 C°, for one hour then water was used for quenching. The aging process was conducted by holding the specimens in the furnace at 160 C° for 8 hours. The main idea of this research was to study the effect of the welding speed and the heat-treating process especially aging response, on the mechanical properties. Different travel speeds were used in this welding; those speeds were 125,380 and 760 mm/min. At the travel speed of 760 mm/min, the joint efficiency exceed 93 %, while the ductility was less than 3 %. The micro hardness test showed that the hardness in the nugget zone for the aged specimens was lower than the hardness in the base metal.

Rajakumar et al. [53] showed that the Al (6061-T6) alloy is more commonly used in friction stir welding for many reasons. One of those reasons is it provides a joint that is light weight and has excellent mechanical properties such as high strength and good corrosion resistance. He showed that the grain size and nugget zone strength could affect the joint strength. Therefore. He developed an empirical relationship, which predicts both the tensile strength and grain size of friction stir welding an Al (6061-T6) joint. Perumalla et al. [54] studied the effect of the welding parameters on the load-extension curves; those parameters included rotation speed, travel speed, plunge depth, and shoulder diameter. Load – extension curves are very important in welding joint in that they evaluate the fracture stress and the amount of load that the specimens can carry. An Instron machine was used for a tensile test, and then the load – extension curves were plotted. He showed that by increasing the rotation speed and travel speed and decreasing the shoulder diameter led to an increase in the maximum load. However, the plunge depth did have effect on the load value which represents the y – axis of the curve. Increasing the shoulder diameter, rotation speed, travel speed, and plunge depth led to an increase in extension. On the other hand, lesser extension and maximum load described the Al (6061-T6) base metal.

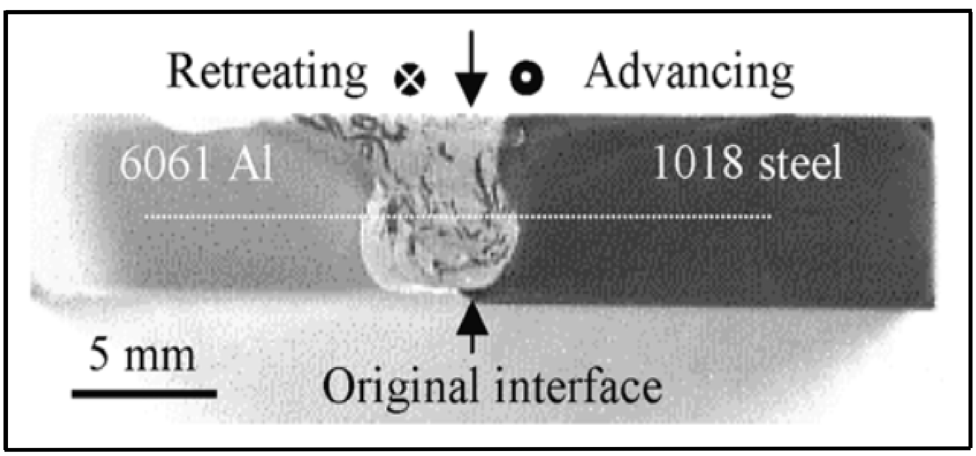


Figure (2.5) Overview photograph of the cross-section of the welded sheet material. The line indicates positions where micro hardness was measured [61] [50][62].

2.6 Goals of the Thesis

The main idea of this research was to study the joining of similar and dissimilar materials using the friction stir welding method. The materials used were titanium alloy (Ti-6Al-4V), aluminum alloy (6061-T6), 304 stainless steel, 1018 steel, and copper 110. The friction stir welding process took place between the titanium to 304 stainless steel, aluminum to 1018 steel, aluminum to copper, and aluminum to aluminum. The objective was to improve the mechanical properties of the welded joints by controlling the friction stir welding variables. These properties included the tensile strength, the bending test (i.e., fracture stress or cracks), the reduction of defects such as voids, porosity, and hardness, as well as the metallographic analysis of the joints such as the microstructure. Load – displacement and stress – strain curves were obtained using an Instron 5500 R machine. The purpose of these curves was to find the fracture stress and ultimate tensile strength, respectively. Moreover, another goal of the research was to find the metallurgical changes and the intermetallic compounds that occur between the materials in the joint area. These compounds can exist during FSW between titanium and stainless steel, but do not occur with other metals like aluminum. My research also aimed to compare all the specimens before and after the heat treating process. Another comparison took place before and after the heat treating process, changing one of the three welding parameters each time while the other two are constant. The three parameters are tilt angle, rotation speed, and travel speed. Some researchers used an interlayer such as copper or nickel between the hard materials because of the formation of brittle intermetallic compounds. They were intended to minimize the formation of the compounds that form during the welding process. The bonding process that happens using three metals is not practical for many reasons, including the high cost. Theoretically, defects can take place in the welded zone because two different materials that have entirely different properties, either physical or chemical and mechanical, are being joined. So, this research focused only on the direct bonding between those materials, without a third metal as the interlayer. There are many challenges, either in the theoretical or practical part. These challenges could be due to the specific properties of some of the materials, like the titanium and its alloys that have high hardness, or even because of the formation of intermetallic compounds. The other challenge was some of the materials are not entirely soluble during the friction stir welding process.

CHAPTER 3 : EXPERMENTAL WORK

3.1 Materials properties

3.1.1 Titanium Alloy (Ti-6Al-4V) and 304 SS

Titanium and its alloys have unique mechanical properties such as high hardness and low density. 304 SS has excellent resistance to corrosion, so it the most common metal used around the world. The nominal chemical compositions for titanium alloy Ti-6Al-4V and 304 stainless steel are shown below in Table (3.1) which was taken from [55]. The titanium material is very expensive because the hard machining and the difficulty for finding what you need of thickness.

Table (3.1) Nominal chemical compositions (wt %) of Ti-6Al-4V and SS304

304 SS	Fe	Cr	Ni	Mn	Si	C	N	P
	Bal	18.4	8.15	1.6	0.42	0.08	0.05	0.03
Ti-6Al-4V	Ti	Al	V	Fe	O	C	H	Others
	Bal	6.21	3.9	0.14	0.2	0.01	0.0045	<0.40

3.1.2 Pure Copper 110

This type of copper has purity reaching 99.9 % with an oxygen percent estimated at 0.04%. Also, the electrical conductivity of this type of copper is very high, higher than any metal except for silver. This conductivity can make copper more difficult to weld during the friction stir welding method. The nominal chemical compositions for copper used in this research are shown below in Table (3.2) which was taken from [56].

Table (3.2) Nominal chemical compositions of pure copper 110 (wt %).

Elements	Cu + Ag	Fe	Bi	Sb	As	Pb	S
Copper	99.9	0.005	0.001	0.002	0.002	0.005	0.005

3.1.3 Aluminum (6061 – T6)

Aluminum (6061- T6) has good mechanical properties, making it the most common alloy of aluminum for general use. This type of aluminum, called tampered aluminum, can be solutionized and artificially aged. Moreover, it exhibits excellent mechanical properties during the welding process. The nominal chemical compositions and mechanical properties for Al 6061-T6 are shown below in Tables (3.3) and (3.4), [50] and [57].

Table (3.3) Nominal chemical compositions for Al (6061-T6)

Al 6061-T6	Si	Mg	Cu	Fe	Cr	Mn	Al
	0.4-0.8	0.8-1.2	0.15-0.4	<0.7	0.04-0.35	<0.15	Bal

Table (3.4) Mechanical properties for Al (6061-T6) suppliers.

	Yield stress MPa	UTS MPa	Elastic modulus MPa	Elongation %
Al(6061-T6)	276	310	68.9	12

3.1.4 Steel (1018)

This type of steel, which is known as mild/low carbon steel, has acceptable properties like strength, toughness, and ductility. The nominal chemical compositions and the mechanical properties are shown below in Tables (3.5) and (3.6).

Table (3.5) Nominal chemical compositions for 1018 steel

	C	Mn	P	S	Fe
AISI (1018)	0.14-0.2	0.6-0.9	<0.04	<0.05	Bal

Table (3.6) Mechanical properties for 1018 steel

	Yield stress MPa	UTS MPa	Elastic modulus MPa	Elongation %
Steel (1018)	370	440	205	15

3.2 Friction Stir Welding Machine

A ram turret milling machine, (Model XLO, EX-Cell-O Corporation) shown in Figure (3.1), was modified for performing friction stir welding. The machine specifications are model S4OZ5, input 120-volt, 50-60 Hz, and 10Amps max. That machine was manufactured in the USA by G. K. Heller Corp.

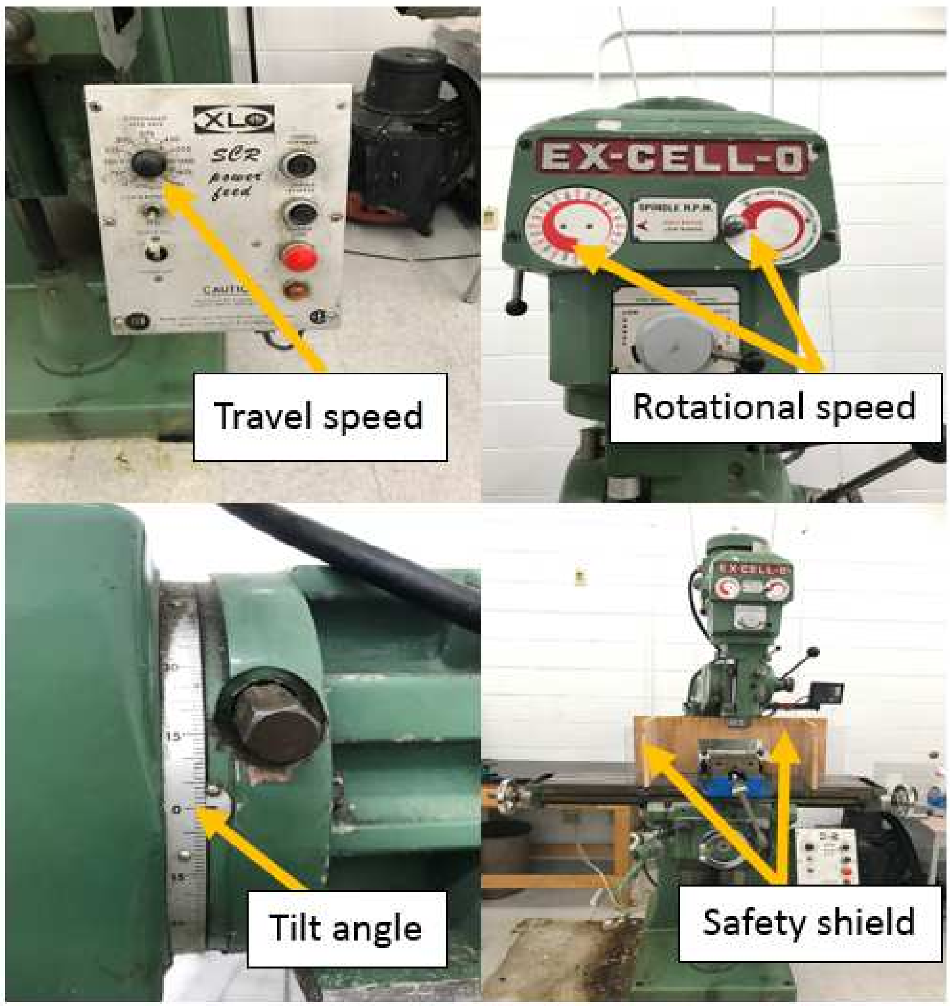


Figure (3.1) Milling machine which was modified for friction stir welding (a) Control panel with travel speed adjustment, (b) Rotation speed adjustment knob, (c) Tilt adjustment system, and (d) safety shield.

3.3 Experimental Procedure

Al (6061-T6) sheets were used for the friction stir welding process, which is regarded as the welding between similar materials. The dimensions for the sheets were 4 x 2 x 0.25 inches or 101.6 x 50.8 x 6.35 millimeters. Three different parameters were used during this process with two values for each. Those parameters included rotation speed, travel speed, and tilt angle. According to those parameters, eight specimens were welded and investigated with different tests, such as the hardness test, the tensile test, and the bending test, both before and after the heat treating process. The best and worst specimens from those eight specimens also were investigated using the for microstructure test before and after heat treating. The comparison was conducted by changing one of the parameters and keeping the other two as constants.

3.4 Friction stir welding tool

Two different tool designs were used for this research, as shown in Figure (3.2). The first design was a fixed tool machined from a single piece of rod-stock. A potential disadvantage of this geometry was that if the pin broke, the whole tool would need to be replaced. The second design was an adjustable tool, where the pin was inserted into a tool-holder. The benefits of this design include the ability to replace broken pins as well as to adjust the length of the pin to suit the thickness of the sheets being joined. Three different materials were used for manufacturing the tools – H13 and A2 steels for the fixed tool design and H13 with a tungsten carbide composite for the adjustable tool design. The tool dimensions were pin diameter 0.25 inch, pin length 0.2 inch, and shoulder diameter 1 inch. There were two different concave angles, the first one was at the shank side at 15 degrees, while the second one was at the pin side at 6 degrees. There are some Solid Work drawings in appendix part which illustrate these two different angles. The main purpose for those angles was so that the shoulder could behave as the reservoir for the material while the angle at the shank side gave good connection with the machine collet. Also, a dome was designed at the tip of the pin in order to eliminate the stress concentration. Because the milling machine has different collet sizes, the tool shank was manufactured with different measurements to match that sizes. All the tools were heat treated to HRC 50 – 60 at Winston Heat Treating Inc. Figures (3.2) and (3.3) show the friction stir welding tools used in this study and the rod used to manufacture the pin for the adjustable tool, respectively.

Figure (3.2) (a) and (b) are fixed tool, and (c) the adjustable tool

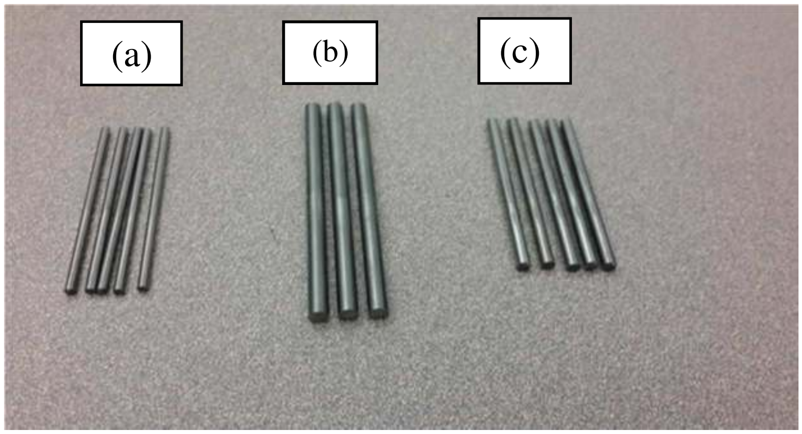


Figure (3.3) Different sizes of adjustable tool pin (a) 3/16 inch, (b) ¼ inch, and (c) 1/8 inch

3.5 Heat Treating of Processes Samples

During friction stir welding, the welded zone and some of the surrounding areas get heated and become overaged. The processed samples were heat treated back to the T6 condition using box furnaces. The samples were first solution heat treated at 980º F (526ºC) for one hour, then quenched in water, and then aged for one hour at 400ºF (205ºC).

3.6 Hardness test

The hardness of the eight Al-Al specimens was measured using a MACROMET® 5121Rockwell hardness tester. A number of measurements were made at a spacing of 3 mm from the base metal on one side of the FSW region to the base metal on other side. The HRF scale was used to measure the hardness for both the joint and base metal. Hardness was measured in both the as-welded and the heat treated conditions. Figure (3.4) shows the indentation locations for a typical hardness measurement. The comparison was conducted before and after the heat treating process for all the specimens. Another comparison was made when two of the three parameters were constant and the third one was varied.

Figure (3.4) Shows the specimen hardness which illustrate the position and the distance between each two points (3mm).

3.7 Tension Test

An Instron 5500 R electro-mechanical universal testing machine with a load capacity of 150000 N was used to conduct the tension tests, Figure (3.5). These tests were conducted using straight-sided specimens without a narrower gauge section (not dog-bone shape) due to limitations in time and financial resources. The primary purpose of the test was to determine the stress required to fracture the specimen, and not the entire stress strain curve. Figure (3.6) shows a sketch of a typical specimen of Al to Al and Al to steel joints. The load to failure was converted to tensile strength by dividing by the cross-sectional area. A software called Bluehill2 was connected to the test device to capture the data. This data was saved in an excel file with thousands of readings reached to the 2000 – 6000 reading. The tension test results showed that the fracture occurred in the weak region which was between the TMAZ and HAZ as shown below in Figure (3.6).

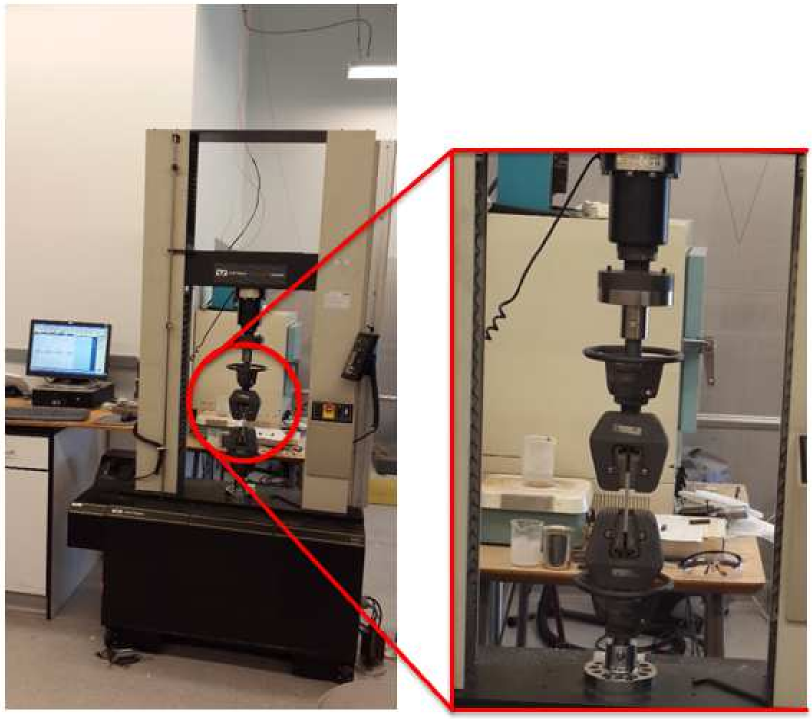


Figure (3.5) Shows the universal testing machine

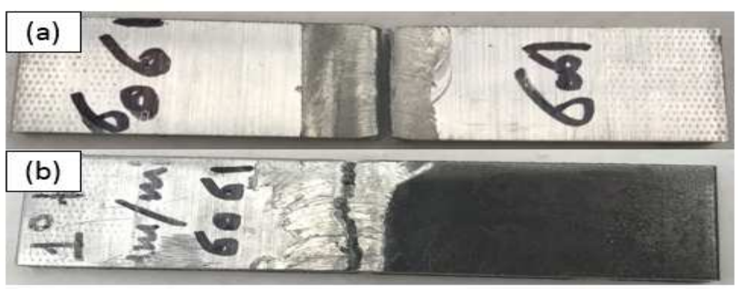


Figure (3.6) Shows (a) aluminum joint and (b) aluminum to steel joint after tension test

3.8 Bending Test

Four - point bend tests were conducted on the specimens using the same testing machine as for the tension tests. Figure (3.7) shows the testing machine and the bend test fixture. Since the FSW region is more than an inch wide, a 4-point bending test with a distributed region of maximum bending moment is better than a 3-point bending test for which the maximum bending moment occurs at a single location directly below the load application location. Figure (3.8) shows a specimen that was subjected to the bend test for both Al to Al and Al to steel joints. Bending tests for all eight specimens before and after the heat treating process were investigated. The negative load was inserted into the Bluehill2 software and the displacement control was 0.5 mm/min. The bending results showed that all the specimens tested did not break completely. This means that the specimens behaved as a ductile material rather than a brittle material. All the specimens that tested were designed as a straight sided shape instead of a dog bone shape to save time and money.

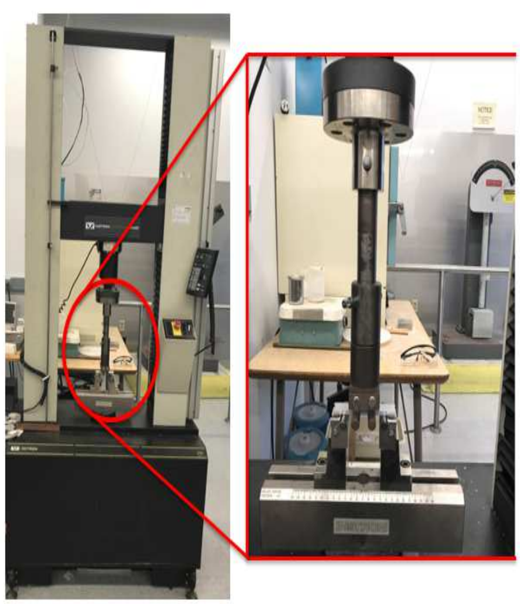


Figure (3.7) Shows the universal testing machine

Figure (3.8) Shows (a) aluminum, and (b) aluminum to steel
Joints after bending test

3.9 Microstructural examination

Specimens were prepared for microstructural examination using standard metallographic specimen preparation procedures. Polished aluminum specimens were etched using Keller's reagent-distilled water (190 ml), nitric acid (5 ml), hydrochloric acid (3 ml), and hydrofluoric acid (2 ml). However, steel region was etched using Nital reagent -ethanol (100 ml) and nitric acid (1-10 ml). Digital images of the microstructure were captured using a Nikon SLR camera mounted to a Buehler/Nikon metallograph. Four specimens of Al to Al and Al to steel joints were chosen for the microstructure test. Two of these specimens were chosen before the heat treating process while the other two were chosen after the heat treating process as shown in Figure (3.9).

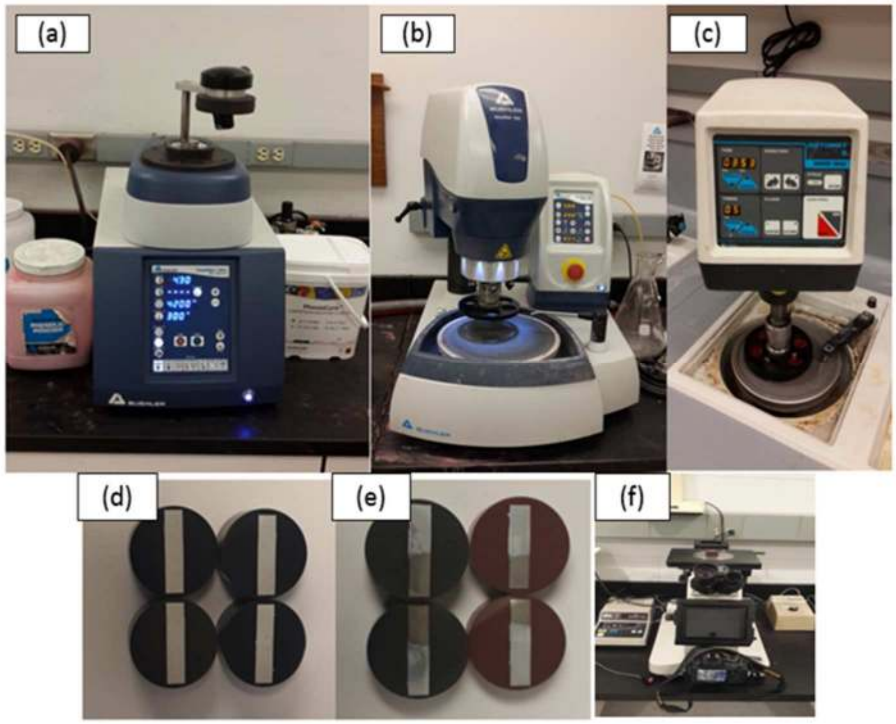


Figure (3.9) Shows (a) mounting machine, (b) and (c) the grinding and polishing machines, (d) and (e) Al and Al to steel specimens after preparations, and (f) the optical microscope

CHAPTER 4 : RESULTS AND DISCUSSION

The goal of this research was to investigate the joining of two dissimilar metals using friction stir welding process. Several combinations of metals were investigated: Ti-6Al-4V and 304 stainless steel; aluminum 6061 and copper 110; and aluminum 6061 and 1018 steel. The combination of two sheets of aluminum 6061 was used to establish base-line information and to verify that the modified milling machine could perform FSW.

4.1 Friction Stir Welding between (Ti-6Al-4V) and (304) Stainless steel

Friction stir welding between these two dissimilar metals was not successful because of the high hardness and strength of the titanium alloy. The milling machine did not have the power and force required to join these two metals. Figure (4.1) illustrates the friction stir welding between these materials. Also, one of the reasons is that the machine used for welding was not perfect because it is an old machine.

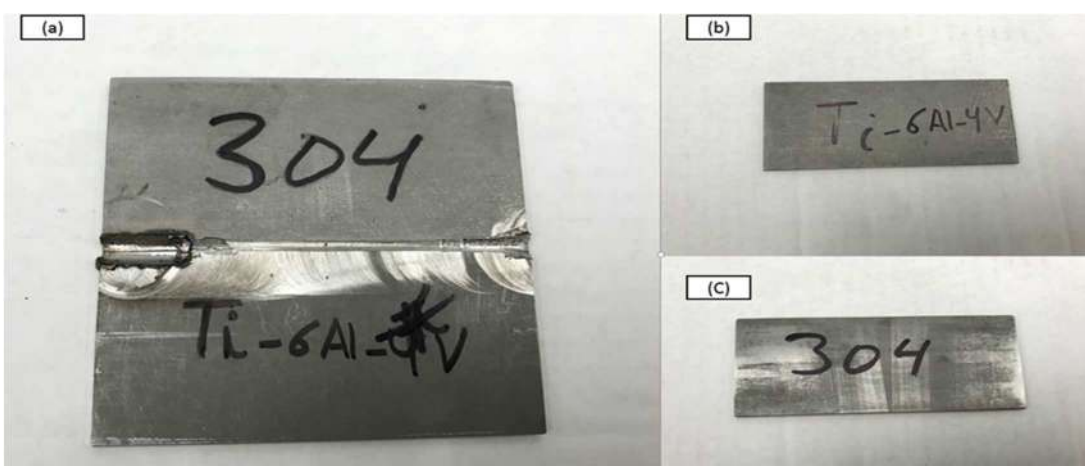


Figure (4.1) Friction stir welding between titanium and 304 stainless steel

4.2 Friction Stir Welding between Al (6061-T6) and Pure Copper (110)

Friction stir welding between these two dissimilar materials also was not successful. The primary reason was that the highest thermal conductivity of copper did not allow for a sufficient temperature increase in the friction stir zone between the tool and the workpieces. Figure (4.2) shows the results of the attempt at joining copper and aluminum. Because friction stir welding requires a backing anvil beneath the pieces, the heat generated as a result of friction was too easily transferred to the backing anvil. Therefore, the temperature was not enough to soften the materials around the pin, leading to the failure of the welding process.

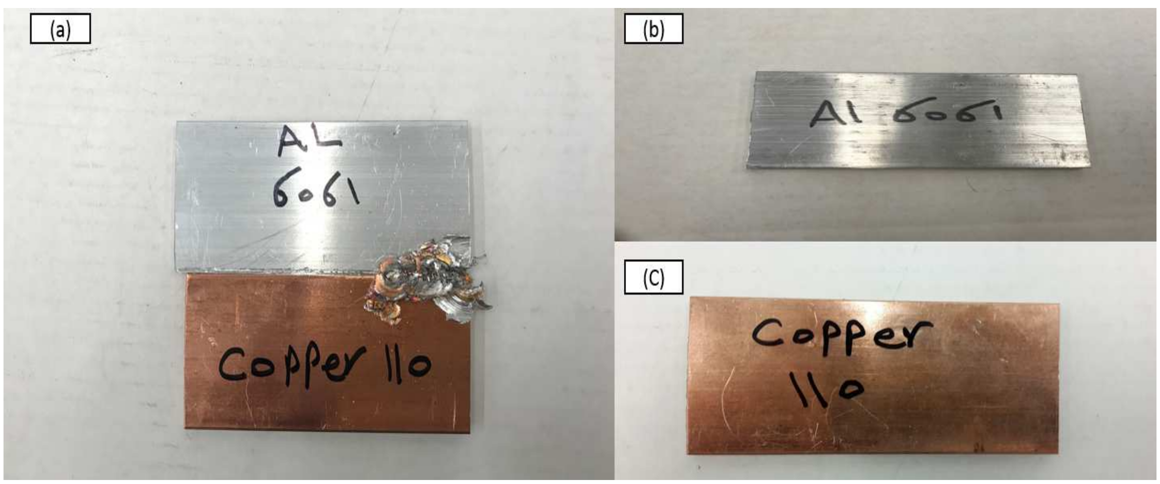


Figure (4.2) Friction stir welding between Al (6061-T6) and pure copper.

4.3 Friction Stir Welding between Two Sheets of Aluminum (6061-T6)

Friction stir welding between this similar materials joint was successful. The aluminum sheet dimensions used in this welding were 4 inches in length, 2 inches wide, and 0.25 inch thick. Table (4.1) shows the various test conditions used to join the two pieces of aluminum (6061-T6) sheet. The rotation speed was counter clockwise during the friction stir welding process. This means that the tool rotation moved counter clockwise and not clockwise along the joint line. Rectangular tension test specimens, such as the one shown in Figure (4.3) were cut from the welded samples. Mechanical properties such as the hardness, the fracture stress, the ultimate tensile strength, and the ductility were measured on all eight specimens. These results are summarized in Table (4.2).

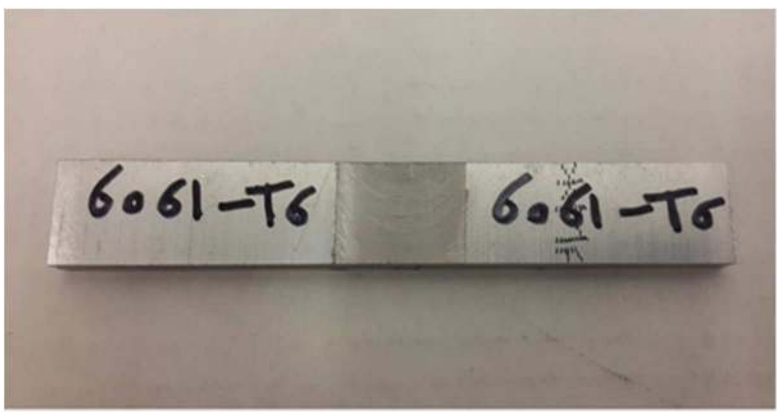


Figure (4.3) Al (6061-T6) specimen

Table (4.1) Shows friction stir welding parameters for aluminum to aluminum joint

Specimens#	Specimen label	Tilt angle (degree)	Rotational speed (RPM)	Travel speed setting (mm/min)
1	AA-0-800-20	0	800	20
2	AA-0-800-25	0	800	25
3	AA-0-1000-20	0	1000	20
4	AA-0-1000-25	0	1000	25
5	AA-1.5-800-20	1.5	800	20
6	AA-1.5-800-25	1.5	800	25
7	AA-1.5-1000-20	1.5	1000	20
8	AA-1.5-1000-25	1.5	1000	25

Table (4.2) Summary of the mechanical properties of the aluminum to aluminum joints

Al (6061-T6)				**Tensile test (UTS) MPa**		**Tensile test Elongation %**		**Joint Hardness (HRF)**		**Standard deviation**		**Bending test (Fracture stress) MPa**	
Samples#	A	R	T	before	after	before	after	before	after	before	after	before	After
1	0	800	20	120	263.8	4.8	6.5	49.4	112.9	5.35	1.96	245.8	412.1
2	0	800	25	46.2	106.2	2	3.9	55.8	110.5	18.4	1.49	354	472.9
3	0	1000	20	113.5	308.4	6.2	8.8	46.5	90.2	5.92	0.9	352.8	565.2
4	0	1000	25	162	293.3	7.2	7.6	48.03	93.03	4.19	0.65	420.9	523.1
5	1.5	800	20	178.6	291	10.2	6.7	51.2	94.3	3.06	0.5	371.8	493
6	1.5	800	25	166.2	300	8.6	7.4	51.5	93.9	4.15	0.43	345.6	483.3
7	1.5	1000	20	141.8	292	8	7.6	50.3	92.9	6.53	0.9	320.1	447.3
8	1.5	1000	25	127.9	221.5	6	7.1	50.9	84.9	6.18	3.34	412.7	493

4.4 Results of the Hardness Test

4.4.1 Effect of Heat Treatment

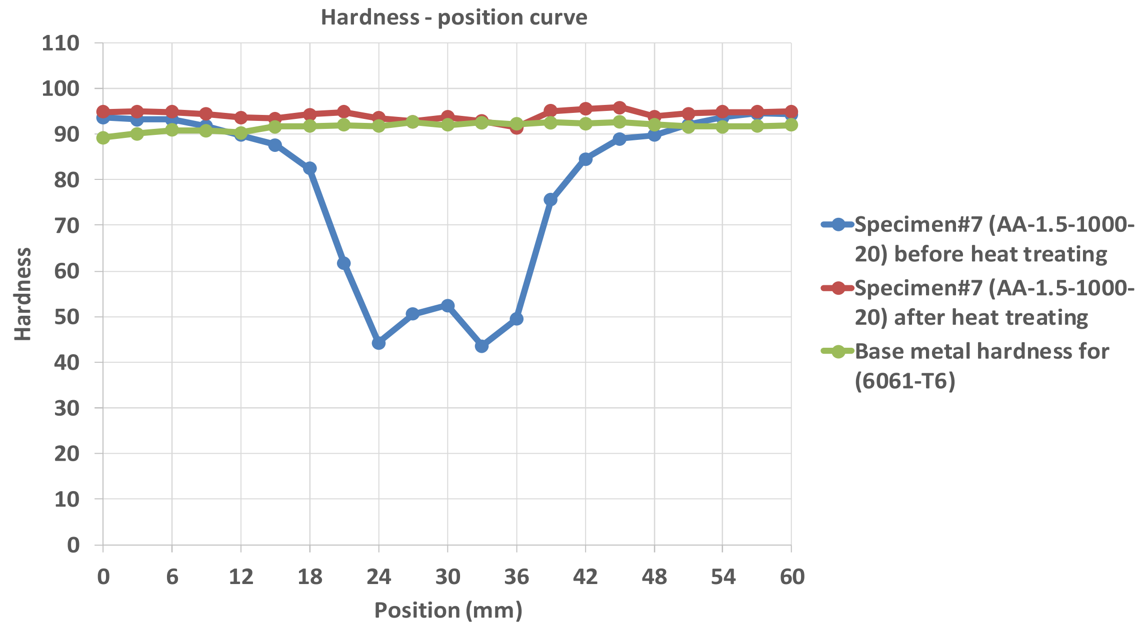


Figure (4.4) The Hardness – position curves before and after heat treating process

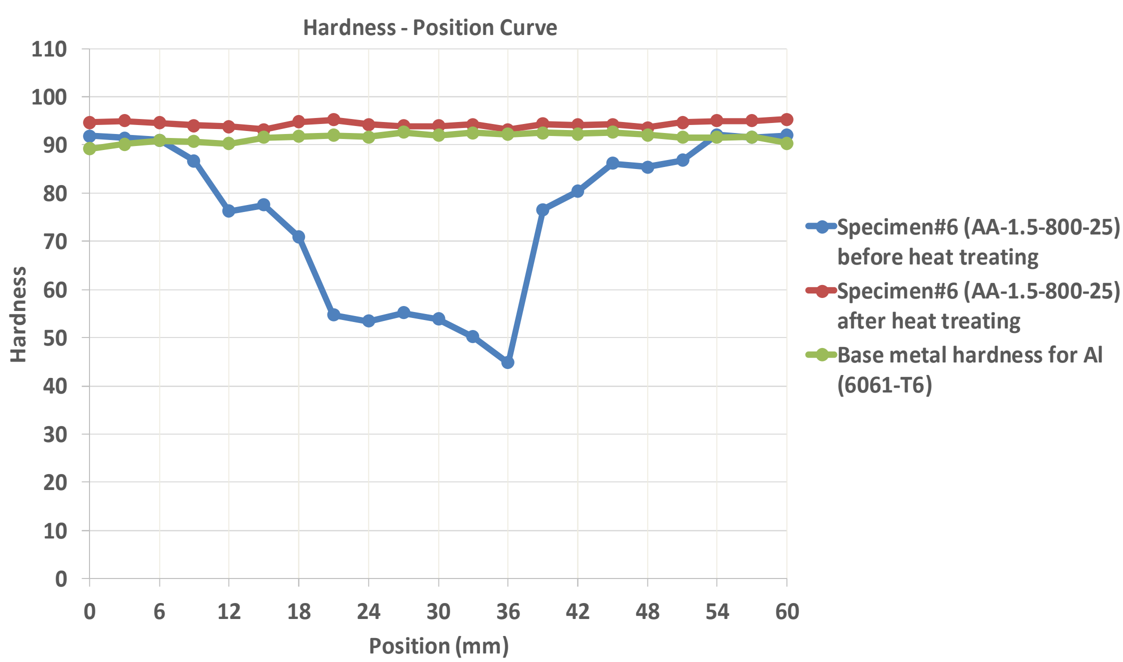


Figure (4.5) The Hardness – position curves before and after heat treating process

Hardness tests were conducted in both the as-welded and the heat-treated conditions. Figures (4.4 and 4.5) show typical variations in hardness over the friction stir welded zone. After FSW, the friction stir welded zone is softer than the base metal because the metal in the heated FSW zone softens due to overaging (blue line). Heat treatment restores the strength in the welded zone, and the hardness is almost constant across the entire welded region (red line). The hardness of the starting base metal (green line) is included for comparison. The hardness of welded metal after heat treatment is restored to the original hardness of the starting 6061-T6 alloy. The hardness for all the joints after the heat treating process are constant and higher than before the heat treating process as shown in the above figures. This means that the friction stir welding conditions and testing procedures method were reliable. A similar observation was made for other combinations of welding conditions between the other specimens before and after heat treating process as shown in the appendix part.

4.5 Effect of Welding Parameters on Properties before and after Heat Treatment

4.5.1 Effect of Varying Tilt Angle before Heat Treatment

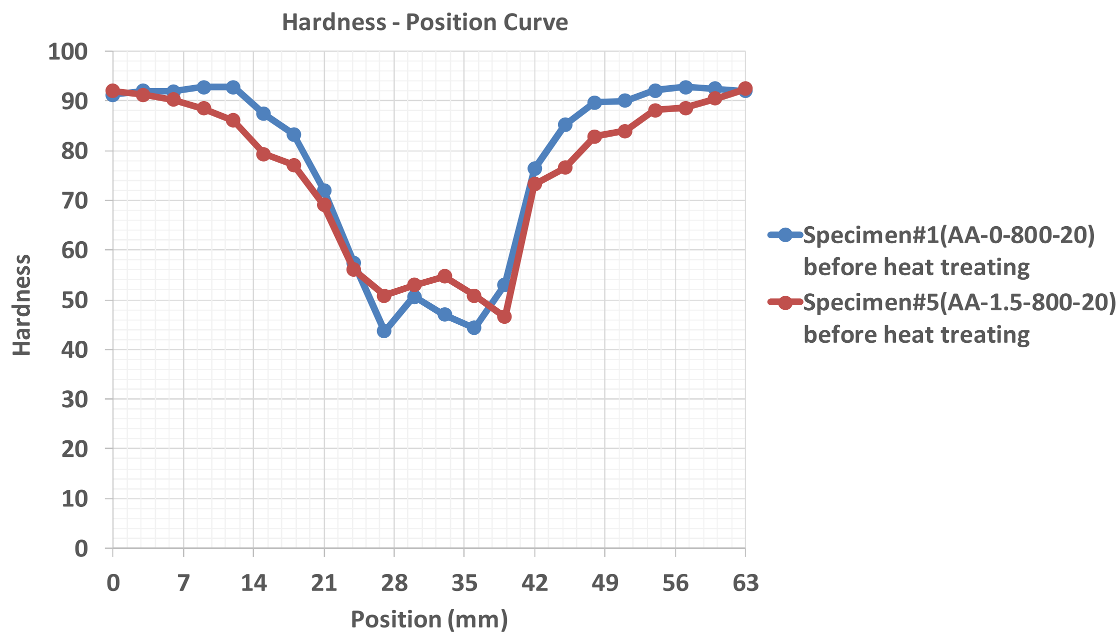


Figure (4.6) The Hardness – position curve before heat treating process at the conditions (R and T are constant while A is varied)

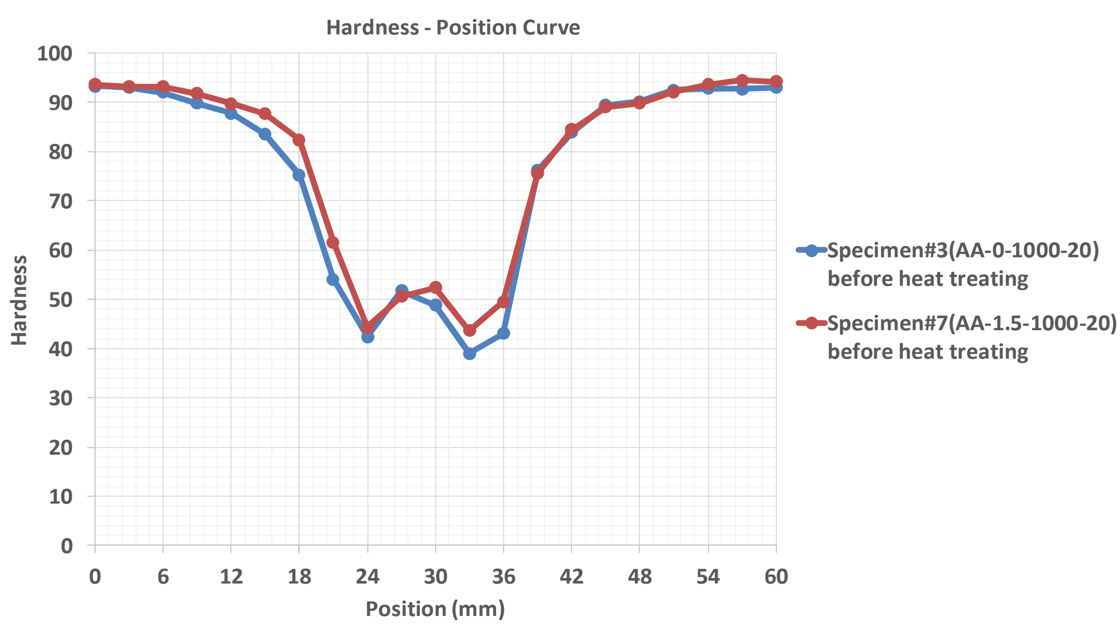


Figure (4.7) The Hardness – position curve before heat treating process at the conditions (R and T are constant while A is varied)

Figures (4.6 and 4.7) compare the variation in hardness for the different specimens. The specimens were welded using the same rotation and travel speeds, but they were welded with a tilt angle of 0º and 1.5º. There is no substantial difference between the two hardness profiles, indicating that the variation in tilt angle over the range of 0º to 1.5º has no significant effect on the hardness of the welded samples. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied. These combinations of welding between different specimens are illustrated in the appendix.

4.5.2 Effect of Varying Travel Speed before Heat Treatment

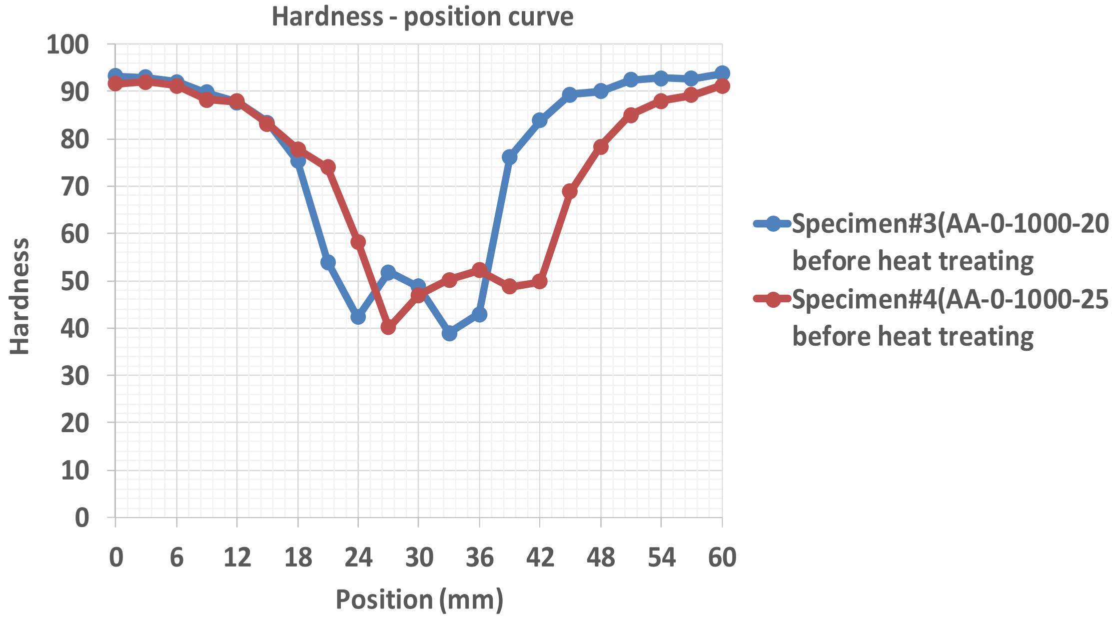


Figure (4.8) The Hardness – position curve before heat treating at the conditions (A and R are constant while T is varied)

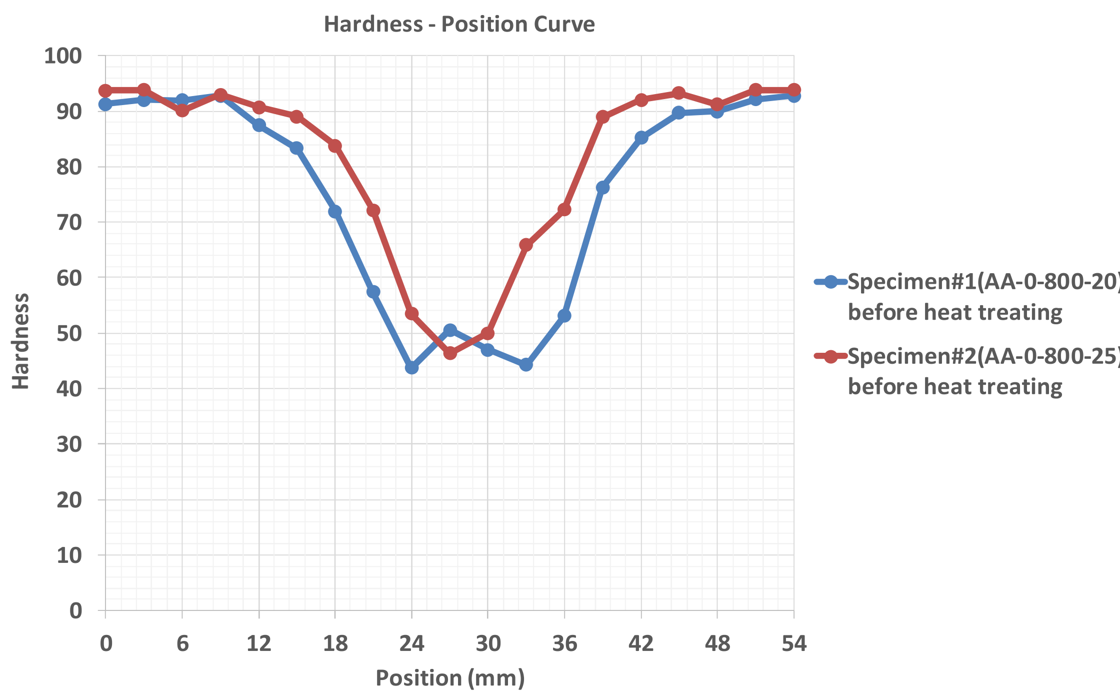


Figure (4.9) The Hardness – position curve before heat treating at the conditions (A and R are constant while T is varied)

Figures (4.8 and 4.9) compare the variation in hardness for four specimens. The specimens were welded using the same rotation speed and tilt angle. The difference was the travel speed when welding the specimens varied between 20 and 25 mm/min. There is no substantial difference between the two hardness profiles, indicating the variation in travel speed over the range from 20 to 25 mm/min has no significant effect on the hardness of the welded samples. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. The figures show that the hardness looks similar, even though the values do not match with each other one hundred percent. That means that the hardness of the samples that have two of the parameters held constant while the third one is varied is the same before the heat treating process.

4.5.3 Effect of Varying Rotation Speed before Heat Treatment

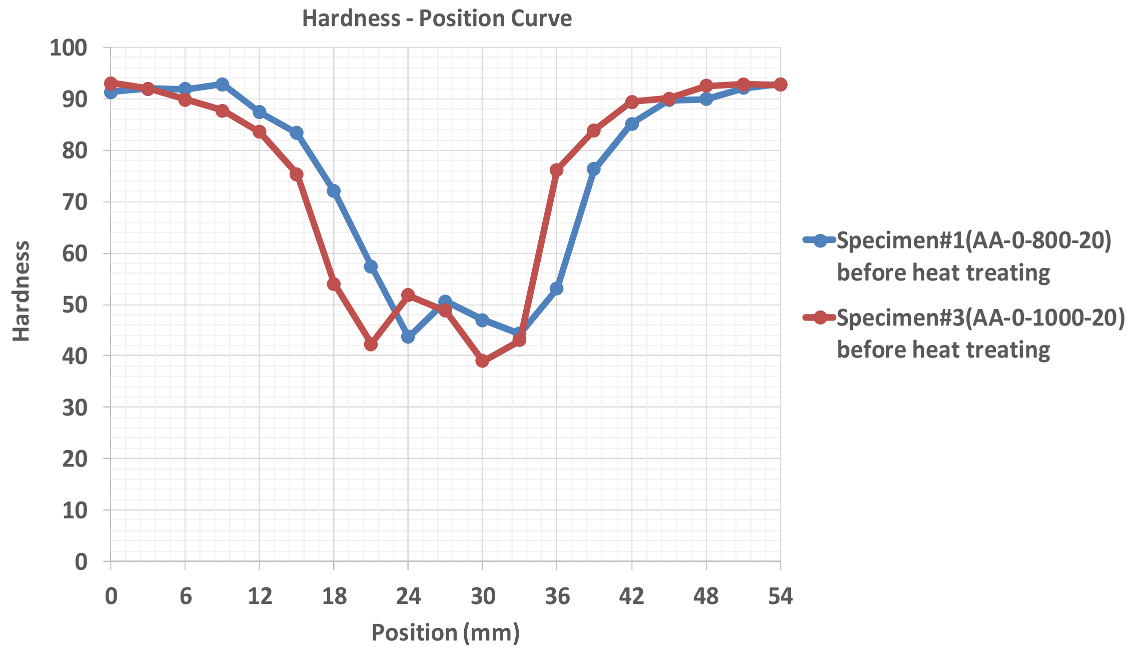


Figure (4.10) The Hardness – position curve before heat treating at the conditions (A and T are constant while R is varied)

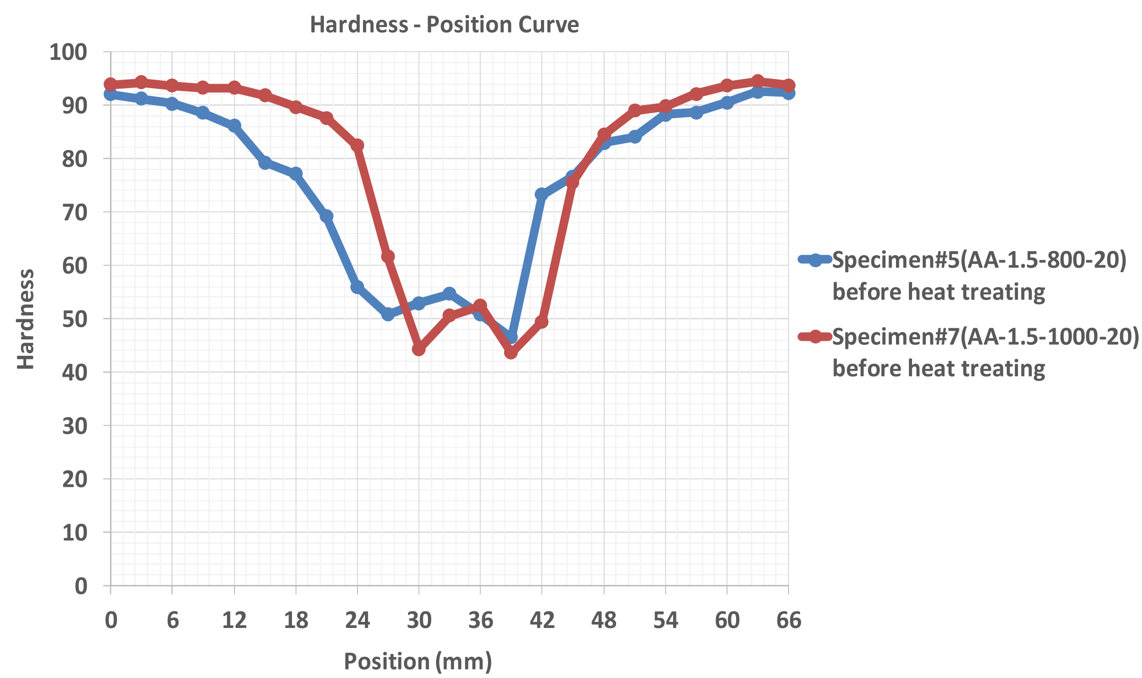


Figure (4.11) The Hardness – position curve before heat treating at the conditions (A and T are constant while R is varied)

Figures (4.10 and 4.11) compare the variation in hardness for specimen #1, #3, #5, and #7. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimen #1 and #5 was 800 rpm and that when welding specimen #3 and #7 was 1000 rpm. According to these curves, there is no substantial difference between the two hardness profiles, indicating the variation in rotation speed over the range from 800 to 1000 rpm has no significant effect on the hardness of the welded samples. Which means there is no effect of welding parameters on mechanical properties such as the hardness before heat treating process. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix. So, friction stir welding of two samples that have same the tilt angle and travel speed but with different rotational speed gives hardness close to each other.

4.5.4 Effect of Varying Tilt Angle after Heat Treatment

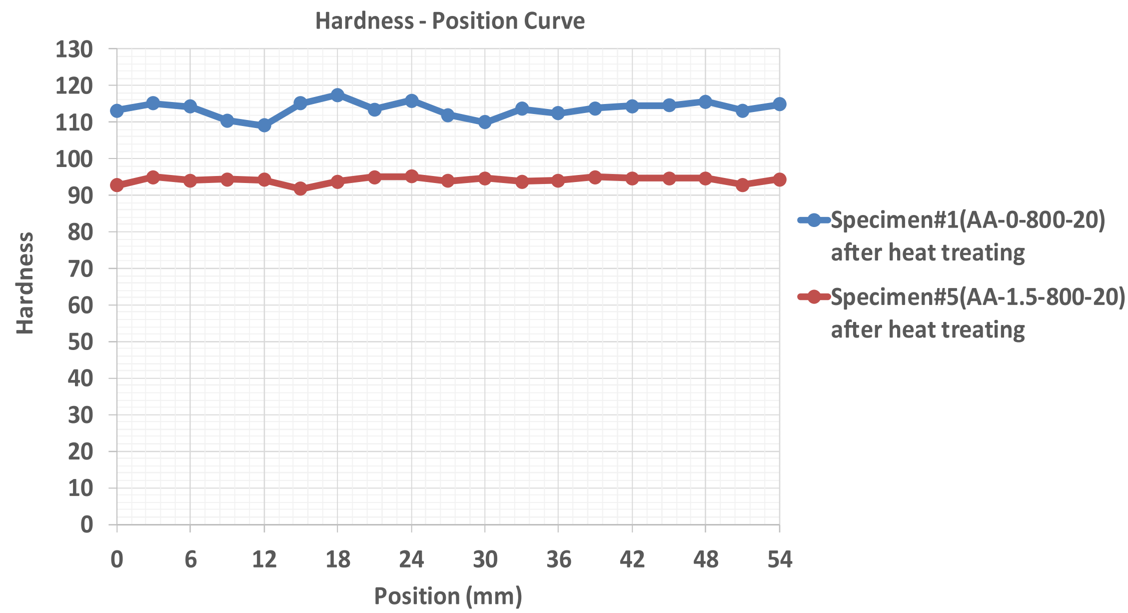


Figure (4.12) The Hardness – position curve after heat treating at the conditions (R and T are constant while A is varied)

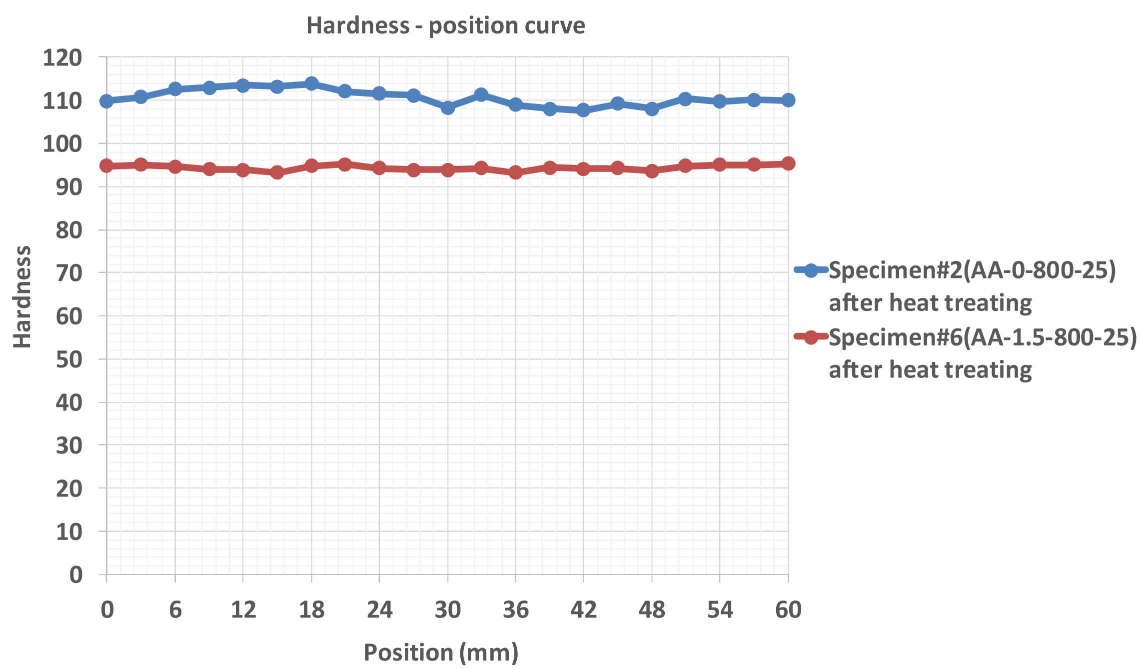


Figure (4.13) The Hardness – position curve after heat treating at the conditions (R and T are constant while A is varied)

All specimens were heat treated to T6 condition after welding. Since the welding parameters did not play a significant role in the hardness profiles after welding and before heat treatment, it can be expected that after heat treatment, all hardness profiles will be similar for all welding conditions. This is indeed what was observed, as seen in figures (4.12 and 4.13). The hardness variation with position falls within a narrow band in the range of 90 to 120 HRF for all the FSW tests conducted (see figures). This comparison shows that the hardness for the specimens with same the rotational and travel speeds but a different tilt angle are constant after heat treating process. Moreover, the specimen's hardness at tilt angle equal to zero degrees is higher than at a tilt angle equal to 1.5 degrees. That means Heat treatment restores the strength in the welded zone, and the hardness is almost constant across the entire welded region. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix.

4.5.5 Effect of Varying Travel Speed after Heat Treatment

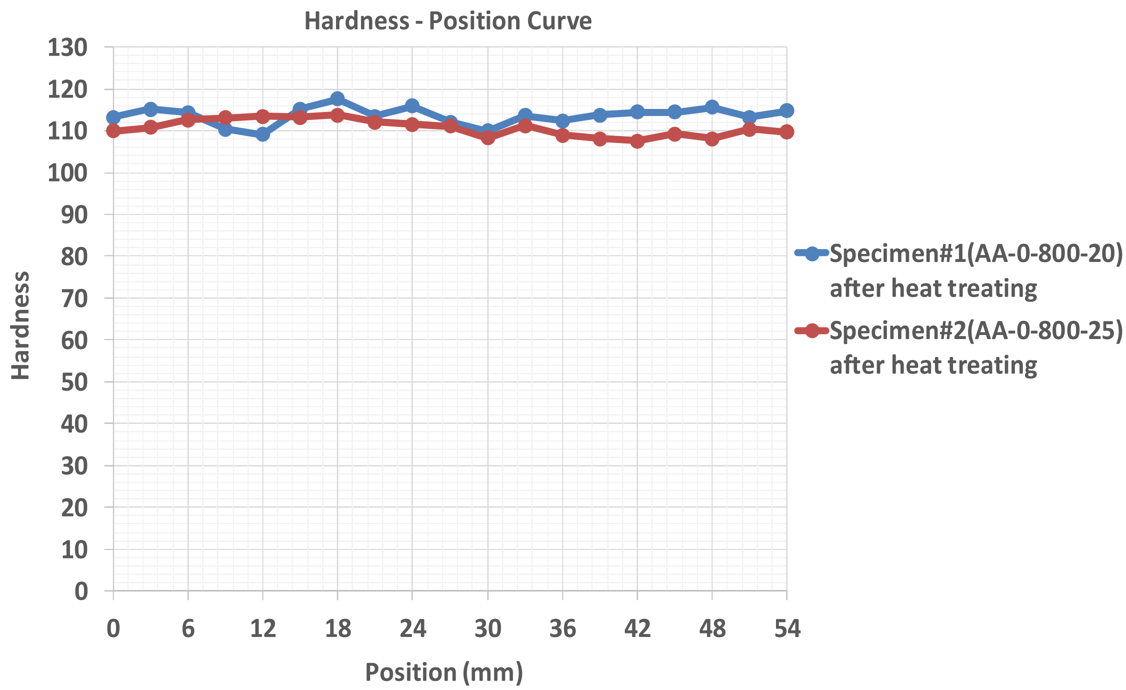


Figure (4.14) The Hardness – position curve after heat treating at the conditions (A and R are constant while T is varied)

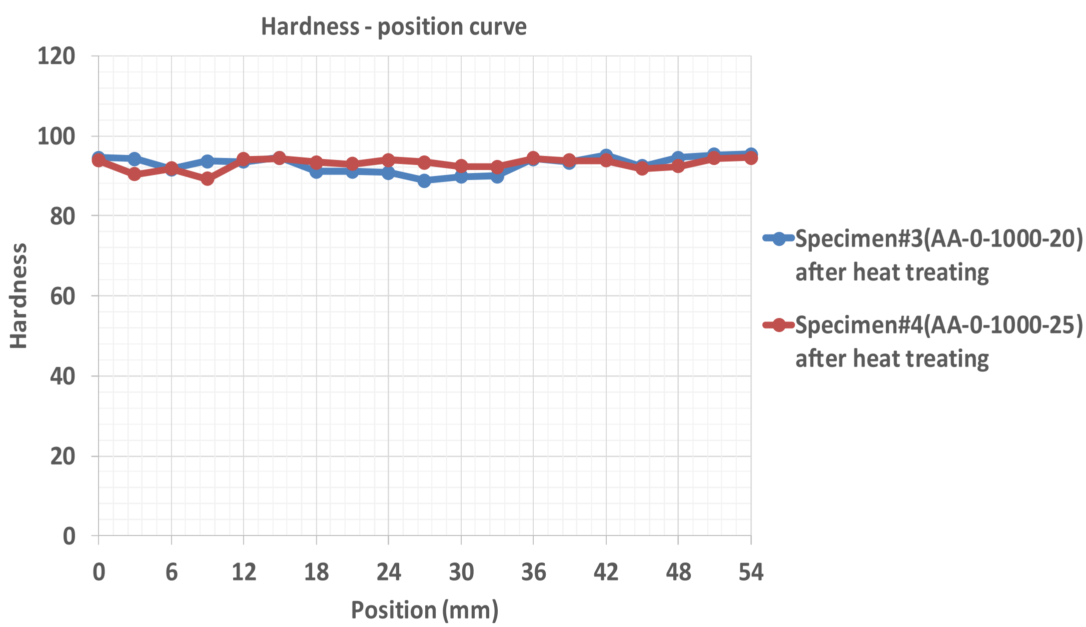


Figure (4.15) The Hardness – position curve after heat treating at the conditions (A and R are constant while T is varied)

All samples were heat treated to T6 condition after welding. Since the welding parameters did not play a significant role in the hardness profiles after welding and before heat treatment, it can be expected that after heat treatment, all hardness profiles will be similar for all welding conditions. This is indeed what was observed, as seen Figures (4.14 and 4.15). The hardness variation with position falls within a narrow band in the range of 80 to 120 HRF for all the FSW tests conducted (see figures). These figures show that the hardness is constant for all samples that have same tilt angle and rotational speed but different travel speed after the heat treating process. During the friction stir welding process, the variations in temperature can take place as a result of the friction, which affect the mechanical properties negatively. So, a heat treating process that include solution heat treating and aging can return the aluminum alloy to its original properties. In other words, Heat treatment restores the strength in the welded zone, and the hardness is almost constant across the entire welded region. The results show that the heat treating procedure for Al (6061-T6) and hardness test were done correctly. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix.

4.5.6 Effect of Varying Rotation Speed after Heat Treatment

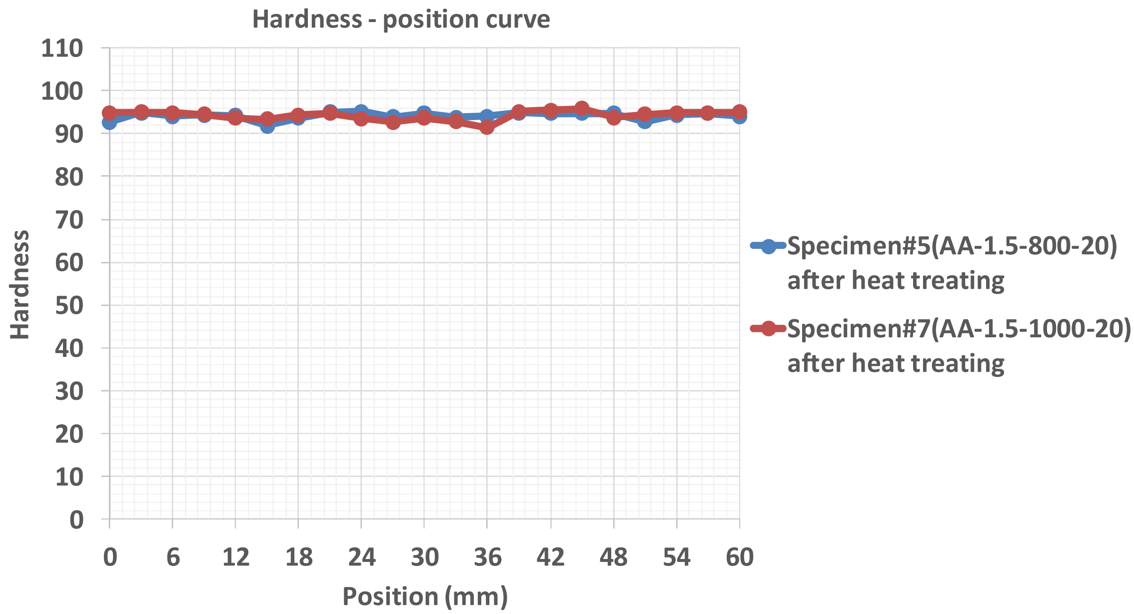


Figure (4.16) The Hardness – position curve after heat treating at the conditions (A and T are constant while R is varied)

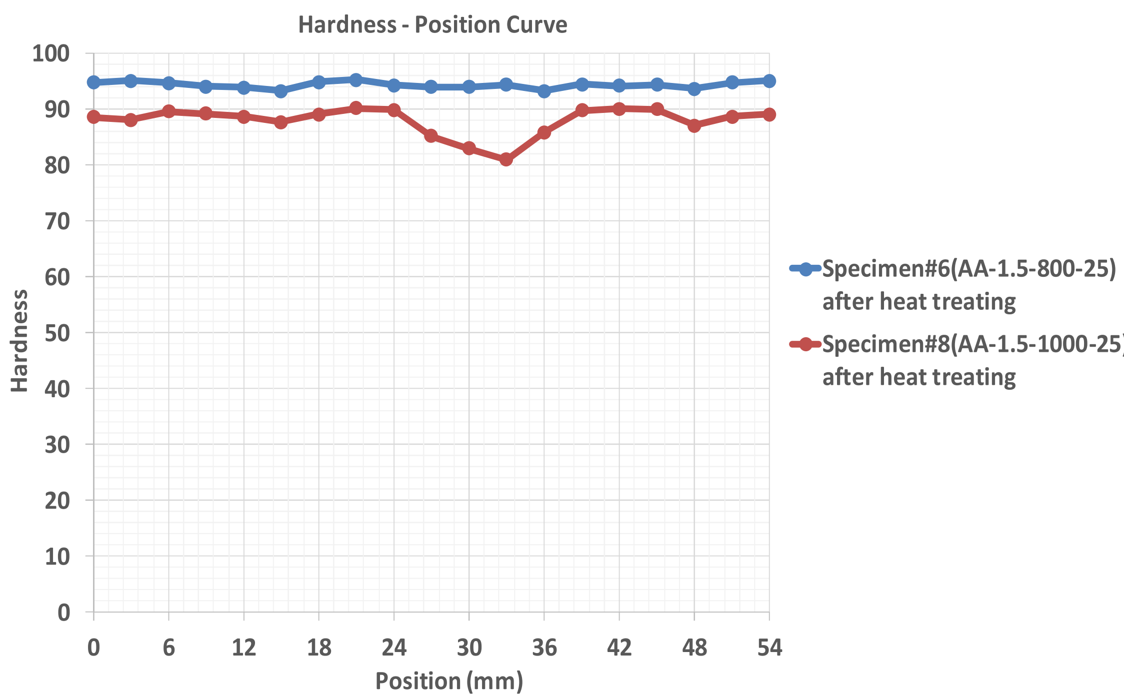


Figure (4.17) The Hardness – position curve after heat treating at the conditions (A and T are constant while R is varied)

Figures (4.16 and 4.17) compare the variation in hardness for specimens #5, #7, #6, and #8. These specimens were heat treated to T6 condition after friction stir welding. Since the welding parameters did not play a significant role in the hardness profiles after welding and before heat treatment, it was expected that after heat treatment, all hardness profiles will be similar for all the welding conditions. This is what was observed, as seen in Figures (4.16 and 4.17). The hardness variation position falls within a narrow band in the range of 80 to 100 HRF for all the FSW tests conducted. It was concluded that heat treatment restores the strength in the welded zone, and the hardness is almost constant across the entire welded region. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix.

4.6 Tension Test

4.6.1 Tension Test Comparison before and after Heat Treatment

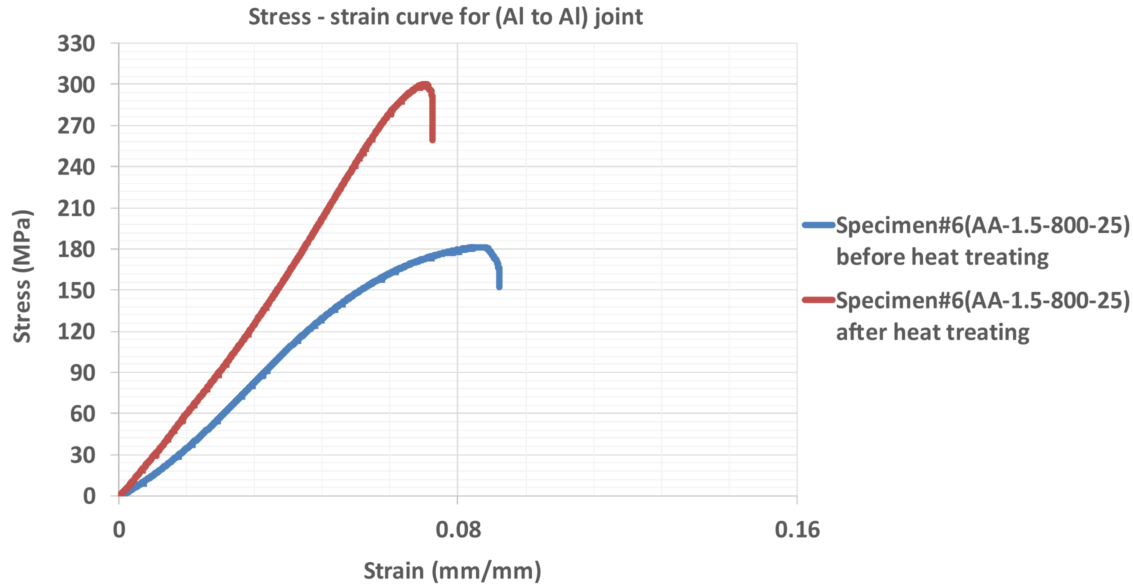


Figure (4.18) The Stress – strain curves for tension test before and after heat treating

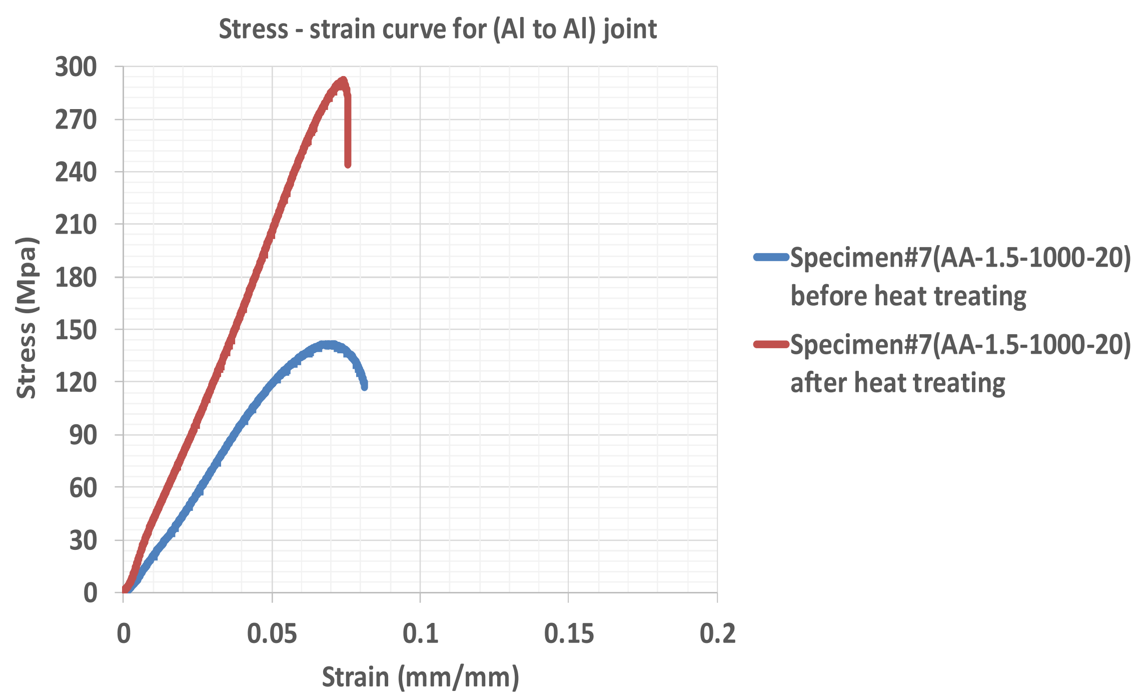


Figure (4.19) The Stress – strain curves for tension test before and after heat treating

Tension tests were conducted on both the as-welded and the heat-treated conditions. According to Figures (4.18 and 4.19), the tension strength for specimens #6 and #7 after the heat treating process is higher than the tension strength for these specimens before the heat treating process. Heat treatment restores the strength in the welded zone, and the strength is always higher across the entire welded region. All specimens before and after heat treatment showed limited tensile ductility. Which means heat treatment effect the mechanical properties such as the ultimate tensile strength positively. A similar observation was made for other combinations of welding conditions between different specimens with different welding parameters according to the comparison before and after heat treatment as shown in the appendix.

4.7 Effect of Welding Parameters on Properties before and after Heat Treatment

4.7.1 Effect of Varying Tilt Angle before Heat Treatment

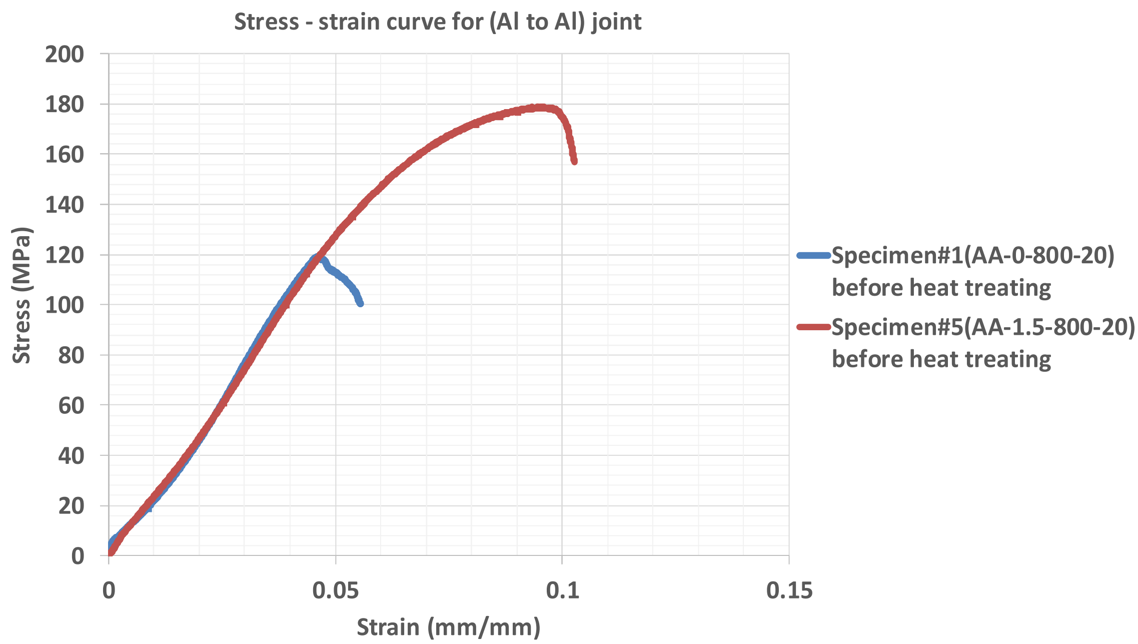


Figure (4.20) Stress – strain curves for tension test at the conditions (R and T are constant while A is varied)

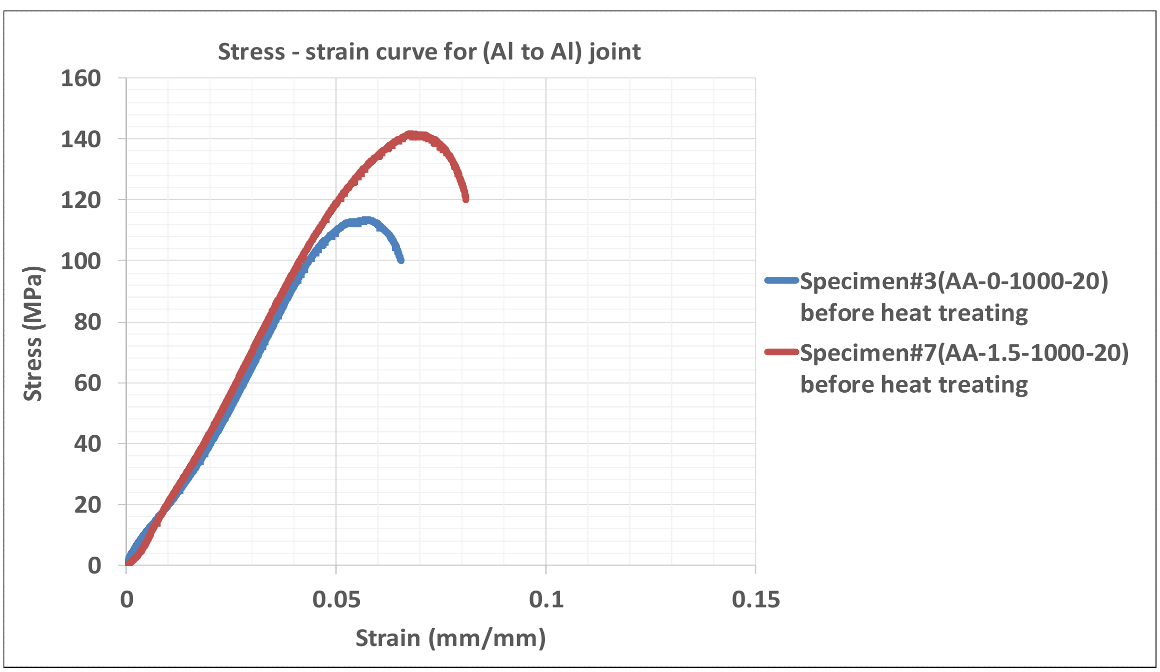


Figure (4.21) Stress – strain curves for tension test at the conditions (R and T are constant while A is varied)

Figures (4.20 and 4.21) compare the variation in strength for specimens #1, #5, #3, and #7. The specimens were welded using the same rotation and travel speeds, but were welded with varied tilt angles of 0º and 1.5º. There is a substantial difference between the two strength profiles, indicating the variation in tilt angle over the range of 0º to 1.5º has a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix. The figures show that the tensile strength for all the specimens which have a tilt angle equal to 1.5º was higher than the specimens at a tilt angle equal to 0º. In other words, friction stir welding done at a tilt angle equal to 1.5 degrees improved the joint properties, such as the hardness, and provided a joint with high homogeneity. This result corresponds to the literature review results, which means adjusting the milling machine tilt angle between 1-3 degrees when the rotational and travel speeds are constant improves the welding quality [21]. The welding quality includes any improvement in mechanical properties such as tensile strength, bending, and hardness.

4.7.2 Effect of Varying Travel Speed before Heat Treatment

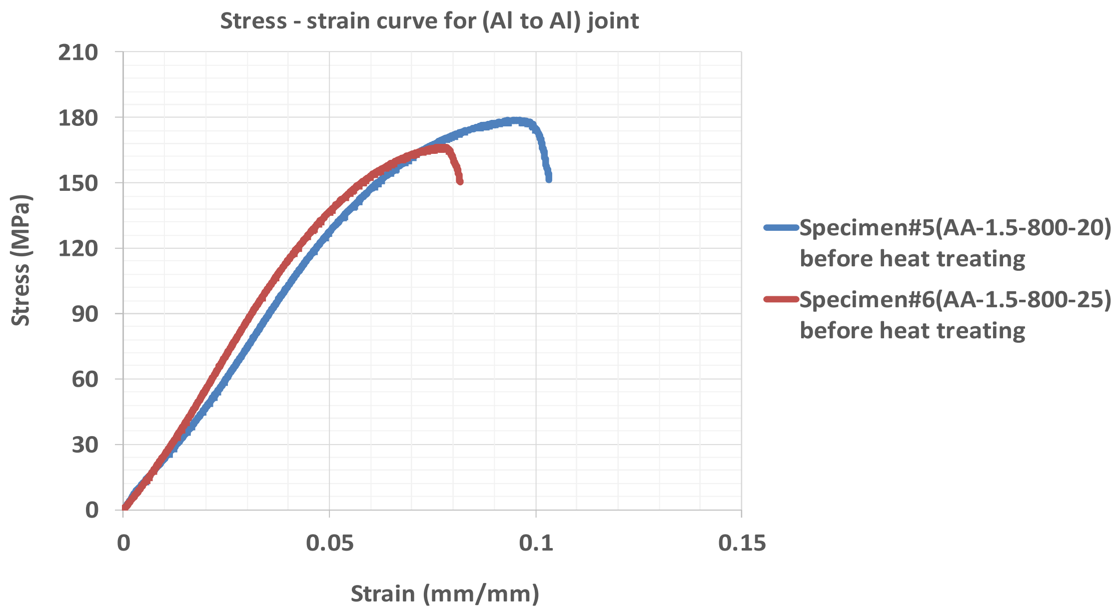


Figure (4.22) The stress – strain curves for tension test at the conditions (A and R are constant while T is varied)

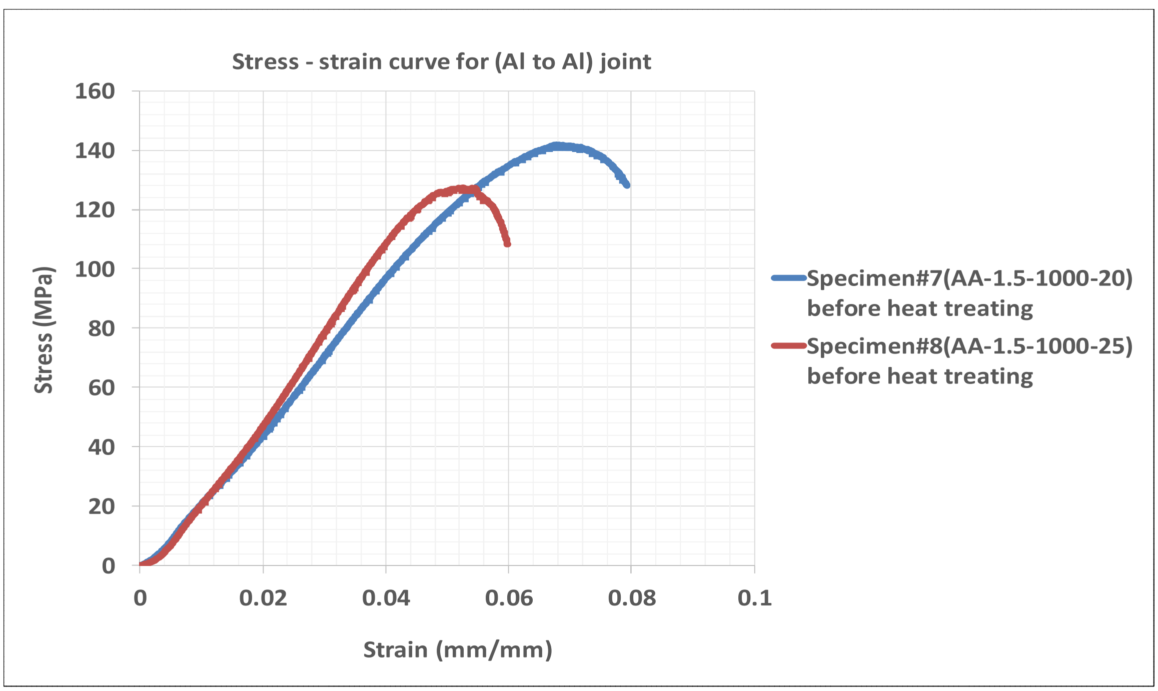


Figure (4.23) The stress – strain curves for tension test at the conditions (A and R are constant while T is varied)

Figures (4.22 and 4.23) compare the variation in strength for specimen #5, #6, #7, and #8. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimen #5 and #7 was 20 mm/min and when welding the specimens #6 and #8 was 25 mm/min. There is a substantial difference between the two strength profiles, indicating the variation in travel speed over the range from 20 to 25 mm/min has a significant effect on the tension strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. All the specimens that had travel speed equal to 20 mm/min were higher in strength than the specimens at a travel speed equal to 25 mm/min. Decreasing the travel speed during friction stir welding process increases the strength of the welds when the rotational speed and tilt angle are constant. Moreover, decreasing the travel speed can increase the heat generated between the tool and workpieces, which softens the material around the pin. That sufficient heat also increases the stirring and mixing of material around the pin.

4.7.3 Effect of Varying Rotation Speed before Heat Treatment

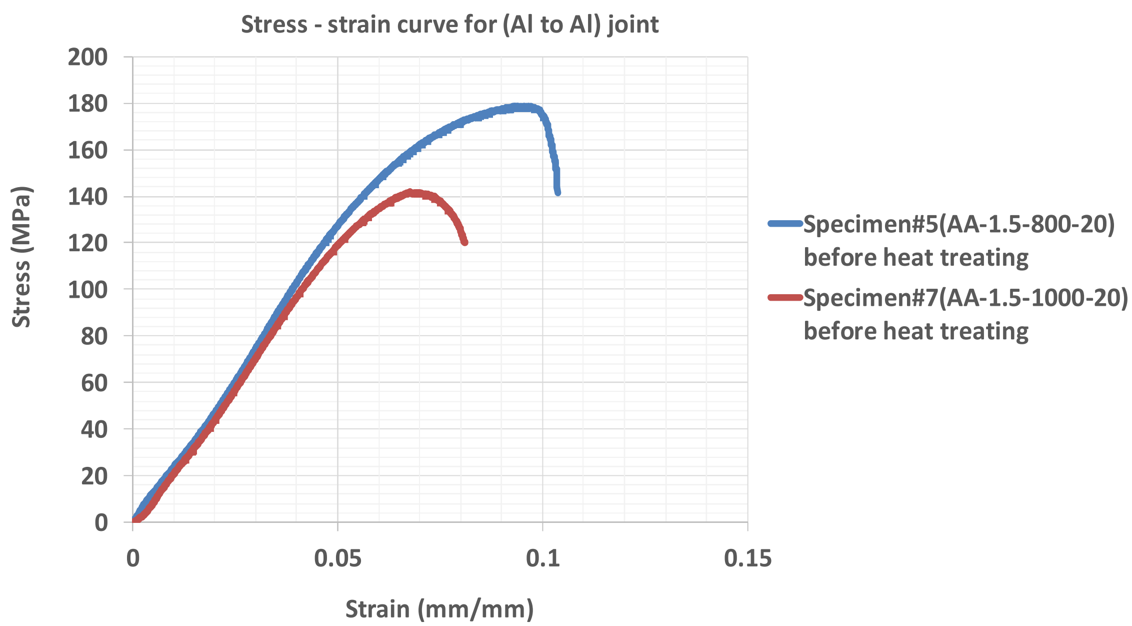


Figure (4.24) The stress – strain curves for tension test at the conditions (A and T are constant while R is varied)

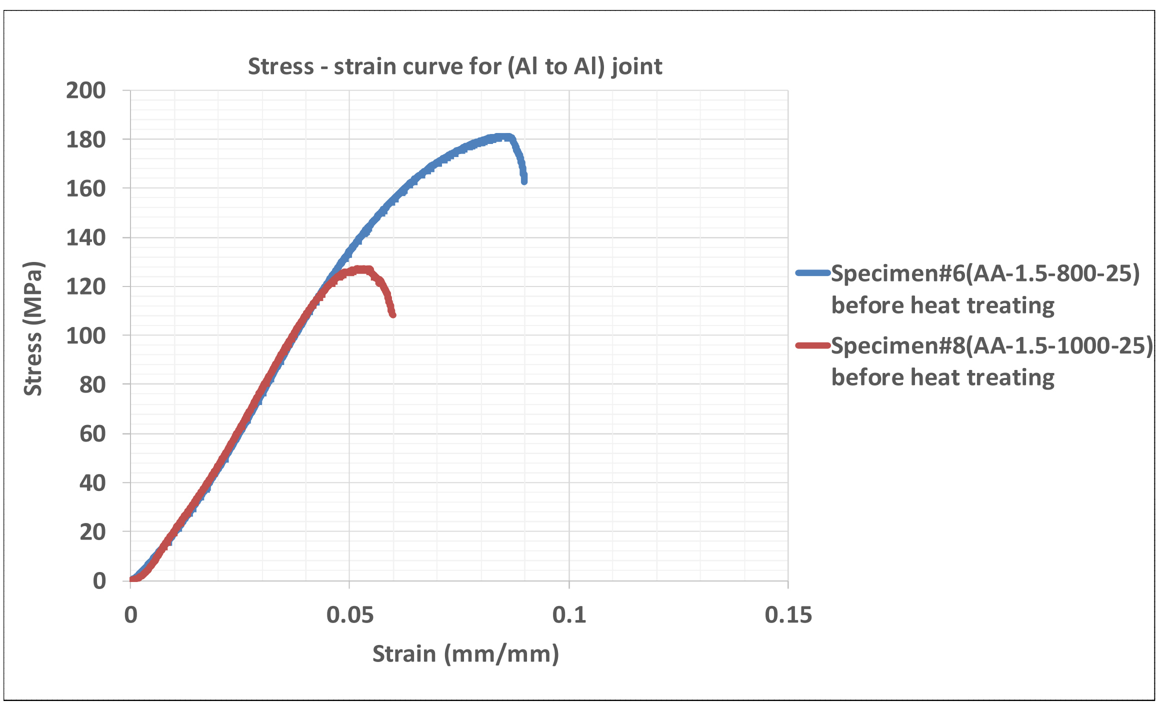


Figure (4.25) The stress – strain curves for tension test at the conditions (A and T are constant while R is varied)

Figures (4.24 and 4.25) compare the variation in strength for specimen #5, #6, #7 and #8. The specimens were welded using the same travel speeds and tilt angles. The difference was that the rotation speed when welding specimen #5 and #6 was 800 rpm and when welding specimen #7 and #8 was 1000 rpm. There is a substantial difference between the two strength profiles, indicating that a variation in rotation speed over the range of 800 to 1000 rpm has a significant effect on the tension strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix. This means all the specimens that have a rotation speed equal to 800 rpm are stronger than the specimens at rotation speeds equal to 1000 rpm, while tilt angle and travel speed are constant. In the other words, the specimens that have a rotation speed of 800 rpm can carry more loads than the specimens at 1000 rpm. This result was not compatible with the literature review results [21]. One of the main reasons is that the milling machine used for welding was not perfect. So, the welding parameters, such as rotation speed, using that milling machine was not easy to control.

4.7.4 Effect of Varying Tilt Angle after Heat Treatment

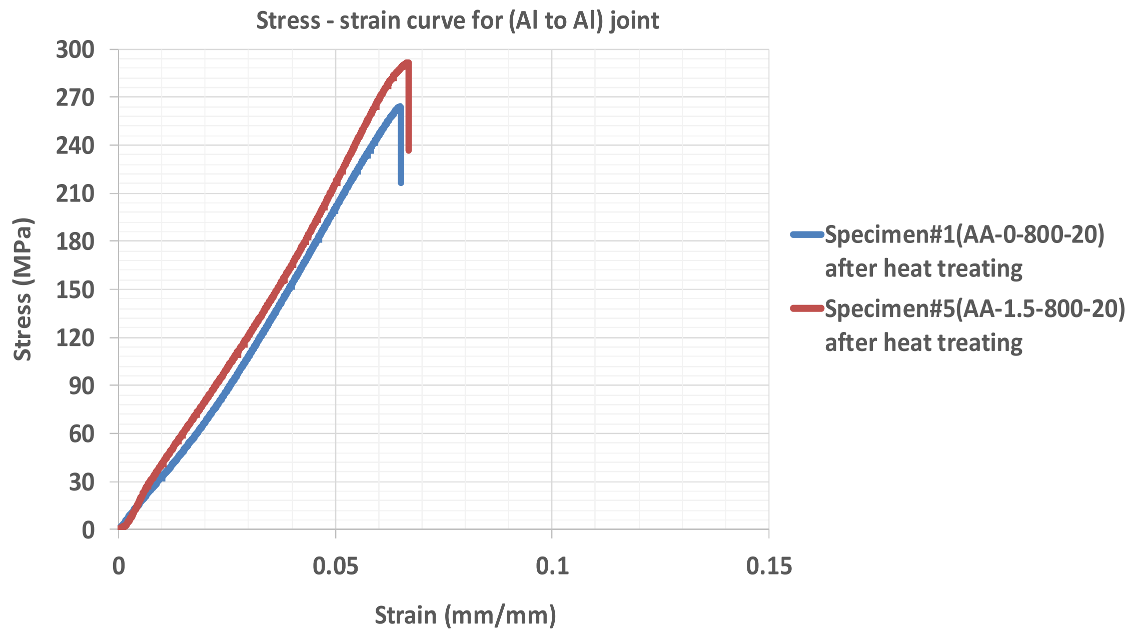


Figure (4.26) The stress – strain curves for tension test at the conditions (R and T are constant while A is varied)

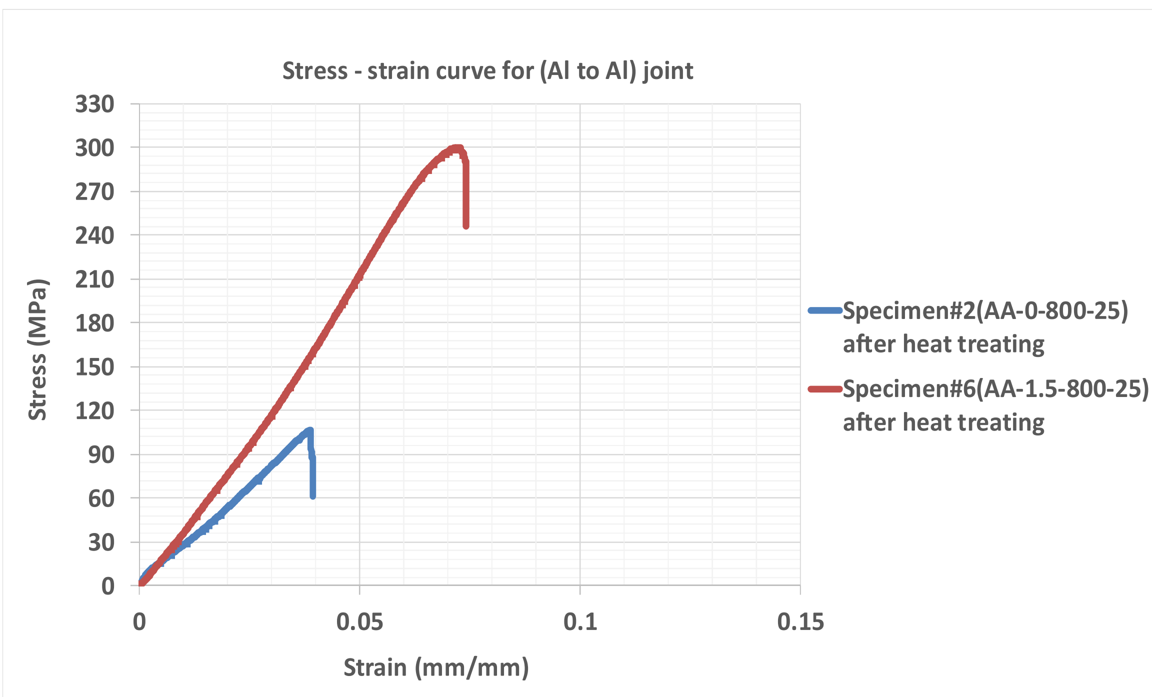


Figure (4.27) The stress – strain curves for tension test at the conditions (R and T are constant while A is varied)

Figures (4.26 and 4.27) compare the variation in strength for specimens #1, #2, #5 and #6. The specimens were welded using the same rotation and travel speeds, but specimens #1 and #2 were welded with a tilt angle of 0º while specimens #5 and #6 had a tilt angle of 1.5º. There is a substantial difference between the two strength profiles, indicating a variation in tilt angle over the range of 0º to 1.5º has a significant effect on the tension strength of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix. According to those figures, the specimens that have a tilt angle equal to 1.5º are stronger than the specimens with tilt angle equal to 0º.

4.7.5 Effect of Varying Travel Speed after Heat Treatment

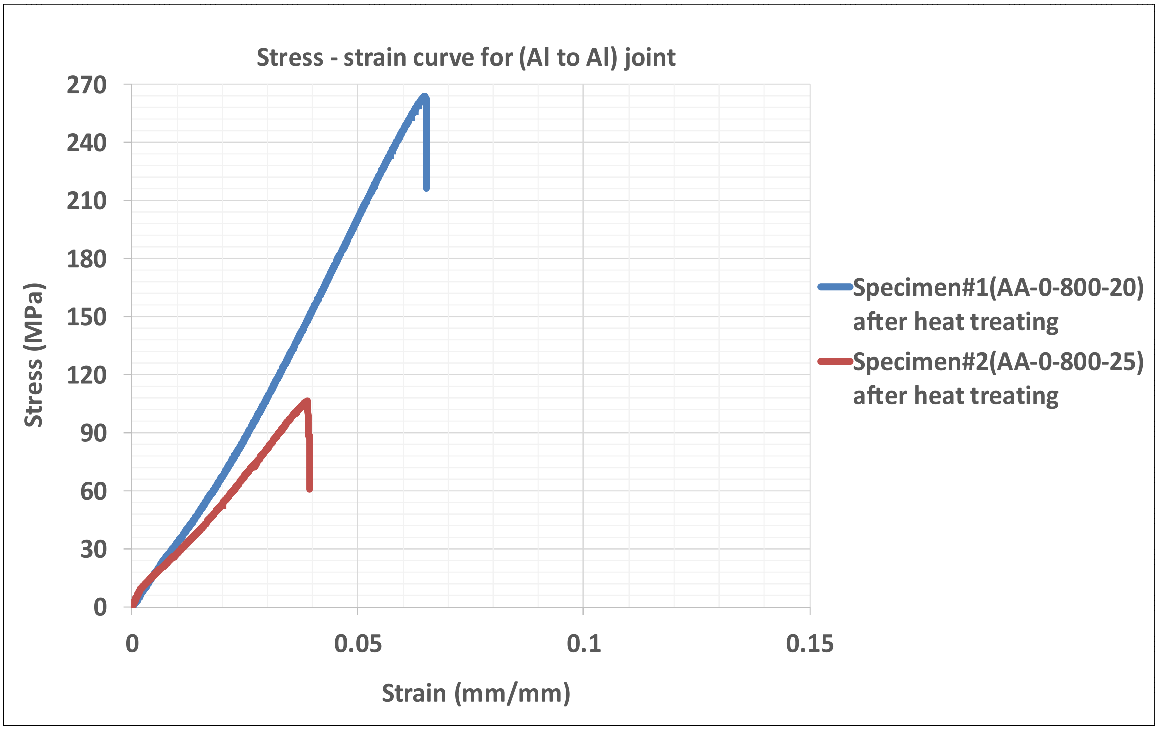


Figure (4.28) The stress – strain curve for tension test at the conditions (A and R are constant while T is varied)

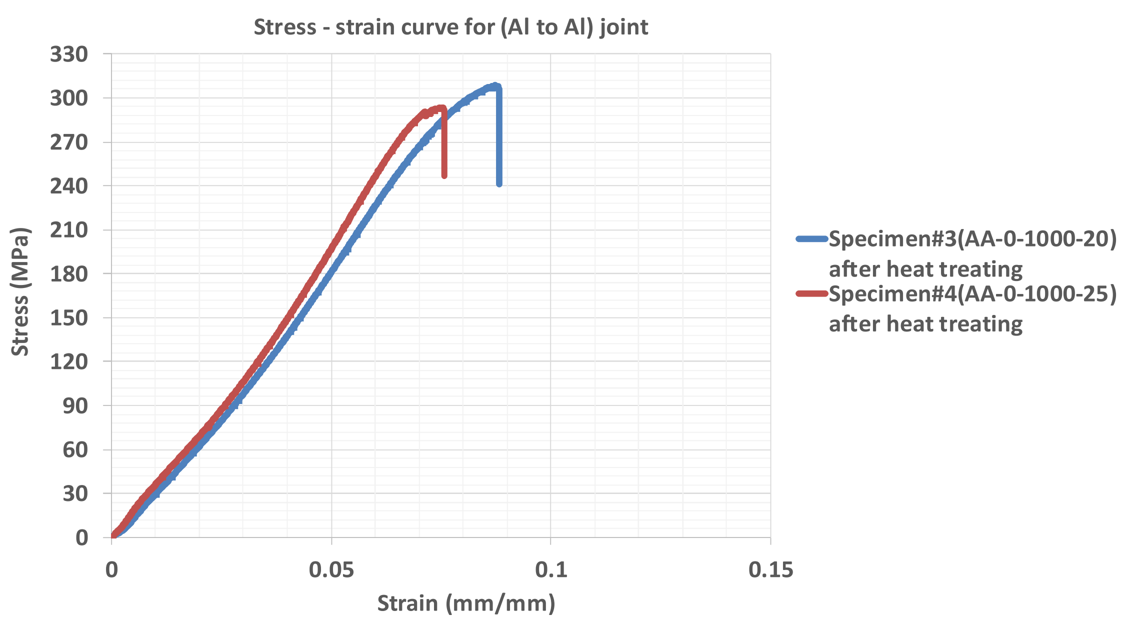


Figure (4.29) The stress – strain curve for tension test at the conditions (A and R are constant while T is varied)

Figures (4.28 and 4.29) compare the variation in strength for specimens #1, #2, #3, and #4. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #1 and #3 was 20 mm/min and when welding specimens #2 and #4 was 25 mm/min. There is a substantial difference between the two strength profiles, indicating a variation in travel speed over the range from 20 to 25 mm/min on an aluminum joint has a significant effect on the tension strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. It was concluded that the specimens that have a travel speed equal to 20 mm/min are stronger than the specimens with a travel speed equal to 25 mm/min, while the tilt angle and rotational speed are constant. As mentioned before, decreasing the travel speed parameter during friction stir welding can improve the mechanical properties of a joint, such as the strength. All the figures show that fracture occurred suddenly, without any indication, which means the joints were brittle.

4.7.6 Effect of Varying Rotation Speed after Heat Treatment

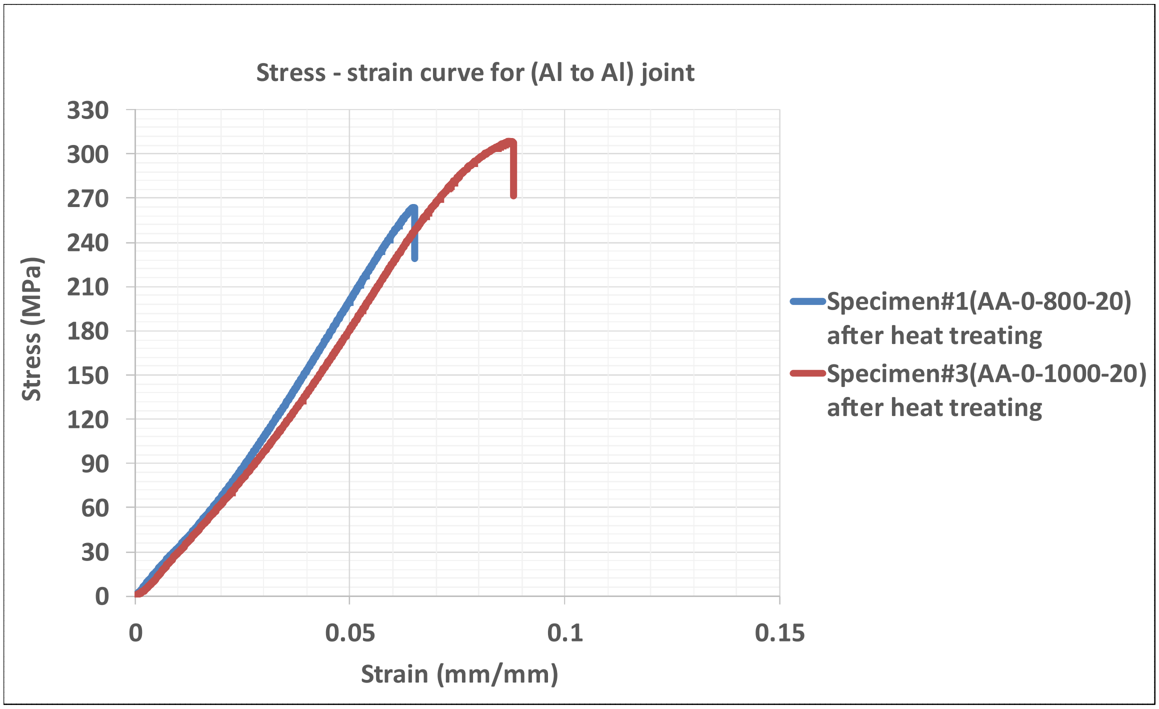


Figure (4.30) The stress – strain curves for tension test at the conditions (A and T are constant while R is varied)

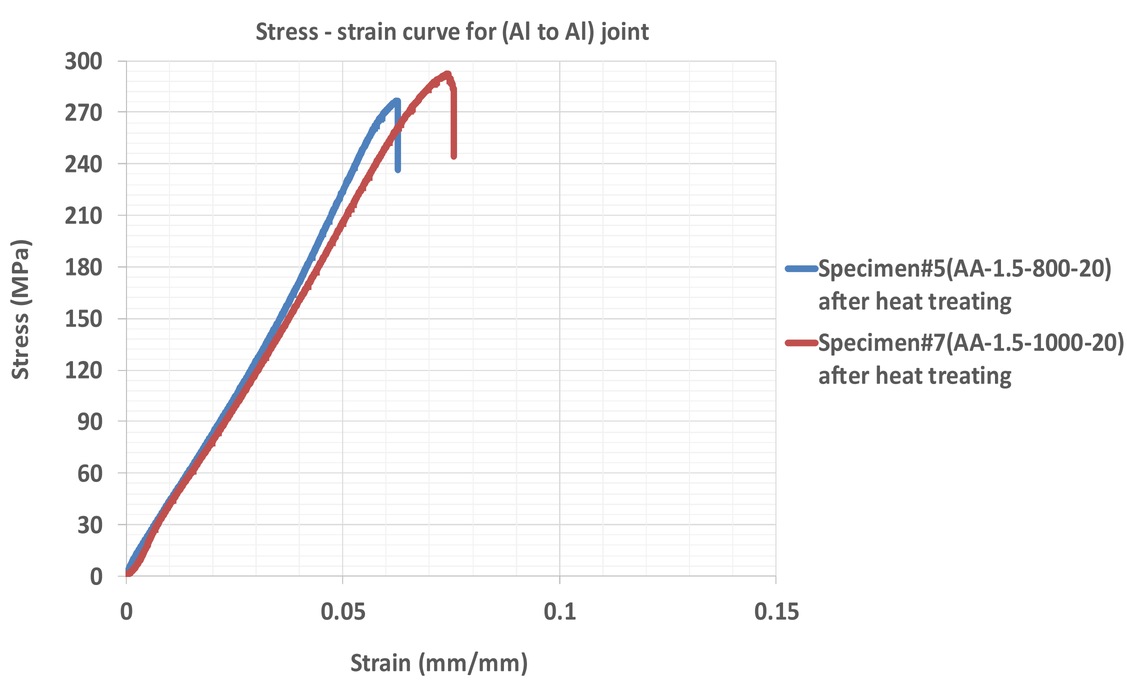


Figure (4.31) The stress – strain curves for tension test at the conditions (A and T are constant while R is varied)

Figures (4.30 and 4.31) compare the variation in strength for different specimens. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #1and #5 was 800 rpm and when welding specimens #3 and #7 was 1000 rpm. There is a substantial difference between the two strength profiles, indicating a variation in rotation speed over the range of 800 to 1000 rpm has a significant effect on the tension strength of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix. It was concluded that the specimens which have a rotational speed equal to 1000 rpm are stronger than the specimens with a rotational speed equal to 800 rpm. The experimental work showed this result while the tilt angle and travel speed were constant. In other words, increasing rotational speed during friction stir welding process generates sufficient temperatures between the shoulder and pin and the workpieces. As mentioned before, that sufficient heat will increase the stirring and mixing as well as soften the materials around the pin.

4.8 Bending Test

4.8.1 Bending Test Comparison before and after Heat Treatment

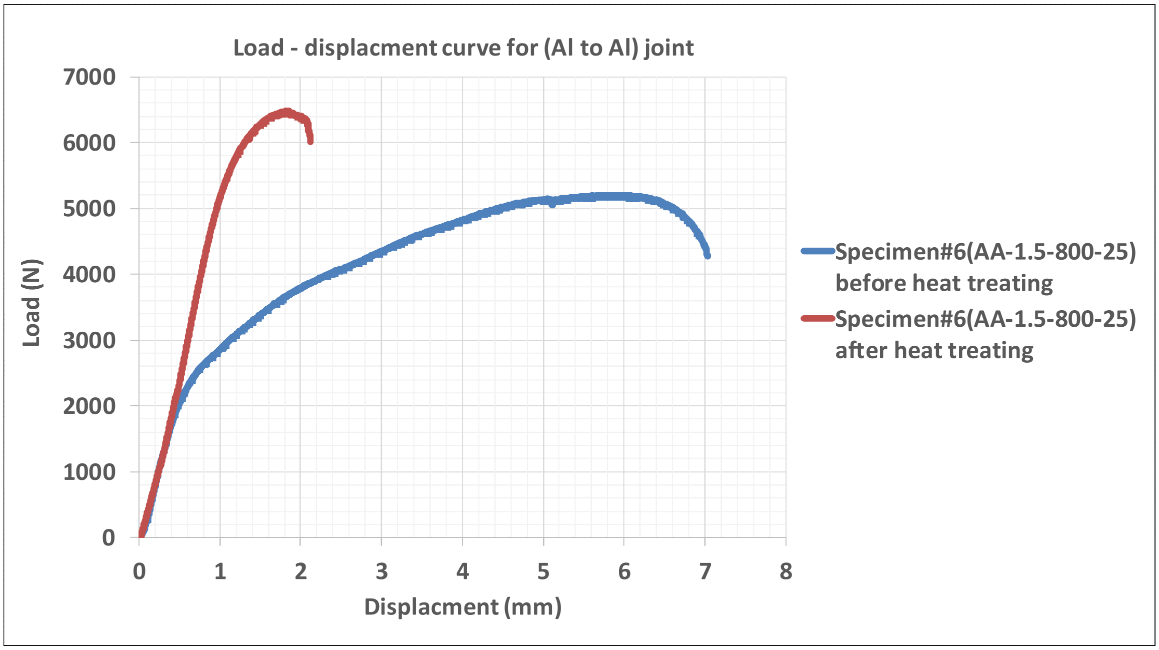


Figure (4.32) Load – displacement curves for bending test before and after heat treating

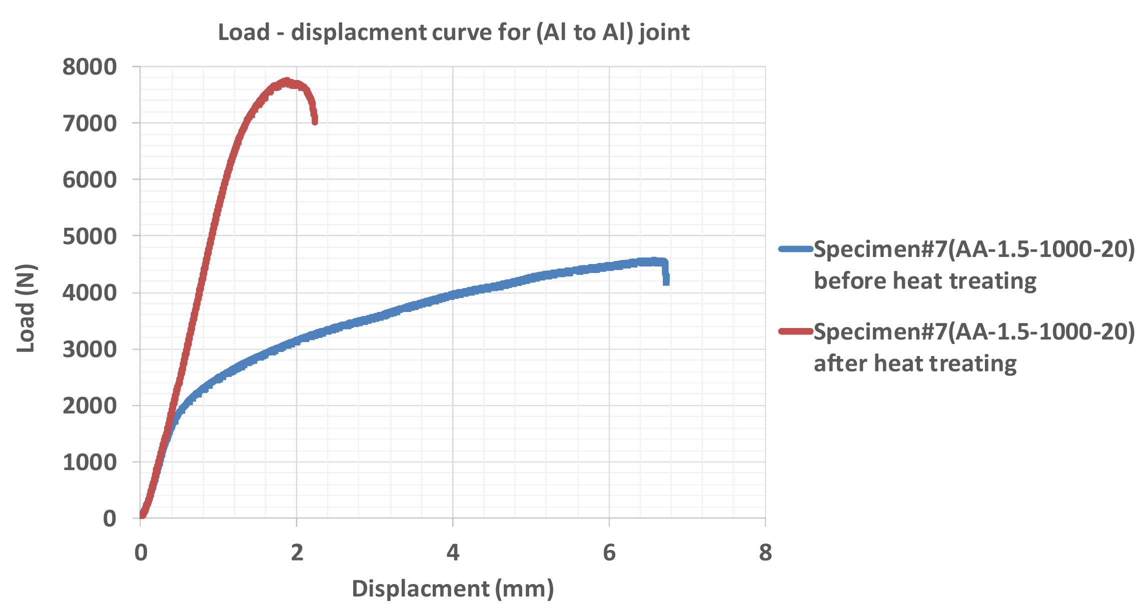


Figure (4.33) Load – displacement curves for bending test before and after heat treating

Tension tests were conducted on both the as-welded and the heat-treated conditions. Figures (4.32 and 4.33) show typical variations in strength over the friction stir welded zone. After FSW, the friction stir welded zone is softer than the base metal because the metal in the heated FSW zone softens during the welding process. Heat treatment restores the strength in the welded zone, and the joint strength becomes higher than it was before heat treatment. The welded zone strength before and after heat treatment is included for comparison. The strength of the welded metal after heat treatment is restored to the original strength of the starting 6061-T6 alloy. This means that the specimens after the heat treating process carry more load than the specimens before the heat treating process. The curve's behavior after the heat treating is brittle, as seen in load – displacement curves, which means fractures occurred suddenly, without any indication. The specimens before heat treating exhibit higher ductility since the weld region has been softened during the welding process and is more ductile. A similar observation was made for other combinations of welding conditions between different specimens as shown in the appendix.

4.9 Effect of Welding Parameters on Properties before and after Heat Treatment

4.9.1 Effect of Varying Tilt Angle before Heat Treatment

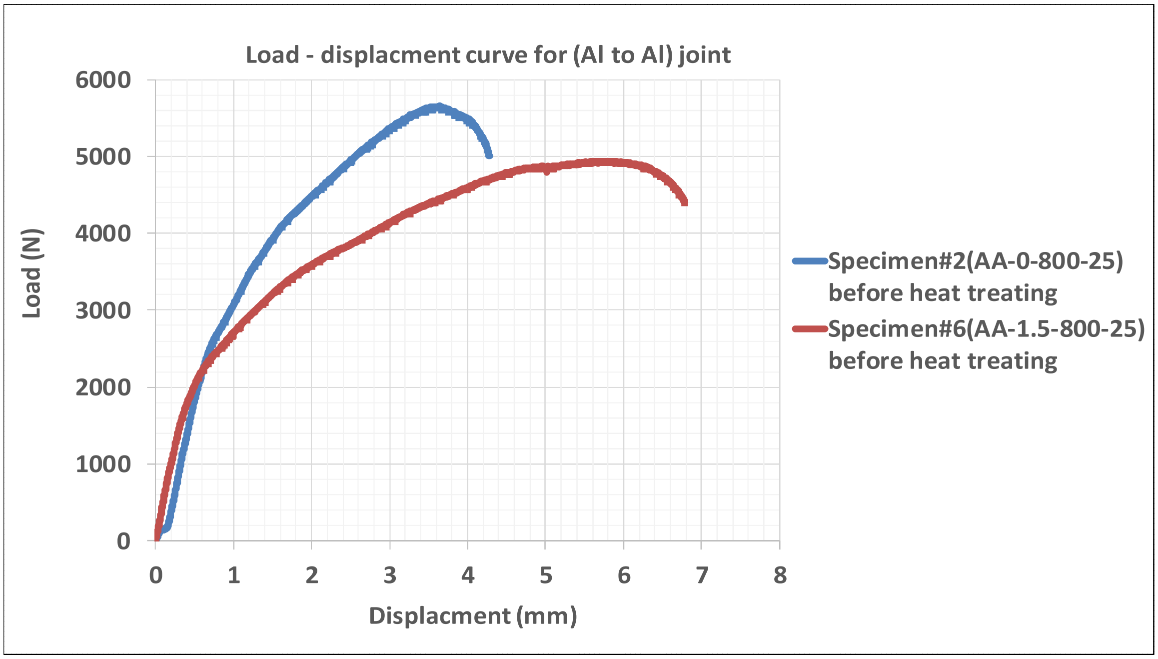


Figure (4.34) Load – displacement curves for bending test before heat treating

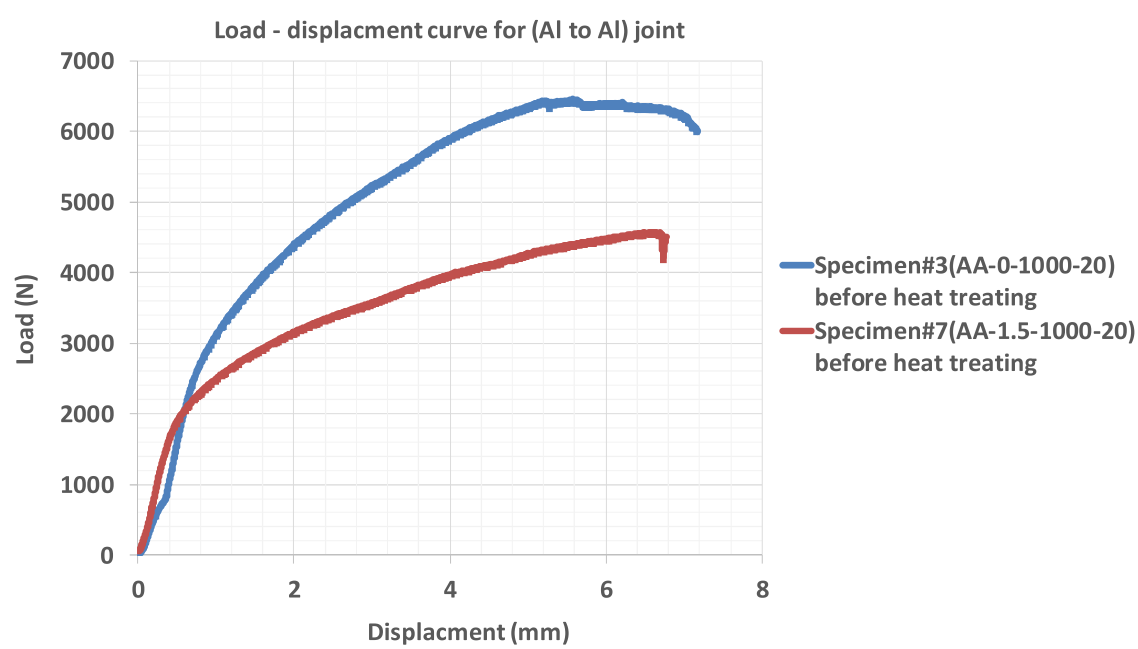


Figure (4.35) Load – displacement curves for bending test before heat treating

Figures (4.34 and 4.35) compare the variation in strength for the specimens #2, #3, #6, and #7. The specimens were welded using the same rotation and travel speeds, but specimens #2 and #3 were welded at a tilt angle of 0º and specimens #6 and #7 were welded at a tilt angle of 1.5º. There is a substantial difference between the two bending strength profiles, indicating a variation in tilt angle over the range of 0º to 1.5º has a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix. All specimens before the heat treating process with tilt angle equal to zero degree are stronger than specimens with a tilt angle equal to 1.5 degree. The comparison between different specimens according to their tilt angle before heat treating is more difficult. In other words, improving the mechanical properties, such as bending strength, by changing one of the friction stir welding parameters before heat treating was almost impossible because the variations in temperature as a result of friction. Also, the milling machine used for friction stir welding played an important role.

4.9.2 Effect of Varying Travel Speed before Heat Treatment

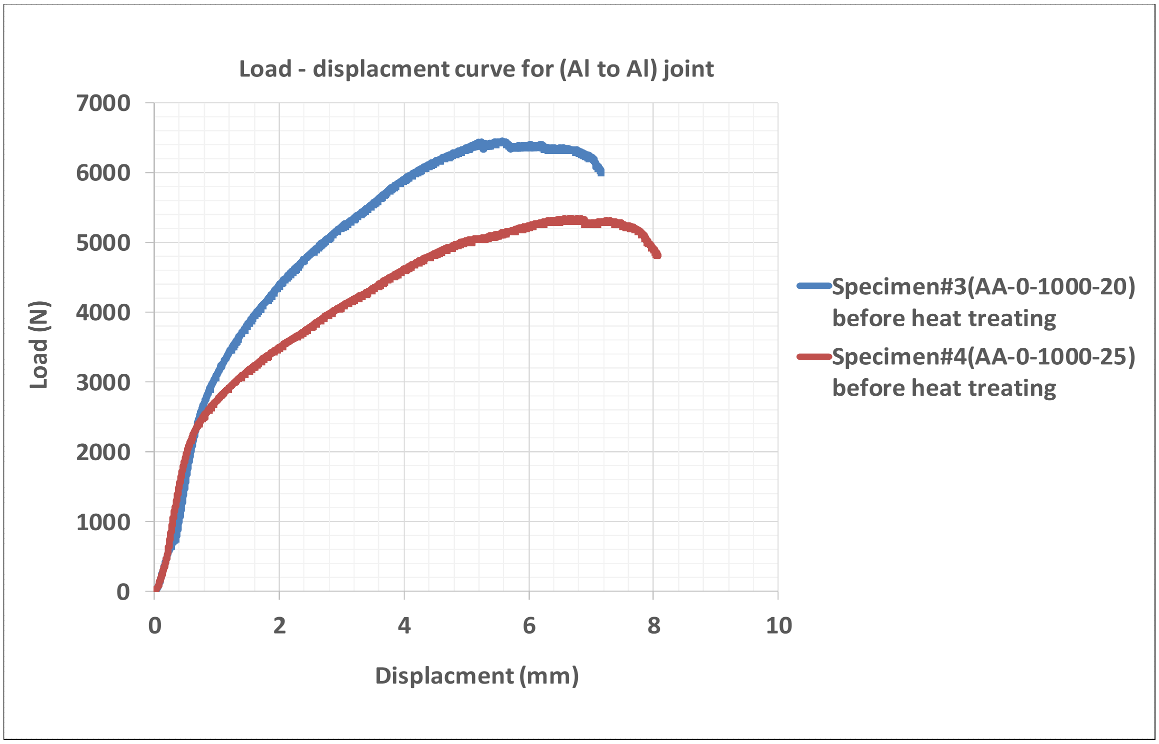


Figure (4.36) Load – displacement curves for bending test before heat treating

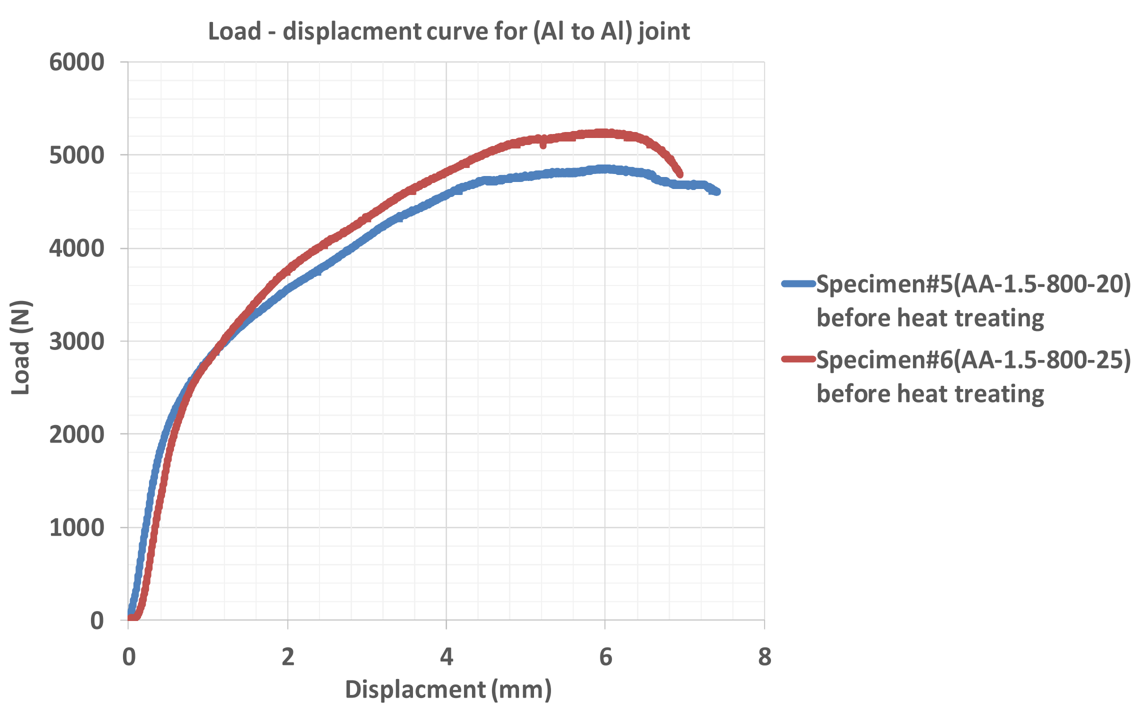


Figure (4.37) Load – displacement curves for bending test before heat treating

Figures (4.36 and 4.37) offer a comparison according to the variation in travel speed. Figure (4.36) shows that the specimen with a travel speed equal to 20 mm/min is stronger than the specimen with a travel speed equal to 25 mm/min. However, figure (4.37) shows that the specimen with a travel speed equal to 25 mm/min is stronger than the specimen with a travel speed equal to 20 mm/min. Again, the comparison before the heat treating process with a change in one of the welding parameters while the other two parameters are constant is difficult. That is because variations in temperature take place during FSW between more than one of welding zones. The experimental work result for figure (4.37) does not mimic the literature review results while figure (4.36) does [21]. The behavior of all the specimens is close to each other, which means using different values of travel speeds, such as 20 to 25mm/min, does not change the specimen behaviors before the heat treating process. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix.

4.9.3 Effect of Varying Rotation speed before Heat Treatment

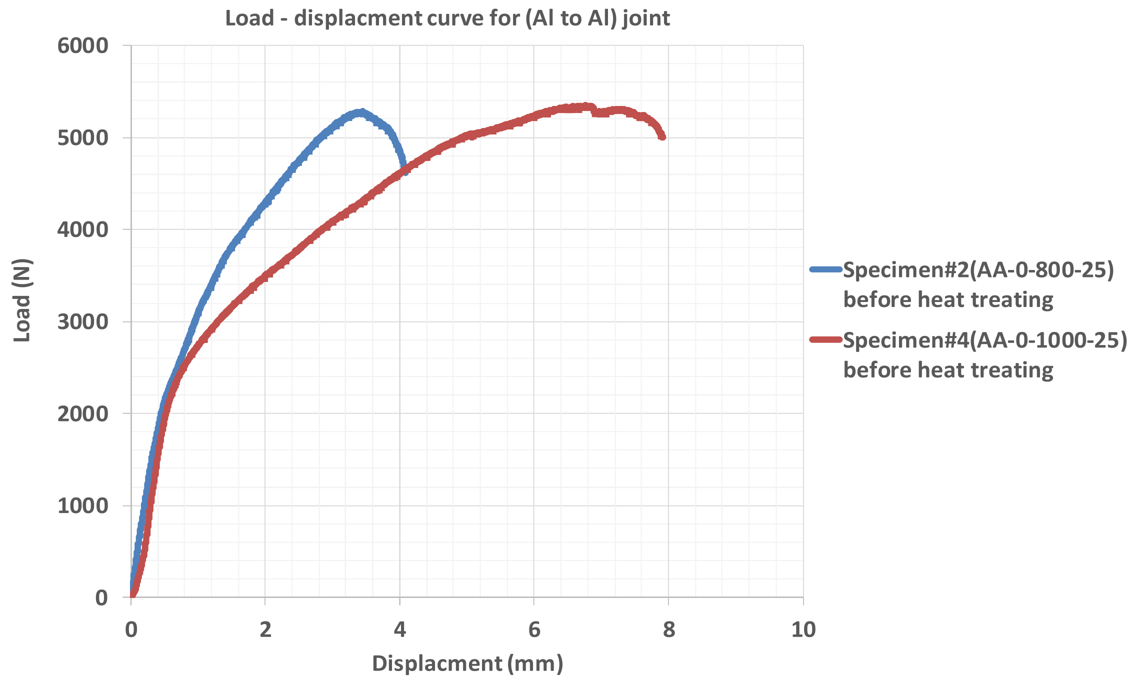


Figure (4.38) Load – displacement curves for bending test before heat treating

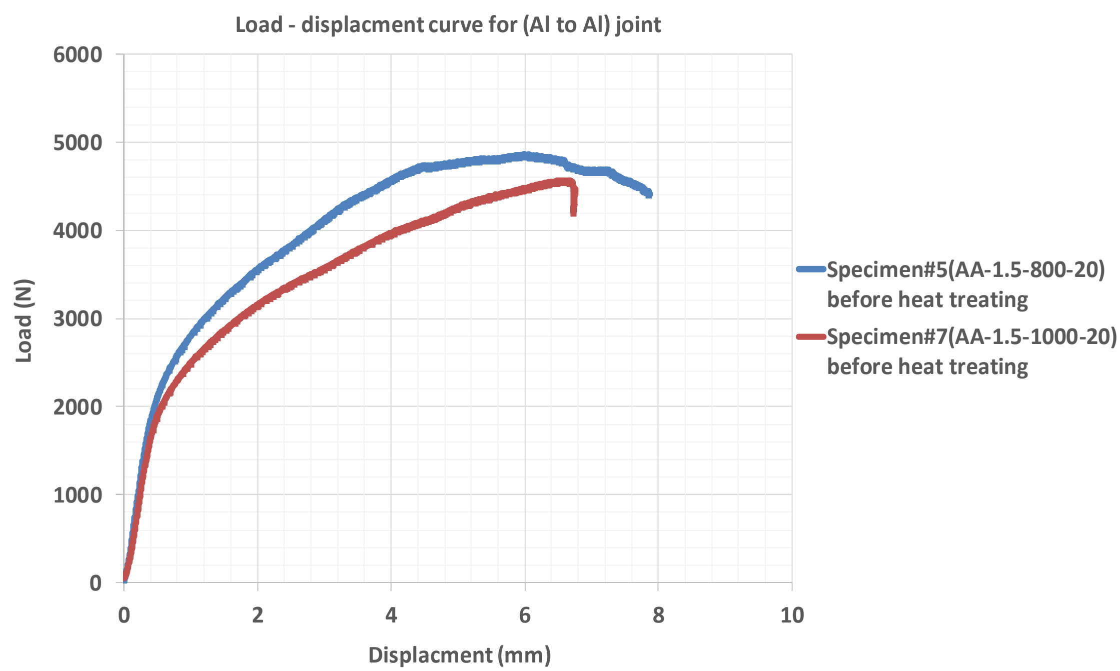


Figure (4.39) Load – displacement curves for bending test before heat treating

Figures (4.38 and 4.39) compare the variation in strength for specimens #2, #4, #5, and #7. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #2 and #5 was 800 rpm and when welding specimens #4 and #7 was 1000 rpm. There is a substantial difference between the two bending strength profiles, indicating a variation in rotation speed over the range of 800 to 1000 rpm has a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix. Those specimens were compared in load - displacement curves, with the tilt angle and travel speed are constant while rotation speed is varied. Figure (4.38) shows that the specimen at rotation speed equal to 1000 rpm is stronger than the specimen at rotation speed equal to 800 rpm. However, figure (4.39) shows that the specimen that have a rotation speed equal to 800 rev/min is stronger than the specimen with a rotation speed of 1000 rpm. So, the effect of the welding parameters on the joint properties before heat treating process is almost random and not regular. In other words, the specimen at 800 rpm carry more loads than the specimens at 1000 rpm.

4.9.4 Effect of Varying Tilt Angle after Heat Treatment

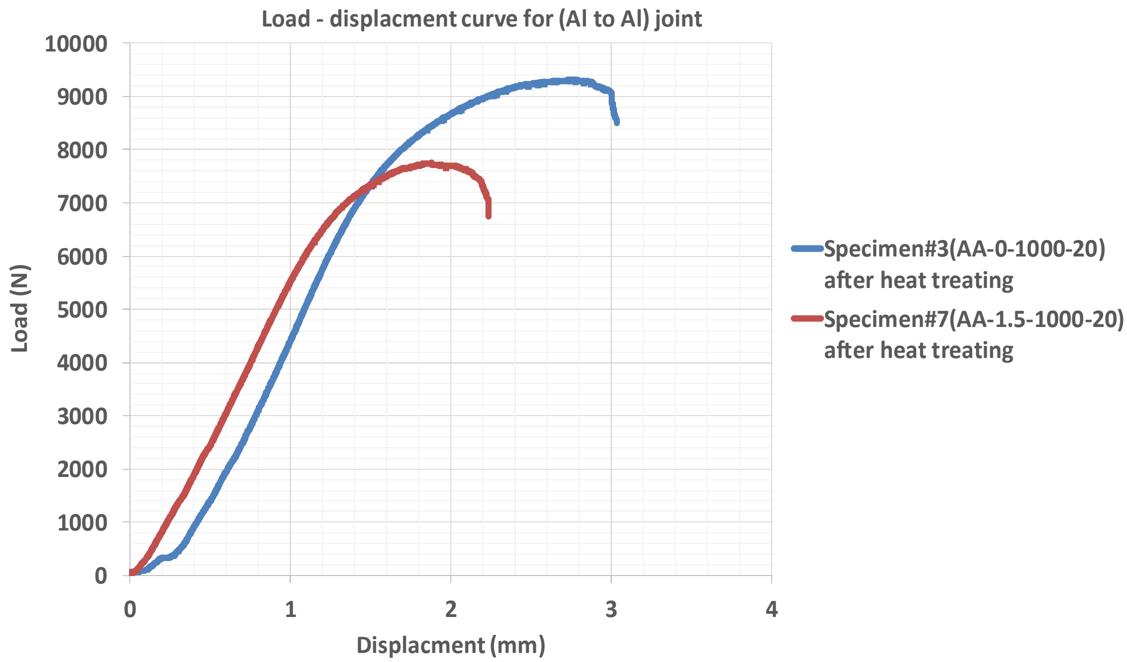


Figure (4.40) Load – displacement curves for bending test after heat treating

Figure (4.40) shows the effect of the tilt angle on the mechanical properties, such as the bending strength. This figure compare the variation in strength for specimen #3 and #7. The specimens were welded using the same rotation and travel speeds, but specimen #3 was welded with a tilt angle of 0º and specimen #7 was welded with a tilt angle of 1.5º. There is a substantial difference between the two strength profiles, indicating a variation in tilt angle over the range of 0º to 1.5º has a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix. The specimen at tilt angle of 0º is higher than the specimen at tilt angle of 1.5º. There are several reasons for this, but the most important one is the variations in temperature in the joint zone as a result of friction between both the shoulder and pin and the workpieces.

4.9.5 Effect of Varying Travel Speed after Heat Treatment

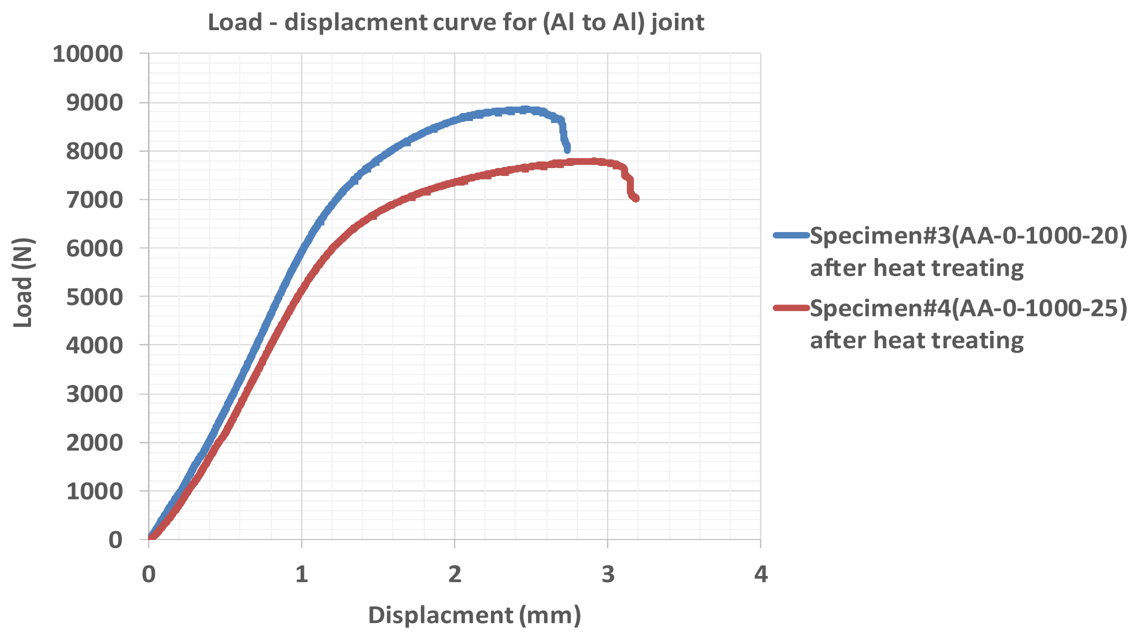


Figure (4.41) Load – displacement curves for bending test after heat treating

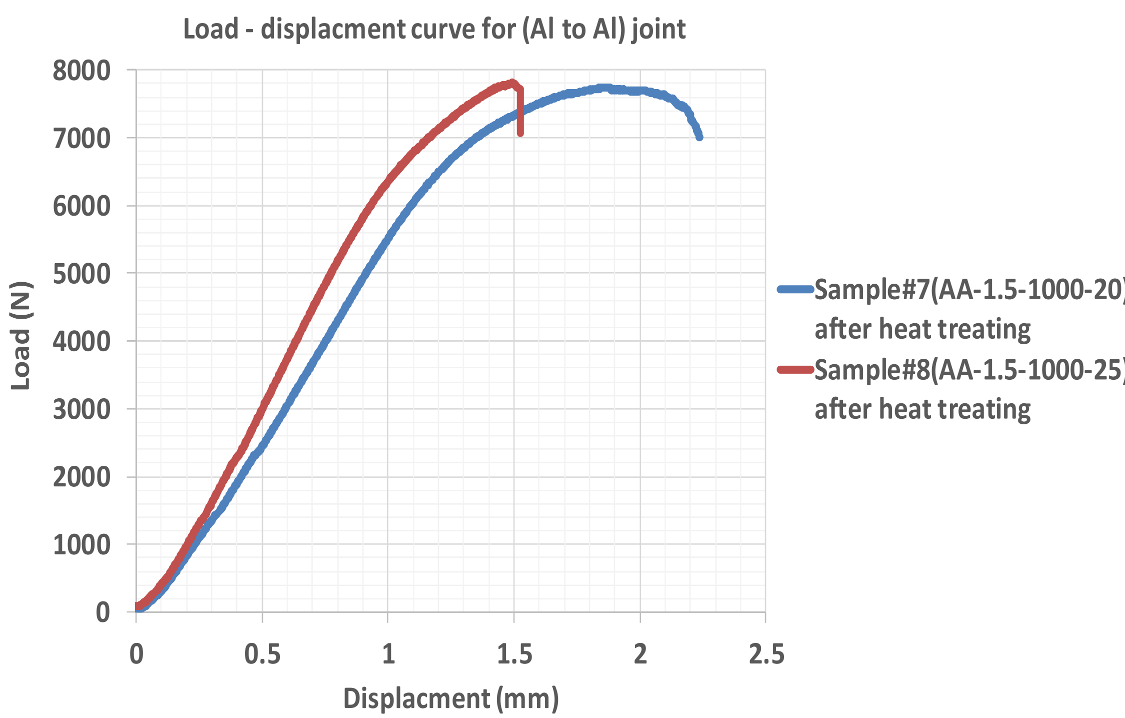


Figure (4.42) Load – displacement curves for bending test after heat treating

Figures (4.41 and 4.42) compare the variation in strength for specimens #3, #4, #7 and #8. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #3 and #7 was 20 mm/min and that when welding specimens #4 and #8 was 25 mm/min. There is a substantial difference between the two strength profiles, indicating the variation in travel speed over the range of 20 to 25 mm/min has a significant effect on the bending strength of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. The effect of the travel speed on mechanical properties, such as the strength, was random. Figure (4.41) shows that the specimen at travel speed equal to 20 mm/min is stronger than the specimen at travel speed equal to 25 mm/min. However, figure (4.42) shows that the specimen with travel speed of 20 mm/min has same the strength of the specimen with travel speed of 25 mm/min. That is due to the variations in temperature in the welded zone and the imperfection of the milling machine.

4.9.6 Effect of Varying Rotation Speed after Heat treatment

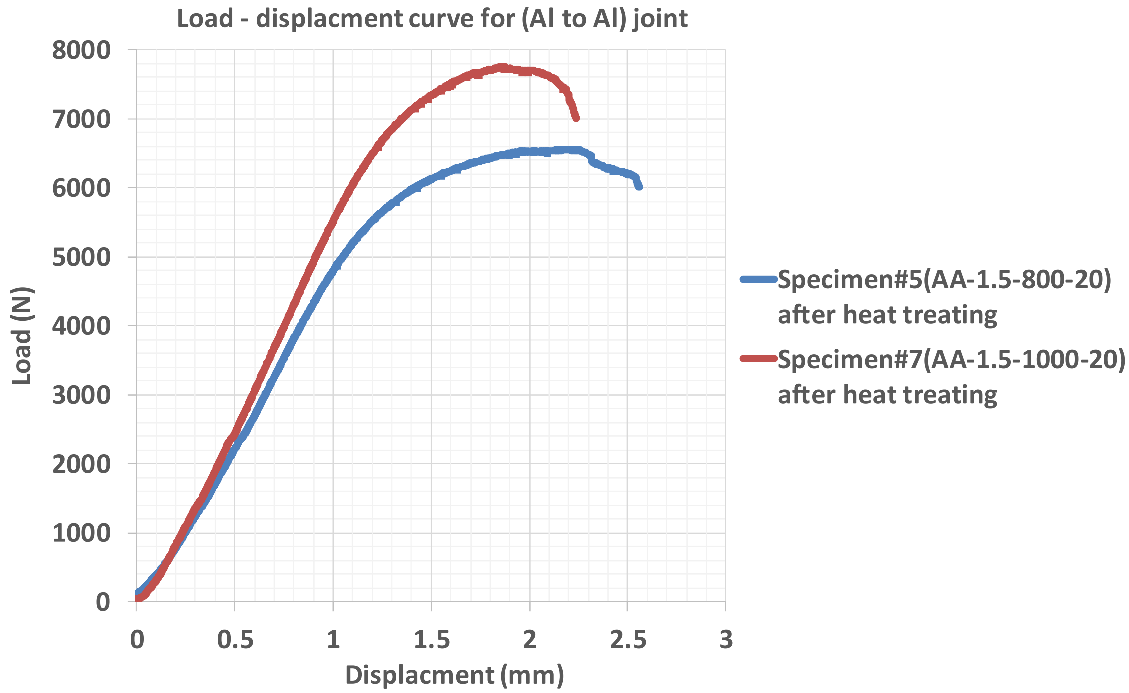


Figure (4.43) Load – displacement curves for bending test after heat treating

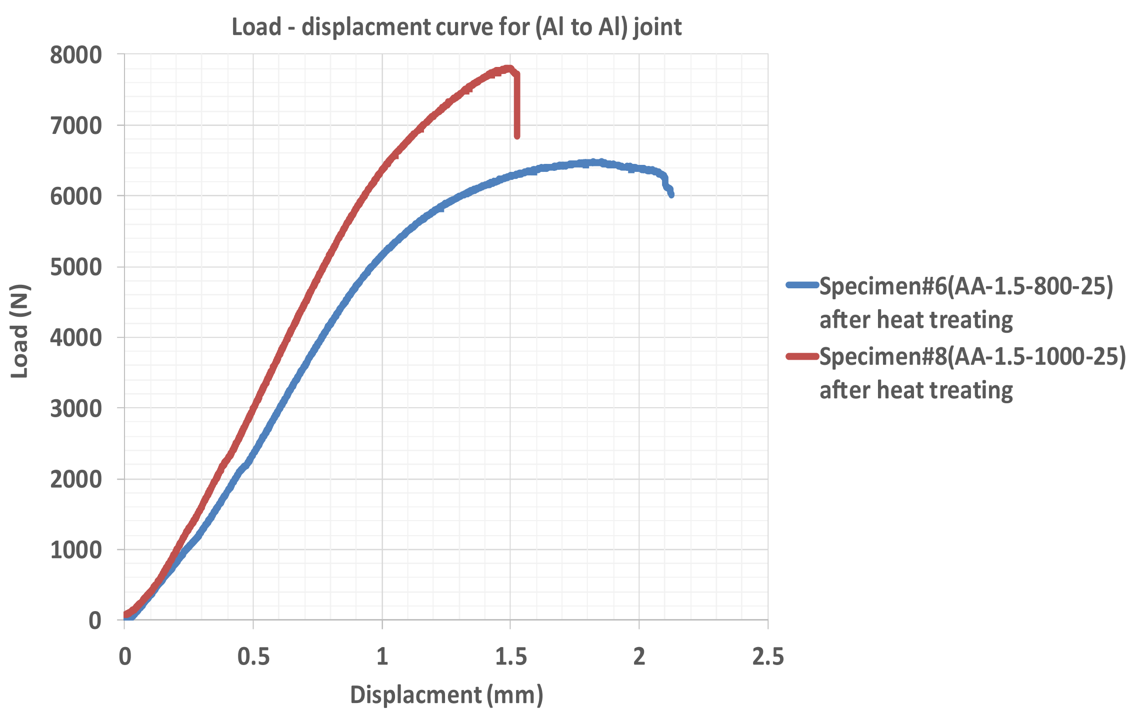


Figure (4.44) Load – displacement curves for bending test after heat treating

Figures (4.43 and 4.44) compare the variation in bending strength for different specimens. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #5 and #6 was 800 rpm and when welding specimens #7 and #8 was 1000 rpm. All the specimens that had higher rotation speed were stronger than the specimens with a lower rotation speed. So, there is a substantial difference between the two strength profiles, indicating the variation in rotation speed over the range of 800 to 1000 rpm has a significant effect on the strength of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix. This experimental work result matches the literature review results. The heat treating process, that included solid solution and aging returns the Al (6061-T6) joint to its original properties. This is what was observed, as seen in the figures. The welding parameters played a significant role in the strength profiles after welding, and it can be expected that after heat treatment, all the bending strength profiles will be stronger at a rotation speed equal to 1000 rpm for all welding conditions.

4.10 Microstructure Test

4.10.1 Optical micrograph for (Al to Al) joint before and after heat treating

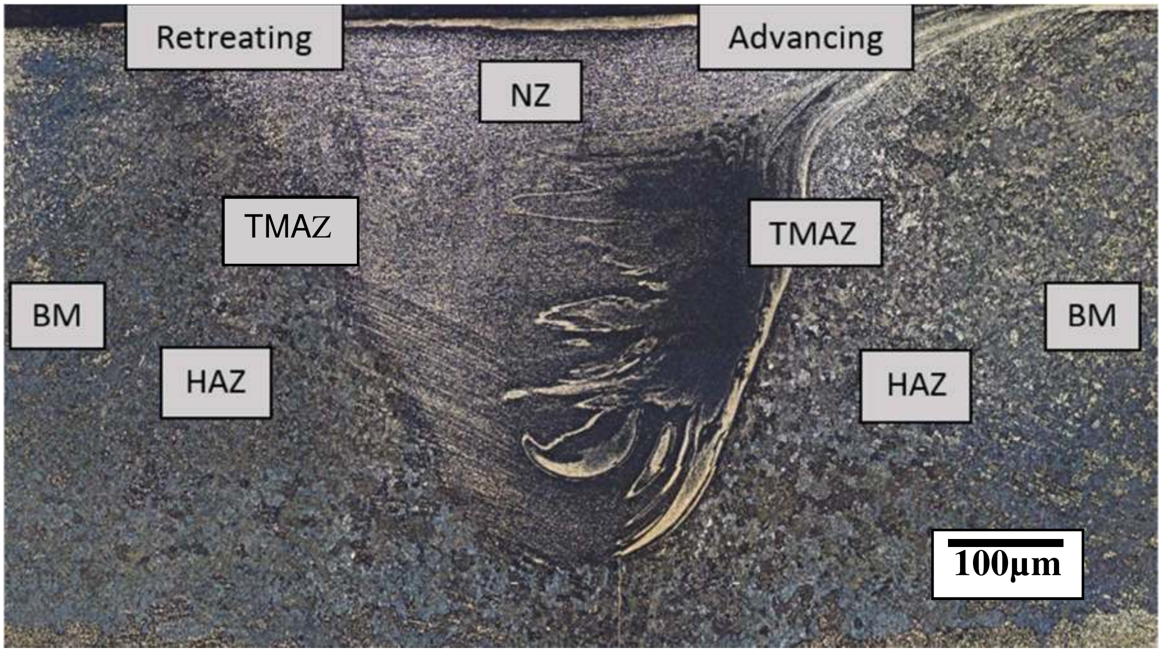


Figure (4.45) Optical micrograph for (Al –Al) joint at the conditions (AA-0-1000-20)

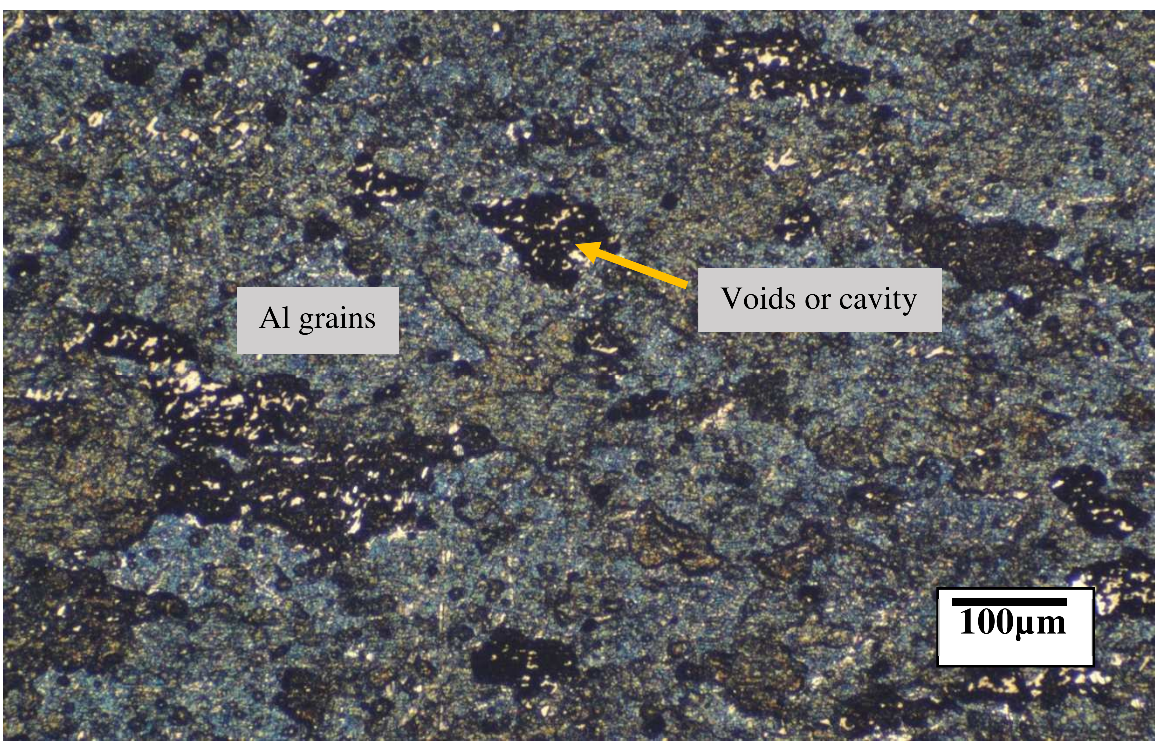


Figure (4.46) Optical micrograph for (Al-Al) joint at the conditions (AA-0-800-25)

According to the figure (4.45), which represent the microstructure for Al (6061-T6) before the heat treating process, the nugget zone has finer grains compared to the thermos mechanically affected zone. Nugget zone can be defined as the area which has direct interaction with the tool pin [58]. Recrystallization can take place due to both the strain and elevated temperature during the welding. The finer dispersed equiaxed grains seen in the nugget zone as a result of dynamic recrystallization process have a magnitude of grain size that is smaller than in the other regions. That means the nugget zone should be harder because it has finer grains. The main reason for the softening joint is the thermal cycles that happen during friction stir welding. These cycles can cause strengthening precipitates, which coarsen or even dissolve the grains. Generally, the friction stir welding microstructure is complex and mainly depends on type of the weld region as well as on its position. Thermos mechanically affected zone is a friction stir welding area which can deform plastically, thermal cycles in this zone can affect the material and microstructure. The third zone, as shown in Figure (4.45), is the heat affected zone (HAZ). Plastic deformation did not occur in this region because it lies far away from the nugget zone or welding center. This region is influenced by the thermal cycles, which affects the microstructure and mechanical properties. The last zone is the base metal. This zone is not deformed plastically and can be experienced by the thermal cycles because the welding [59]. The heat or thermal cycles in the base metal zone do not affect the mechanical properties or the microstructure. Some defects take place, such as the cavity and voids, as shown in Figure (4.46). These defects occur because of the variations in temperature between more than one of the welding zones. Also, some of the intermetallic compounds form during the friction stir welding process because it is solid state welding.

4.11 Friction stir welding between Al (6061-T6) and (1018 steel)

The friction stir welding process was successful between these two dissimilar materials. The friction stir welding process was carried out by fixing the 1018 steel on the advancing side while the aluminum on the retreating side. The welding was conducted by adjusting the pin position with a quarter of diameter at the steel side and the other three quarters at the aluminum side. The base metal hardness for 1018 steel was high, reaching 102 HRF so a heat treatment process was done. An annealing process was done to decrease the high hardness by holding the specimens in the furnace from 870 to 910 Cº. All the procedures done with Al (6061-T6) specimens were also done with this type of dissimilar welding. The figures below show the welding joint, the tension fracture, the bending fracture, the microstructure specimens, and the hardness indenter position between each two points.

Figure (4.47) Friction stir welding specimen between Al (6061-T6) and (1018 steel)

Figure (4.48) Shows the fracture after tension test

Figure (4.49) Shows the hardness positions and the fracture after bending test

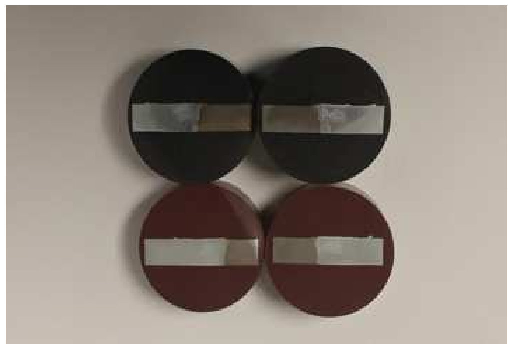


Figure (4.50) Microstructure specimens

Table (4.3) Friction stir welding parameters for aluminum to steel joint

Specimens#	Specimen lapel	Tilt angle (degree)	Rotational speed (RPM)	Travel speed setting (mm/min)
1	AS-0-800-10	0	800	10
2	AS-0-800-12	0	800	12
3	AS-0-1000-10	0	1000	10
4	AS-0-1000-12	0	1000	12
5	AS-1.5-800-10	1.5	800	10
6	AS-1.5-800-12	1.5	800	12
7	AS-1.5-1000-10	1.5	1000	10
8	AS-1.5-1000-12	1.5	1000	12

4.12 Results of the Hardness Test

4.12.1 Hardness Comparison before and after Heat Treatment

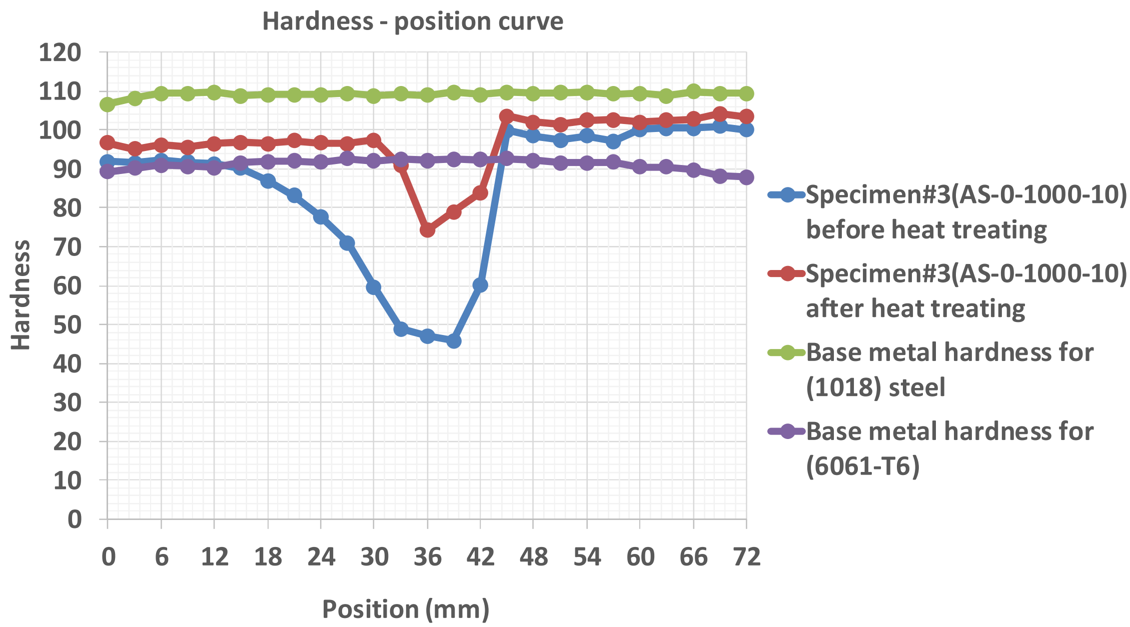


Figure (4.51) The Hardness – position curves before and after heat treating

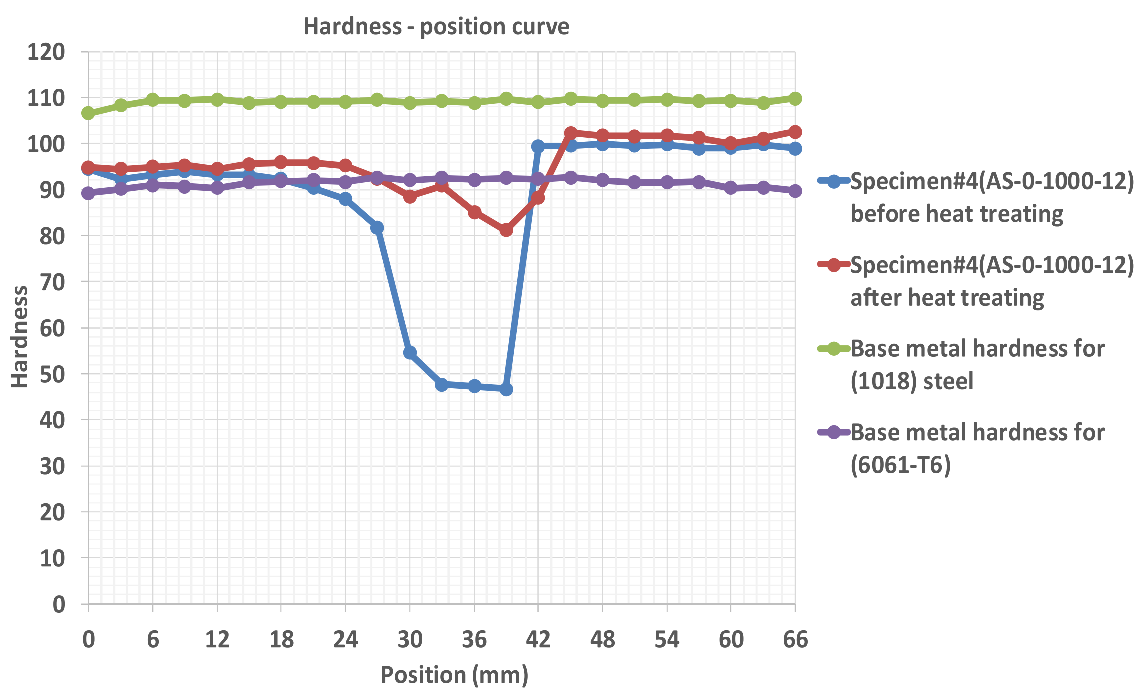


Figure (4.52) The Hardness – position curves before and after heat treating

Hardness tests were conducted on both the as-welded and the heat-treated conditions. Figures (4.51 and 4.52) show typical variations in hardness over the friction stir welded zone. After FSW, the friction stir welded zone is softer than the base metal because the metal in the heated FSW zone softens during the welding process (blue line). Heat treatment restores the strength in the welded zone, and the hardness is higher across the entire welded region (red line) than before heat treatment (blue line). The hardness of the starting base metal of steel (green line) and aluminum (purple line) are included for comparison. These figures show the hardness comparison between each two specimens, before and after the heat treating process, which have same the welding parameters. The welding parameters are tilt angle, rotation speed and travel speed, which were used for the welding of aluminum to steel joints. All the graphs show that the joint before the heat treating process was softer. However, there was an increase in joint hardness after the heat treating process, but the hardness still was not constant. The base metal hardness of aluminum and steel sides before and after the heat treating process was higher than the reference base metal of aluminum, as seen in Figures (4.51 and 4.52). As mentioned before, the improvement in joint hardness after the heat treating process is because heat treating process restores the joint to its original properties. This means that the variations in temperature during friction stir welding process affect the mechanical properties, such as the hardness. According to the graphs, the right side has higher hardness than the left side because the right side represents the base metal of steel while the left side represents the aluminum base metal. So, the aluminum side should be lower in hardness than the steel side.

4.13 Effect of Welding Parameters on Properties before and after Heat Treatment

4.13.1 Effect of Varying Tilt Angle before Heat Treatment

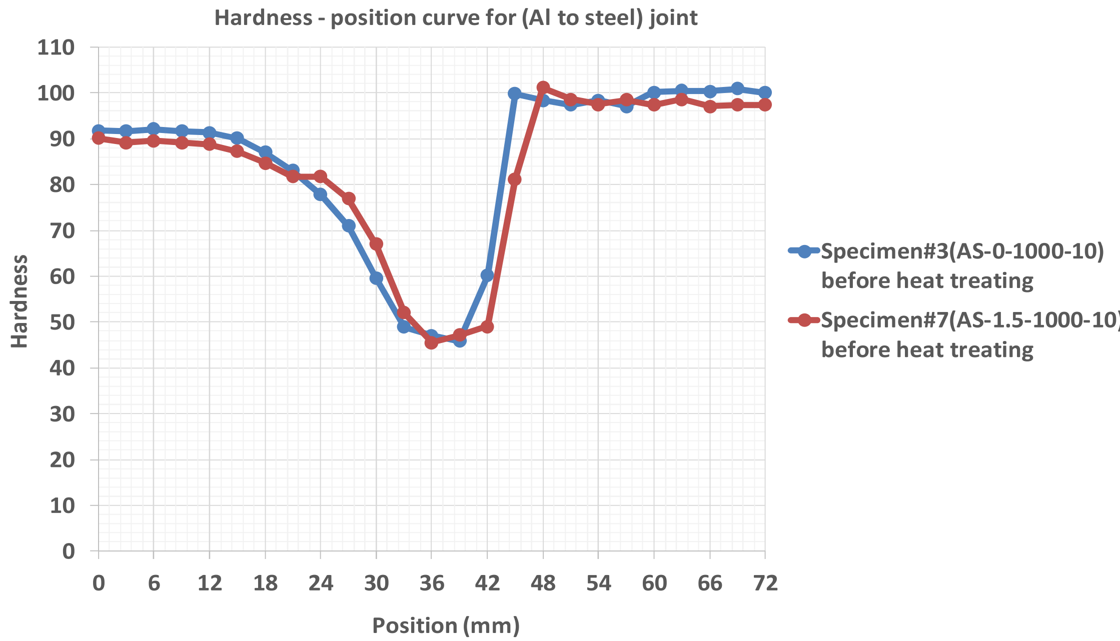


Figure (4.53) Hardness – position curves for the comparison before heat treating

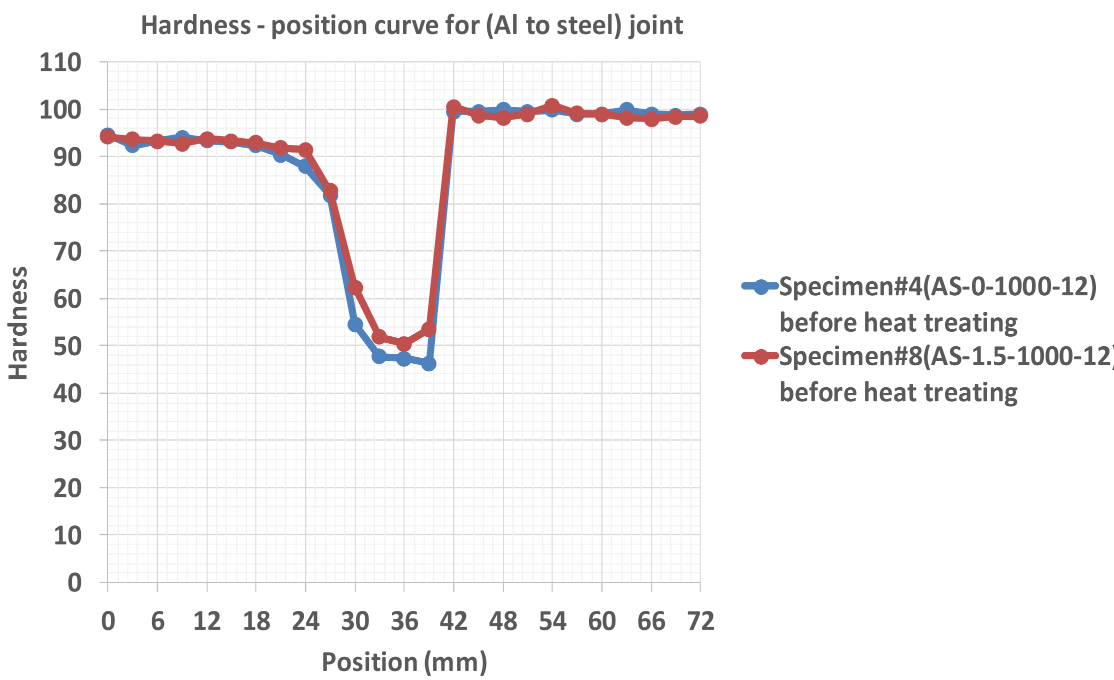


Figure (4.54) Hardness – position curves for the comparison before heat treating

Figures (4.53 and 4.54) compare the variation in hardness for specimen #3, #4, #7 and #8. The specimens were welded using the same rotation and travel speeds, but specimen #3 and #4 were welded with a tilt angle of 0º and specimen #7 and #8 were welded with a tilt angle of 1.5º. There is no substantial difference between the two hardness profiles, indicating the variation in tilt angle over the range of 0º to 1.5º has no significant effect on the hardness of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the tilt angle varied as shown in the appendix. The comparison in hardness took place between specimens that had same rotation and travel speeds but different tilt angles for friction stir welding of aluminum - steel joints. All the graphs show the same overall hardness, which means that the tilt angle does not have an effect on the mechanical properties, such as the hardness, especially before the heat treating process. In other words, the specimens are close to each other in hardness for both the base metals and the joint regions. Another comparison took place between the right and the left sides. The right side had a higher hardness than the left side because it represents the steel base metal.

4.13.2 Effect of Varying Travel Speed before Heat Treatment

Figure (4.55) Hardness – position curves for the comparison before heat treating

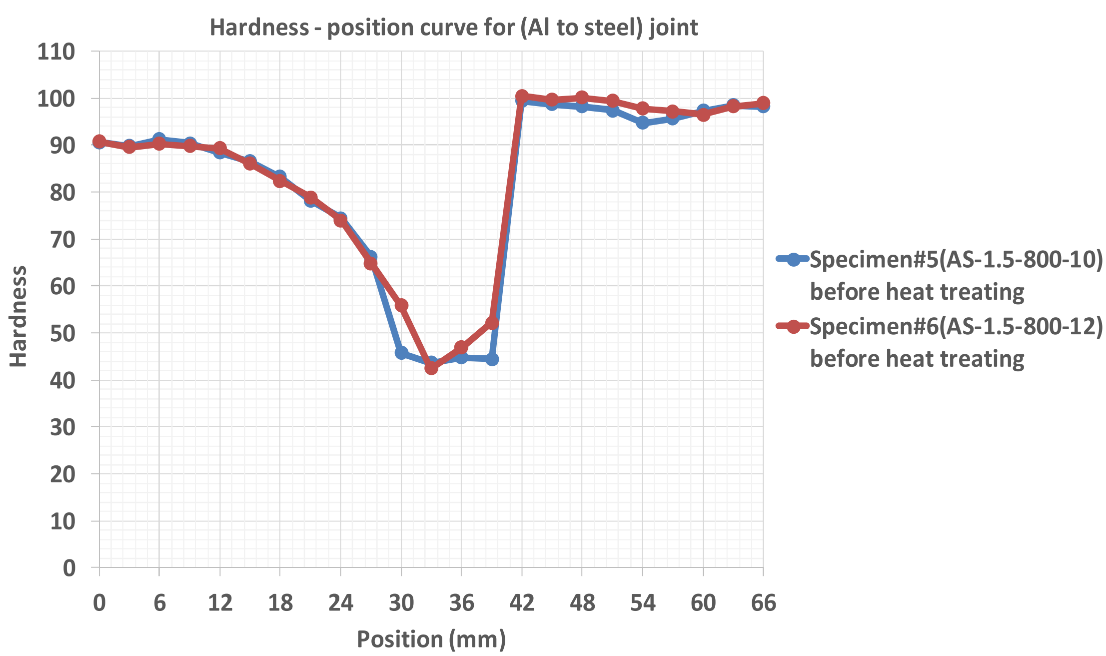


Figure (4.56) Hardness – position curves for the comparison before heat treating

Figures (4.55 and 4.56) compare the variation in hardness for four specimens. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #3 and #5 was 10 mm/min and when welding the specimens #4 and #6 was 12 mm/min. There was no substantial difference between the two hardness profiles, indicating the variation in travel speed over the range from 10 to 12 mm/min had no significant effect on the hardness of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. This comparison was done between each two specimens and before the heat treating process. All the graphs show that the hardness curve behavior of the two specimens is close to each other overall. This means that the travel speed effect is almost nonexistent, especially before the heat treating process. According to the graphs, it is predicted that the right side hardness is higher than the left side because the first one represents the base metal of steel.

4.13.3 Effect of Varying Rotation Speed before Heat Treatment

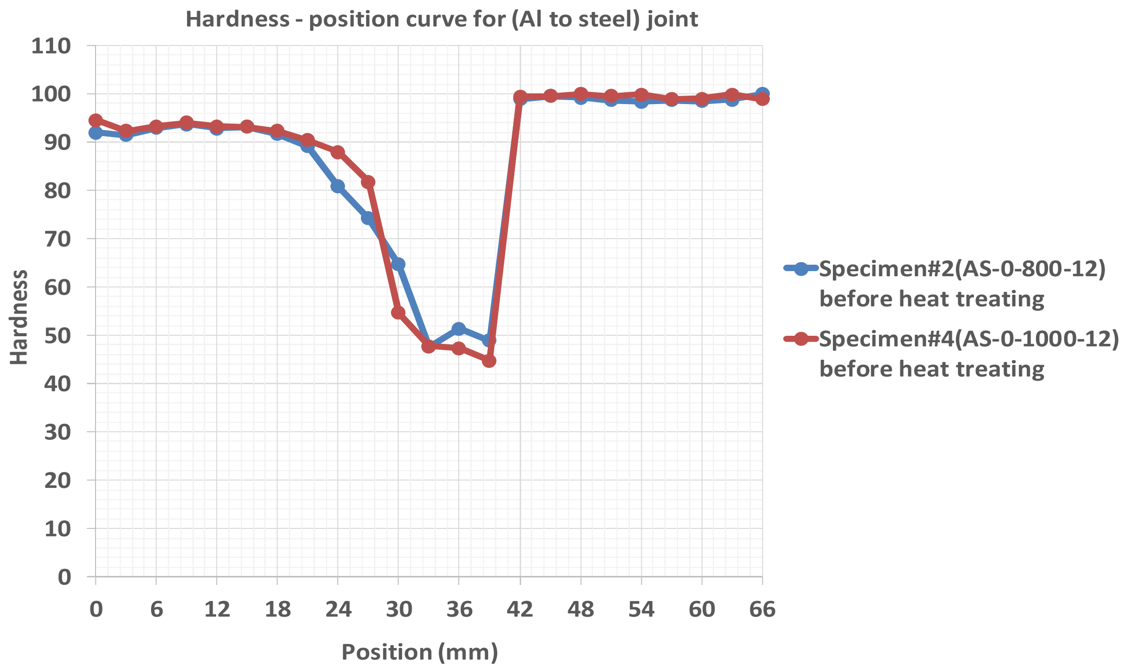


Figure (4.57) Hardness – position curves for the comparison before heat treating

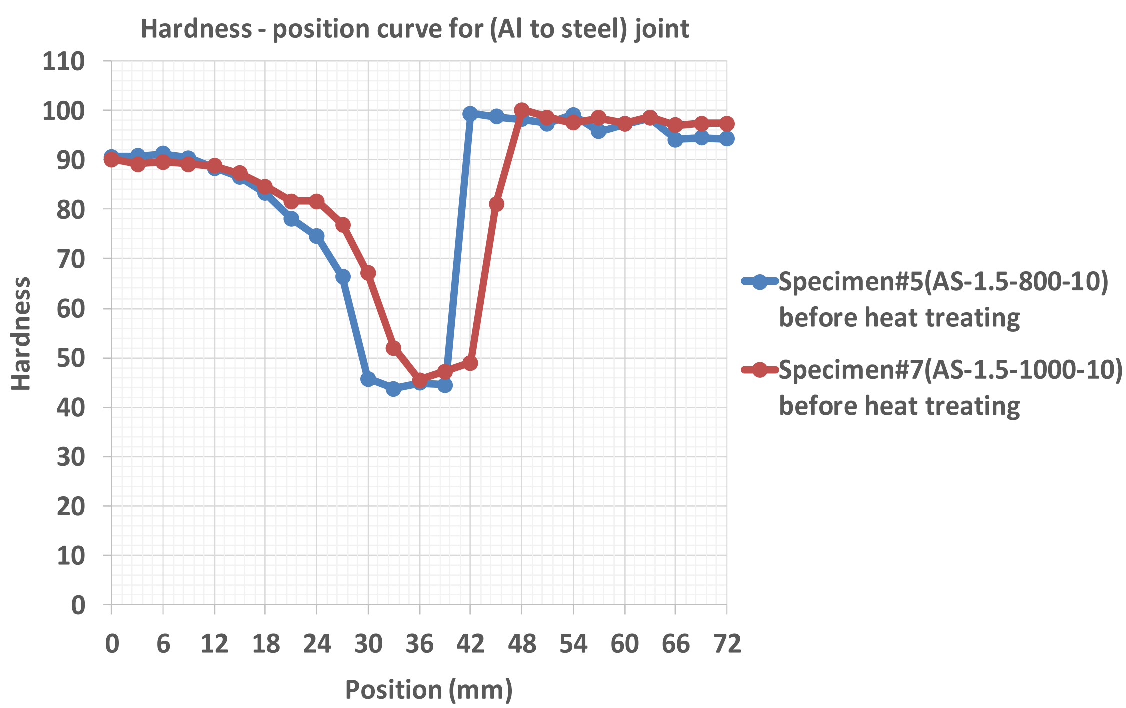


Figure (4.58) Hardness – position curves for the comparison before heat treating

Figures (4.57 and 4.58) compare the variation in hardness for specimens #2, #4, #5 and #7. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #2 and #5 was 800 rpm and when welding specimens #4 and #7 was 1000 rpm. There was no substantial difference between the two hardness profiles, indicating the variation in rotation speed over the range of 800 to 1000 rpm had no significant effect on the hardness of the welded samples. A similar observation was made for other combinations of welding conditions between different specimens in which only the rotation speed was varied as shown in the appendix. According to the curves, the comparison of hardness between the two specimens took place when the tilt angle and travel speed were constant and the rotation speed was variable. The hardness for the two specimens looked the same, but there was a variation in some points. This means that the effect of rotation speed on the mechanical properties before the heat treating process is almost nonexistent. The reason for big variations in heat generation was a result of the friction between the shoulder and pin with the workpieces. These variations order the alloy elements, and thus the atoms, randomly. Therefore, there is no effect of the rotation speed on the mechanical properties such as the hardness before the heat treating process when the tilt angle and travel speed are constant. As mentioned before, the right side of the graph has higher hardness than the left because the right side represents the steel base metal.

4.13.4 Effect of Varying Tilt Angle after Heat Treatment

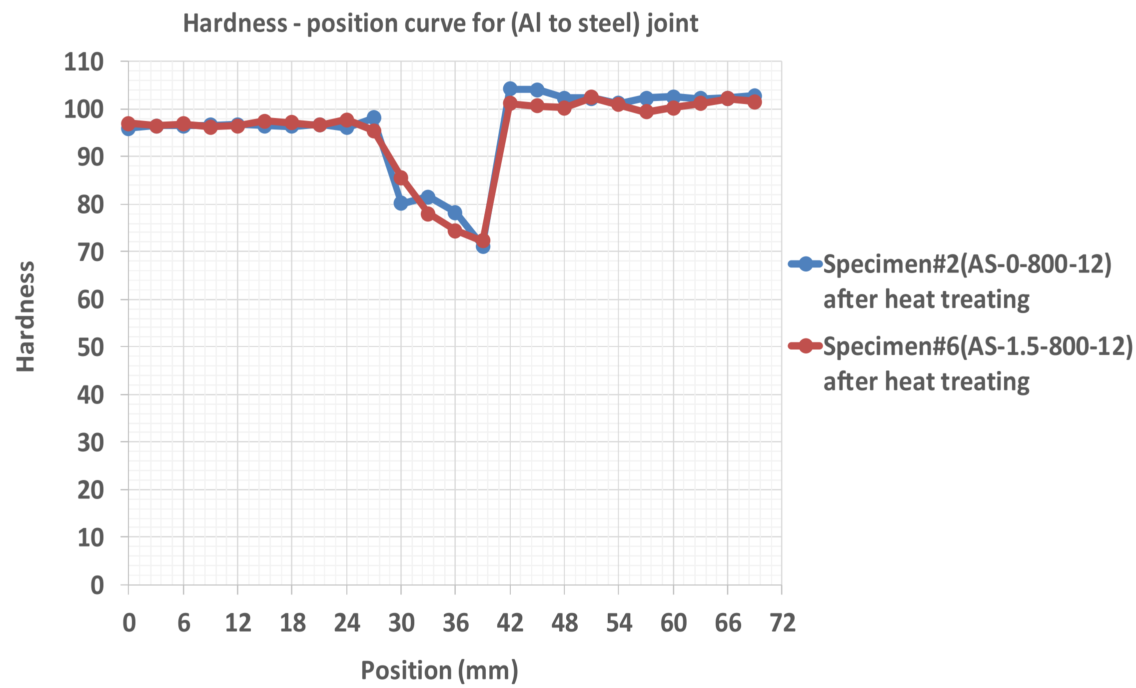


Figure (4.59) Hardness – position curves for comparison after heat treating

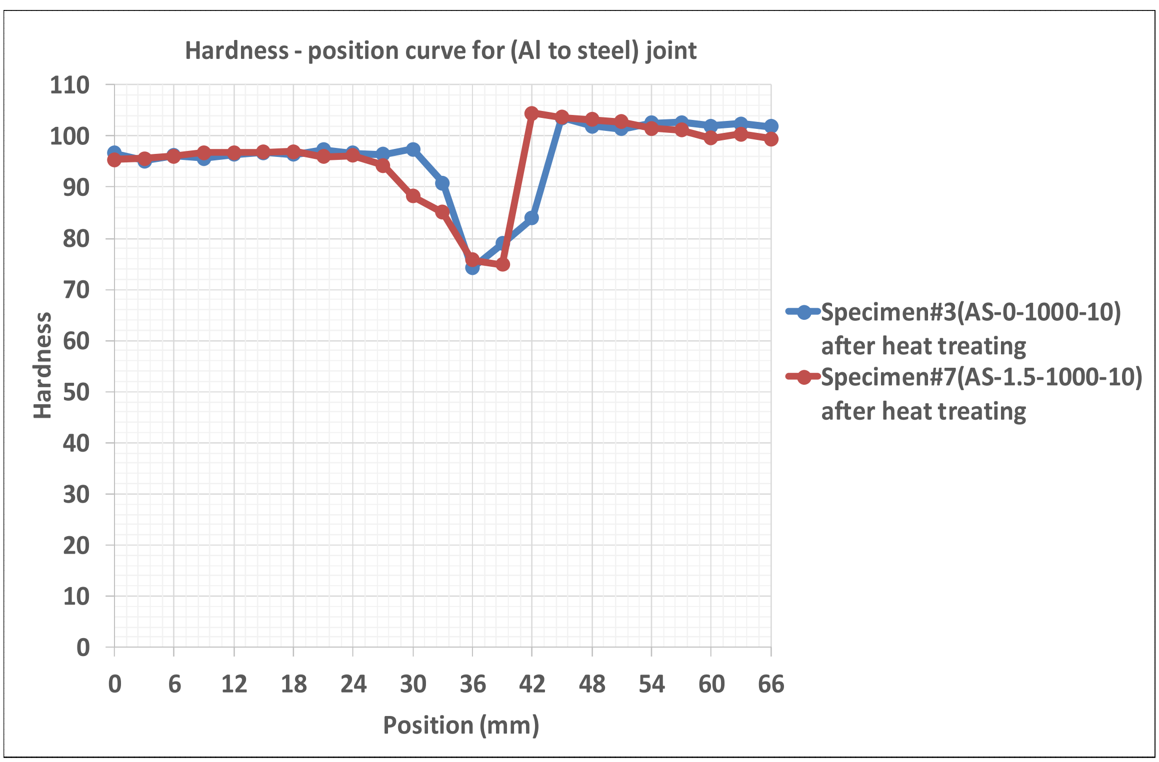


Figure (4.60) Hardness – position curves for comparison after heat treating

Figures (4.59 and 4.60) compare the variation in hardness for different specimens. The specimens were welded using the same rotation and travel speeds, but specimens #2 and #3 were welded with a tilt angle of 0º and specimens #6 and #7 were welded with a tilt angle of 1.5º. There was no substantial difference between the two hardness profiles, indicating the variation in tilt angle over the range of 0º to 1.5º has no significant effect on the hardness of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix. The comparison take place between each two specimens which show that the hardness is very close to each other. This means that the effect of tilt angle before the heat treating process is negligible or even non-existent. Also, the graphs show that the right side has higher hardness than the left side because the right side represents the steel base metal while the left side is for the aluminum.

4.13.5 Effect of Varying Travel Speed after Heat Treatment

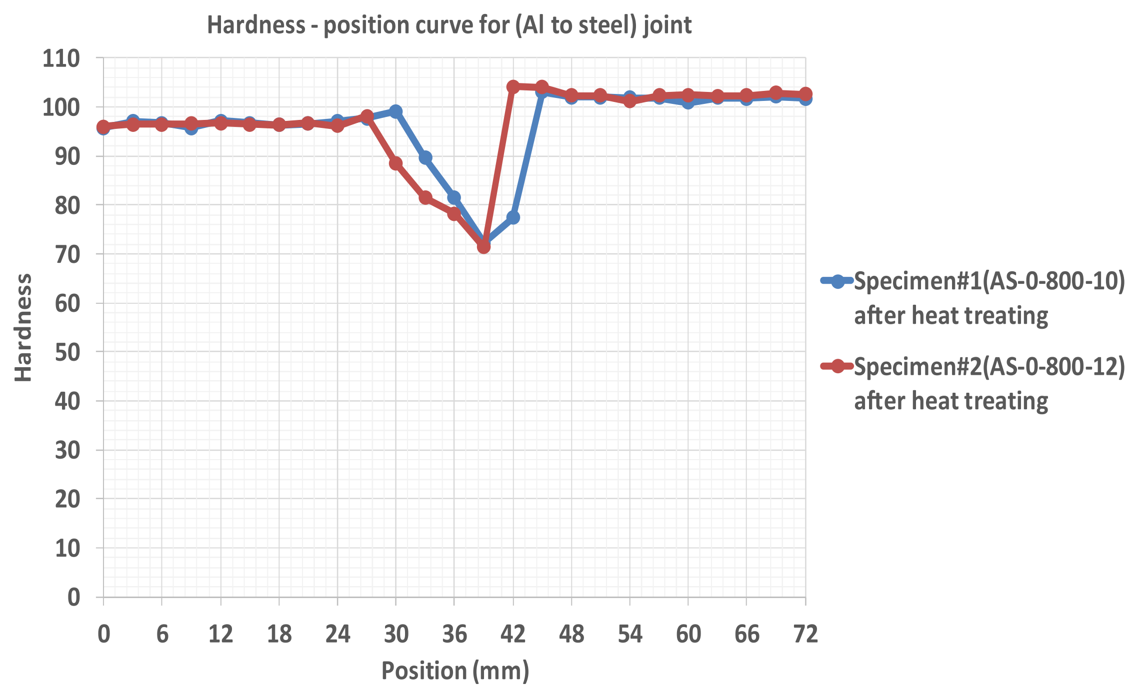


Figure (4.61) Hardness – position curves for comparison after heat treating

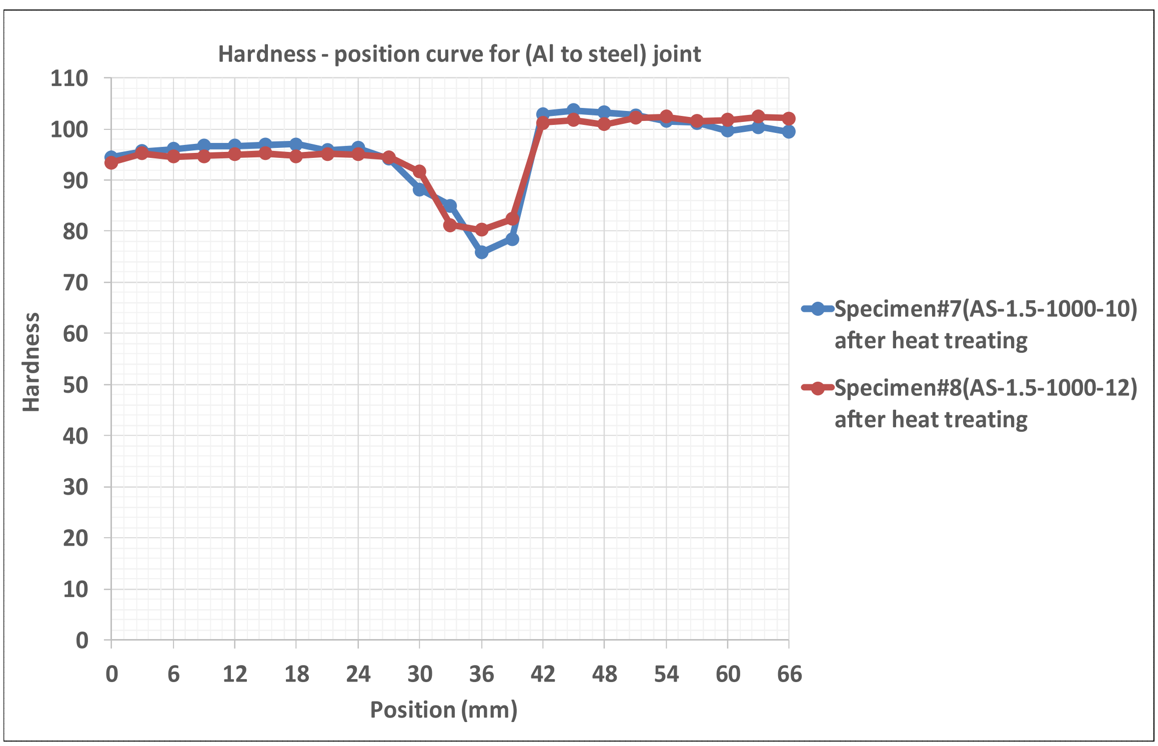


Figure (4.62) Hardness – position curves for comparison after heat treating

Figures (4.61 and 4.62) compare the variation in hardness for specimens #1, #2, #7 and #8. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #1 and #7 was 10 mm/min and when welding specimens #2 and #8 was 12 mm/min. There was no substantial difference between the two hardness profiles, indicating the variation in travel speed over the range of 10 to 12 mm/min had no significant effect on the hardness of the welded specimens. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. According to the graphs, the hardness for each two specimens is close to each other overall. This comparison was done between each of two specimens when the tilt angle and rotation speed were constant and the travel speed was variable. The results show that the effect of travel speed was small or almost non-existent after the heat treating process. The graphs show that the right side hardness is higher than the left side. That is because the right side represents the base metal of steel while the left side is for the aluminum.

4.13.6 Effect of Varying Rotation Speed after Heat Treatment

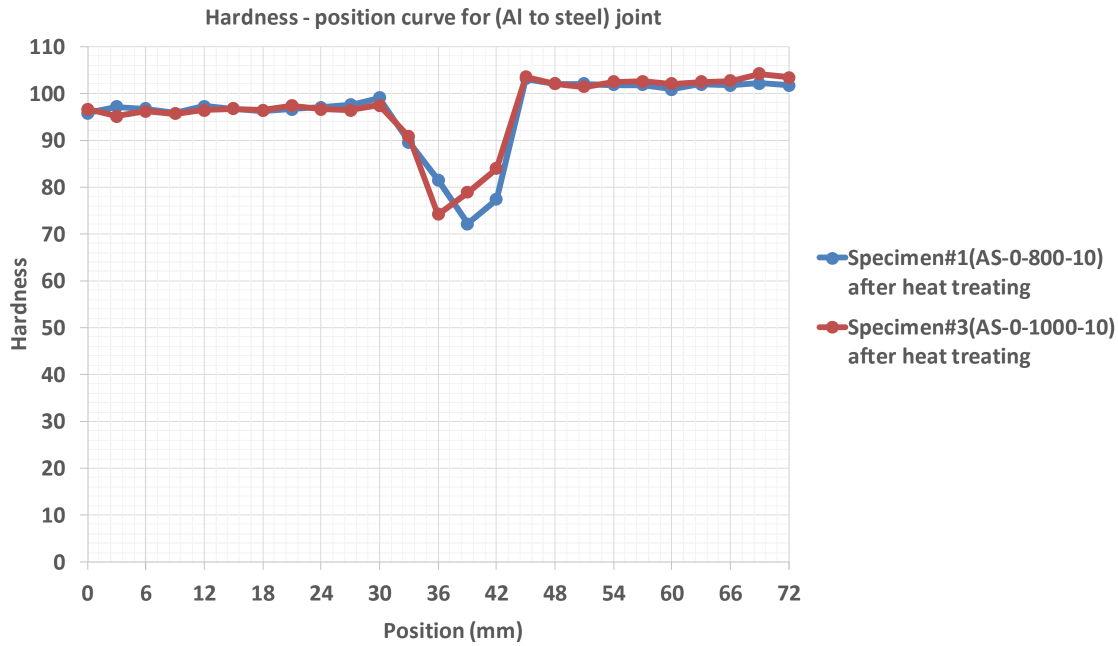


Figure (4.63) Hardness – position curves for comparison after heat treating

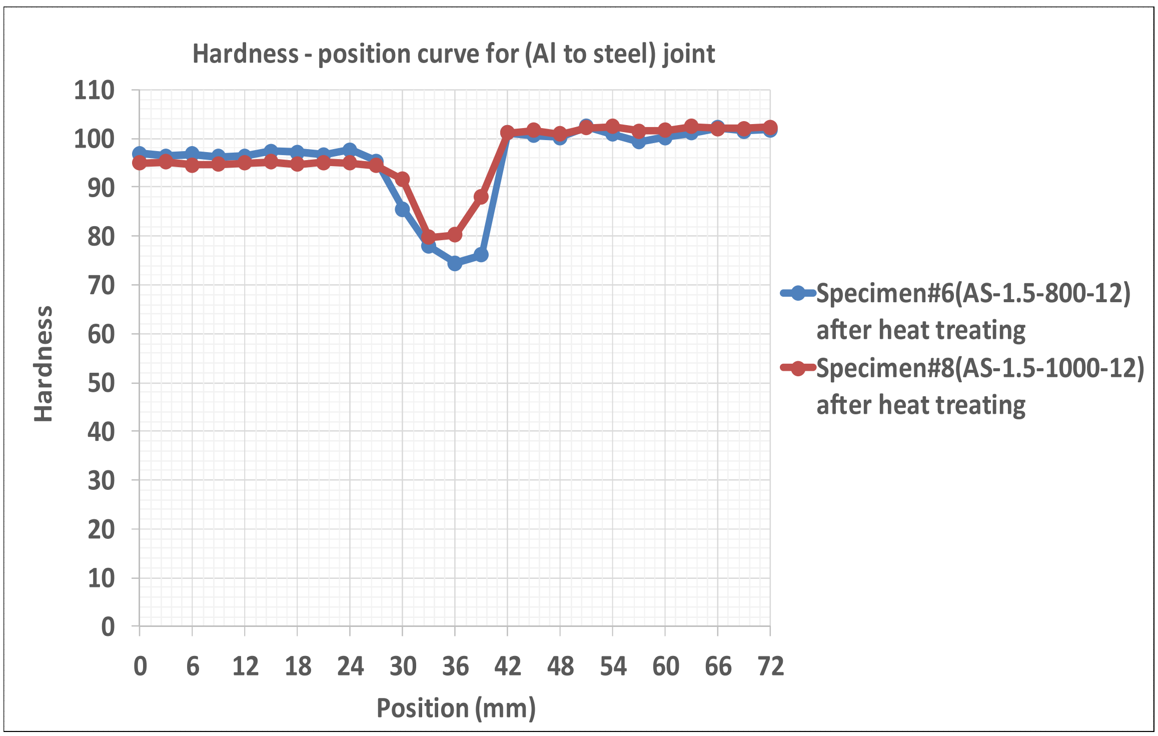


Figure (4.64) Hardness – position curves for comparison after heat treating

Figures (4.63 and 4.64) compare the variation in hardness for specimens #1, #3, #6 and #8. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #1 and #6 was 800 rpm and when welding specimens #3 and #8 was 1000 rpm. There was no substantial difference between the two hardness profiles, indicating the variation in rotation speed over the range of 800 to 1000 rpm had no significant effect on the hardness of the welded samples. A similar observation was made for other combinations of welding conditions between different specimens that have different welding parameters in which only the rotation speed was varied, as shown in the appendix. All the graphs show that the hardness of each of the two specimens is very close to each other when the rotation speed is variable. This means there was no effect of the rotation speed on the mechanical properties, such as the hardness after heat treating process when the other two parameters were constant. The graphs show that the right side hardness is higher than the left side hardness. This is because the right side represents the base metal of steel while the left side is for the aluminum.

4.14 Tension Test

4.14.1 Tension Test Comparison before and after Heat Treatment

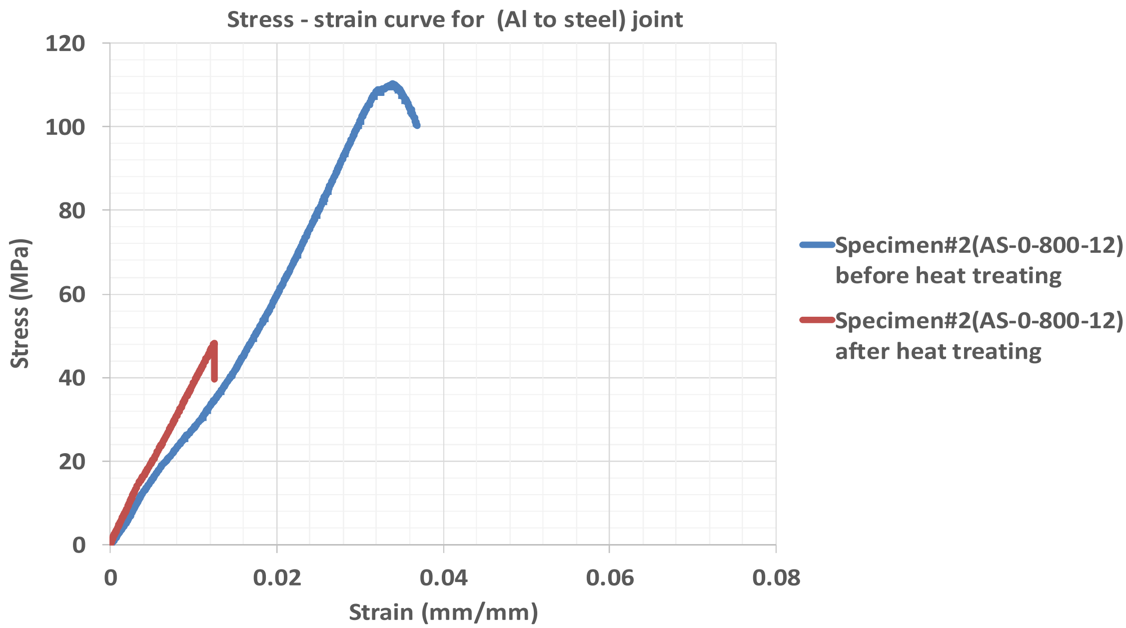


Figure (4.65) Stress – strain curves for tension test before and after heat treating

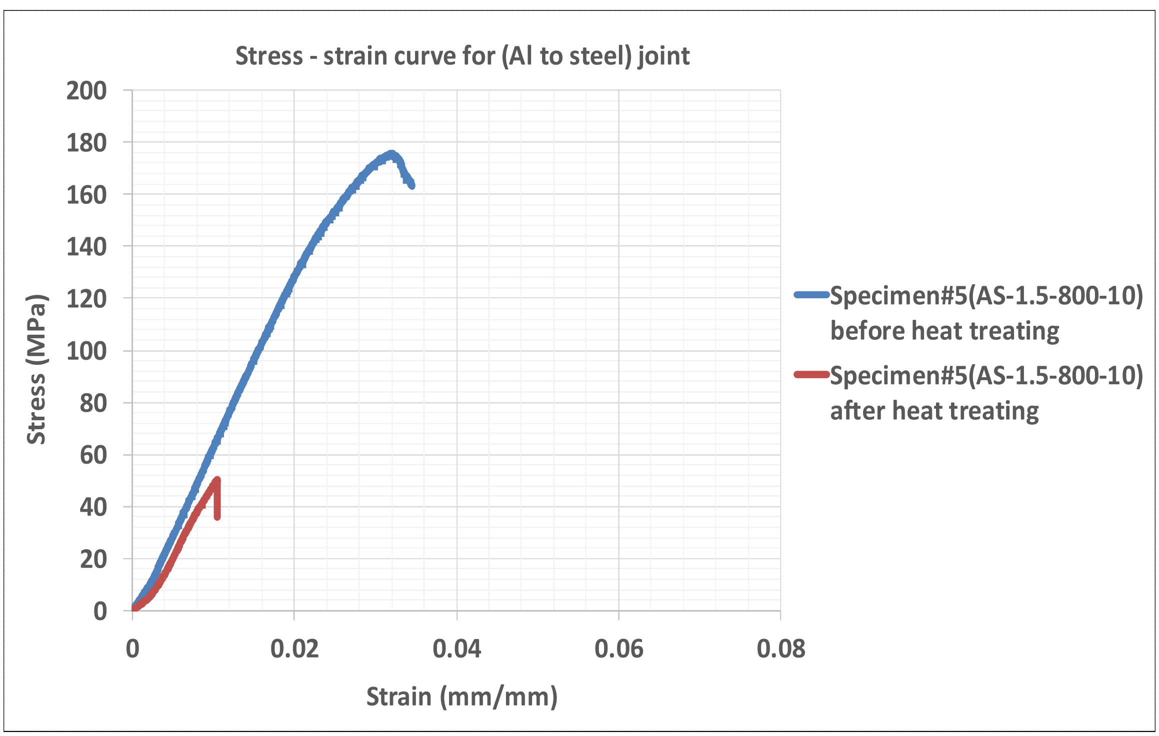


Figure (4.66) Stress – strain curves for tension test before and after heat treating

Tension tests were conducted on both the as-welded and the heat treated conditions. Figures (4.65 and 4.66) show typical variations in strength over the friction stir welded zone. The figures represent the comparison of curves before and after the heat treating process for each of the two specimens. All the specimens had the same welding parameters. According to the graphs, the specimens before the heat treating process are stronger than the specimens after the heat treating process. Moreover, all the graphs behavior is brittle, which means fractures occurred suddenly without any indication. Another important comparison was that the aluminum-steel joints had opposite behavior of the aluminum-aluminum joints. In other words, the strength of the Al to Al joints after the heat treating process were stronger than before the heat treating process. The main reason that the aluminum–steel joints before the heat treating process are stronger than after the heat treating process is during the heat treating process, the atoms that exist in the joint area revert back to their original alloy, such as aluminum atoms to aluminum and steel to steel. This means that the different atoms, like the aluminum and steel in the welded zone, do not accept each other during the heat treating process. A similar observation was made for other combinations of welding conditions between different specimens as shown in the appendix.

4.15 Effect of Welding Parameters on Properties before and after Heat Treatment

4.15.1 Effect of Varying Tilt Angle before Heat Treatment

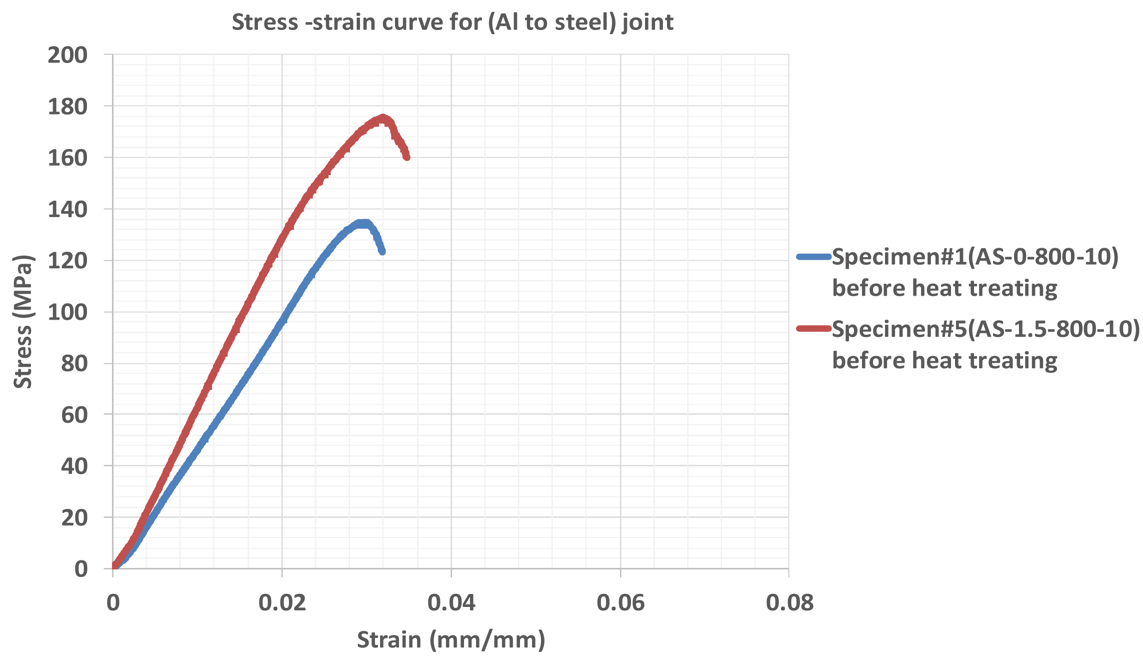


Figure (4.67) Stress – strain curves for tension test before heat treating

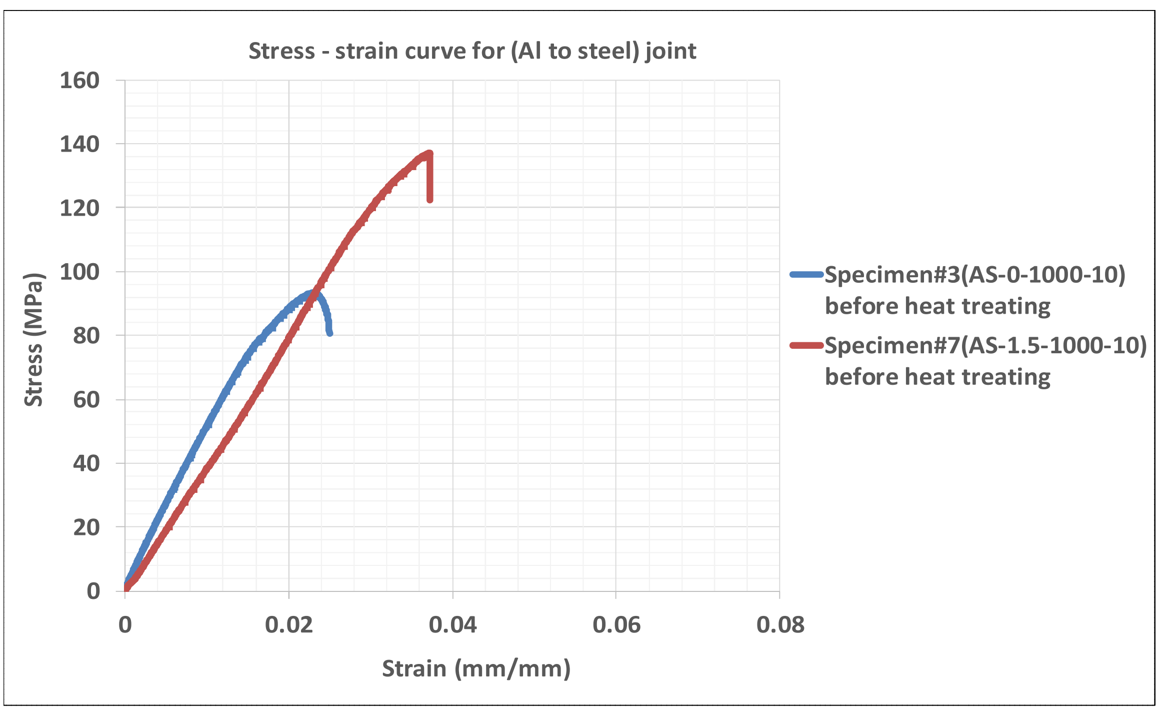


Figure (4.68) Stress – strain curves for tension test before heat treating

Figures (4.67 and 4.68) compare the variation in tension strength for specimens #1, #3, #5, and #7. The specimens were welded using the same rotation and travel speeds, but specimens #1 and #3 were welded with a tilt angle of 0º and specimens #5 and #7 were welded with a tilt angle of 1.5º. There is a substantial difference between the two strength profiles, indicating the variation in tilt angle over the range of 0º to 1.5º had a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix. All the graphs show that the specimens at a tilt angle equal to 1.5º were stronger than the specimens at a tilt angle equal to zeroº. This result corresponds with the literature review results, meaning that the increase in tilt angle between 1-3^{o} improves the mechanical properties such as the strength of the joint.

4.15.2 Effect of Varying Travel Speed before Heat Treatment

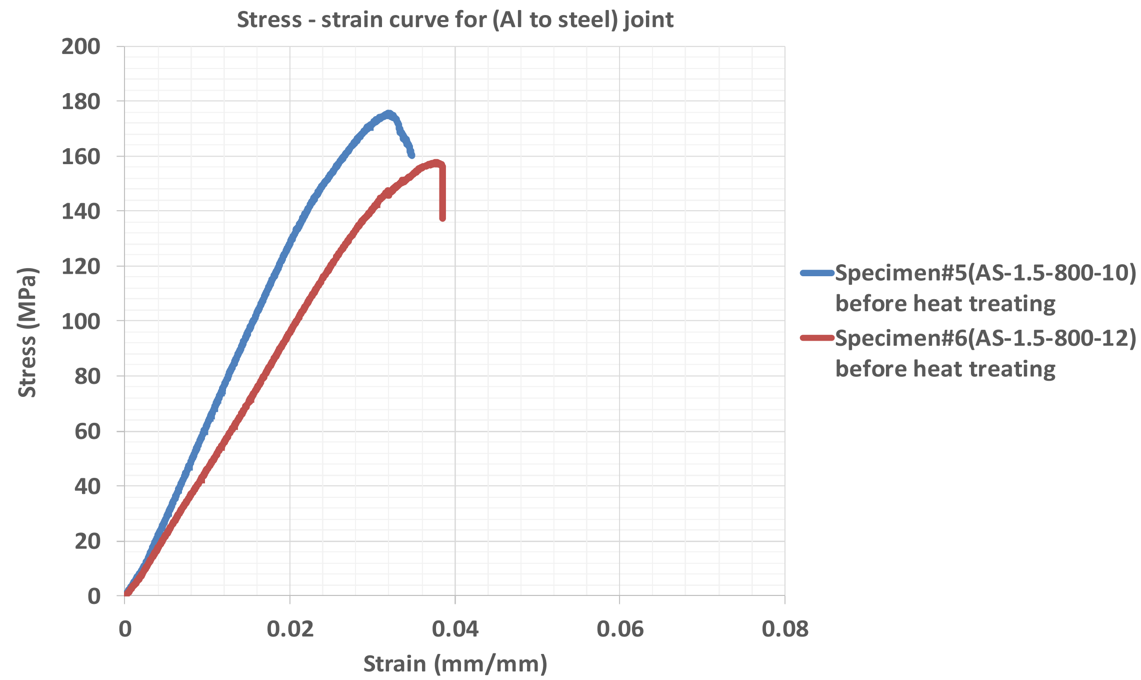


Figure (4.69) Stress – strain curves for tension test before heat treating

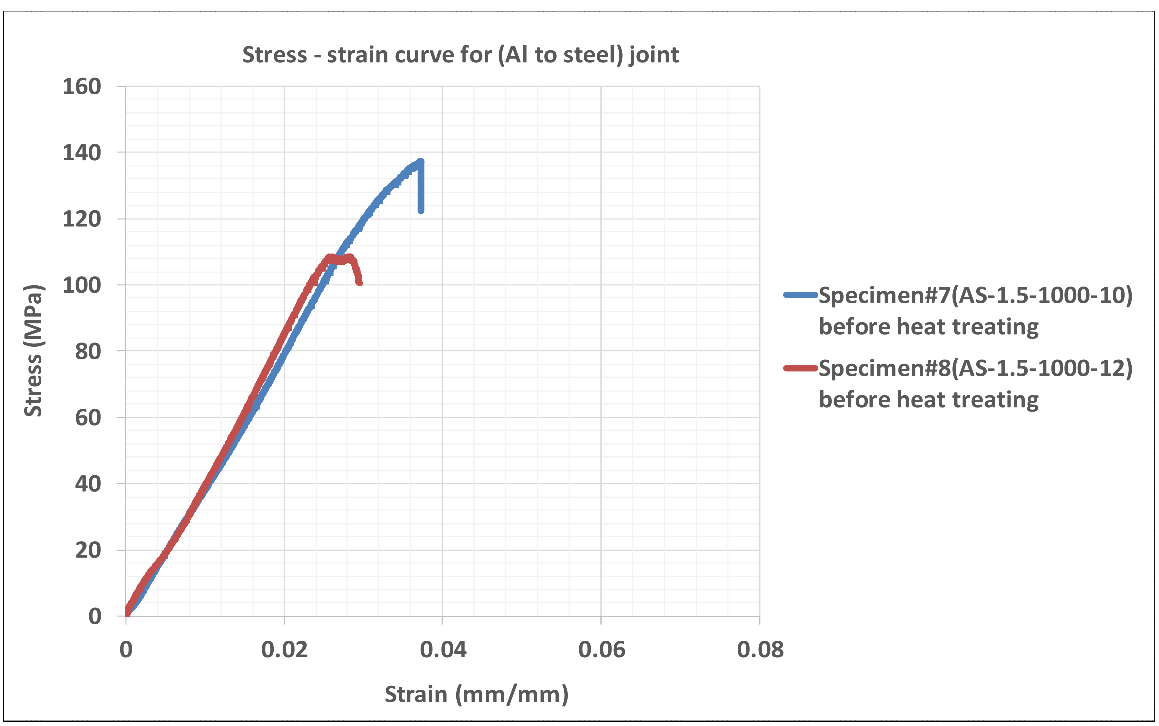


Figure (4.70) Stress – strain curves for tension test before heat treating

Figures (4.69 and 4.70) compare the variation in strength of specimens #5, #6, #7, and #8. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #5 and #7 was 10 mm/min and when welding specimens #6, and #8 was 12 mm/min. There is a substantial difference between the two strength profiles, indicating the variation in travel speed over the range of 10 to 12 mm/min has a significant effect on the strength of the welded specimens. All the specimens which have a travel speed equal to 10 mm/min are stronger than the specimens at a travel speed equal to 12 mm/min. So, welding parameters, such as travel speed, affect the mechanical properties before the heat treating process. This means that the friction stir welding process and tension test procedures were done correctly. This result matches the literature review results. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix part.

4.15.3 Effect of Varying Rotation Speed before Heat Treatment

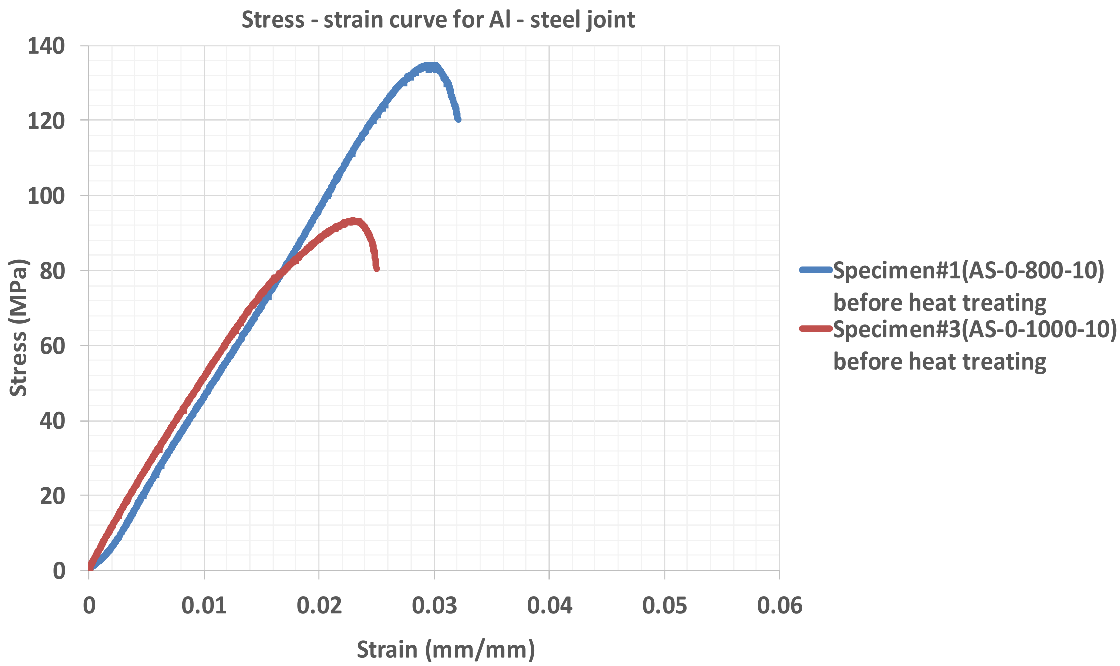


Figure (4.71) Stress – strain curves for tension test before heat treating

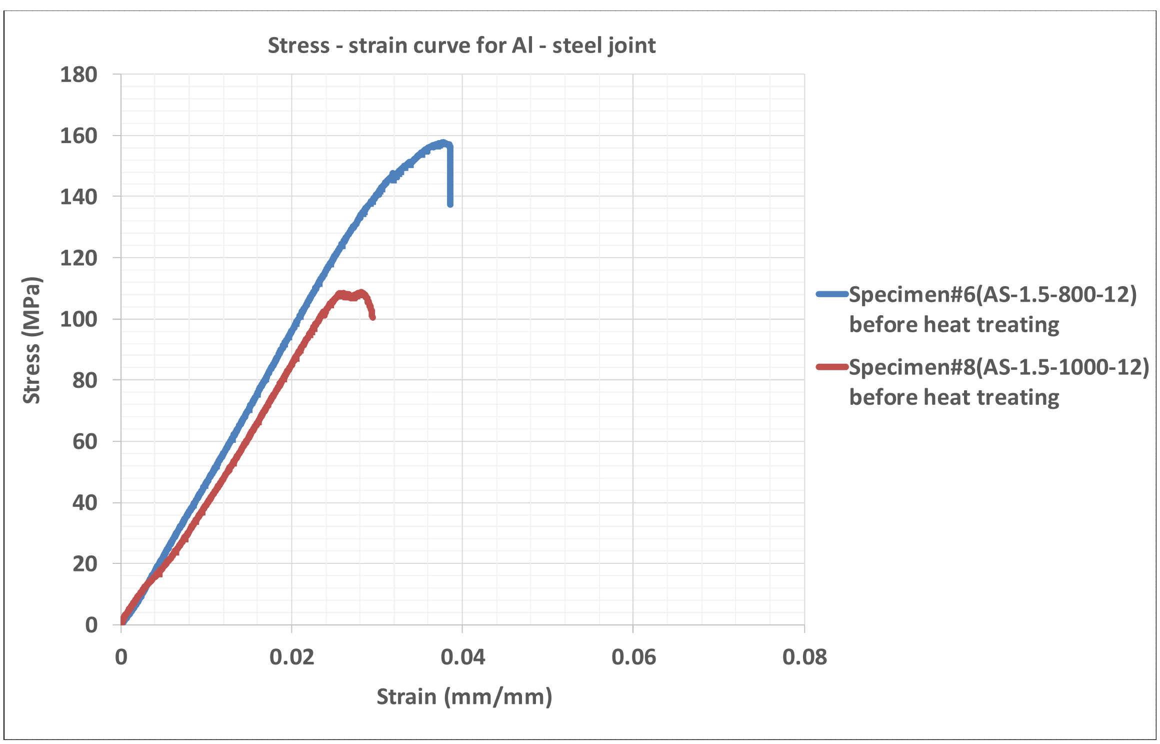


Figure (4.72) Stress – strain curves for tension test before heat treating

Figures (4.71 and 4.72) compare the variation in strength for specimens #1, #3, #6, and #8. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #1 and #6 was 800 rpm and when welding the specimens #3 and #8 was 1000 rpm. There is a substantial difference between the two strength profiles, indicating the variation in rotation speed over the range of 800 to 1000 rpm has a significant effect on the tension strength of the welded specimens. According to the graphs, the specimens that have a rotation speed equal to the 800 rpm are stronger than the specimens at 1000 rpm. The result of this comparison does not mimic the literature review results. The literature review results show that the increase in rotation speed improves the mechanical properties, such as strength, when the tilt angle and travel speed are constant. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix.

4.15.4 Effect of Varying Tilt Angle after Heat Treatment

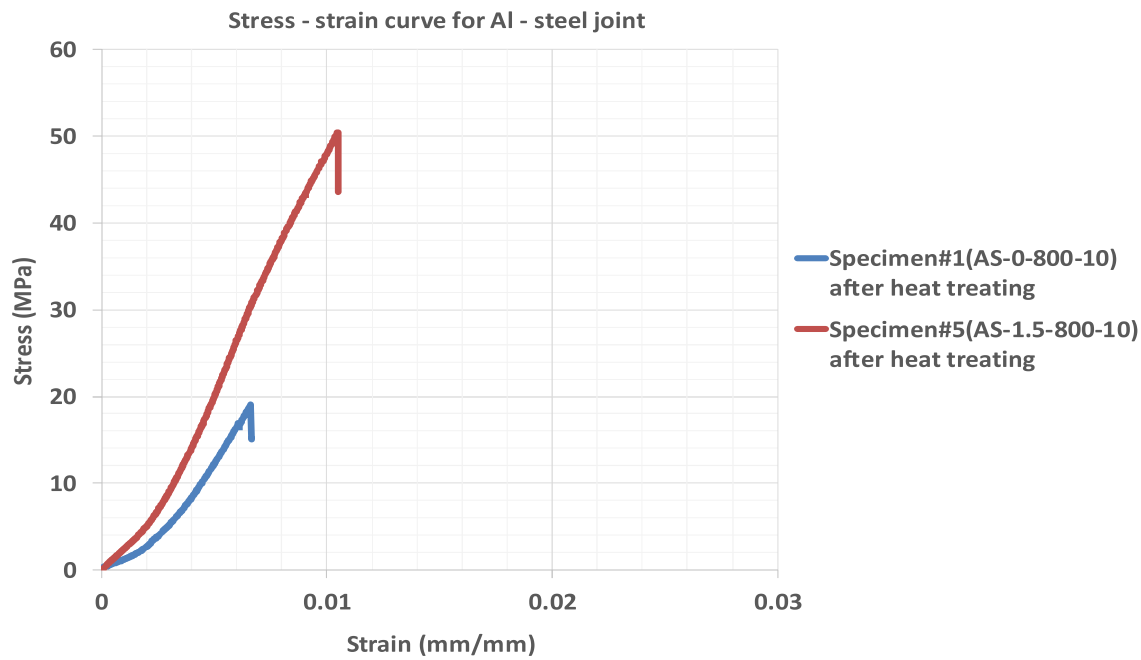


Figure (4.73) Stress – strain curves for tension test after heat trading

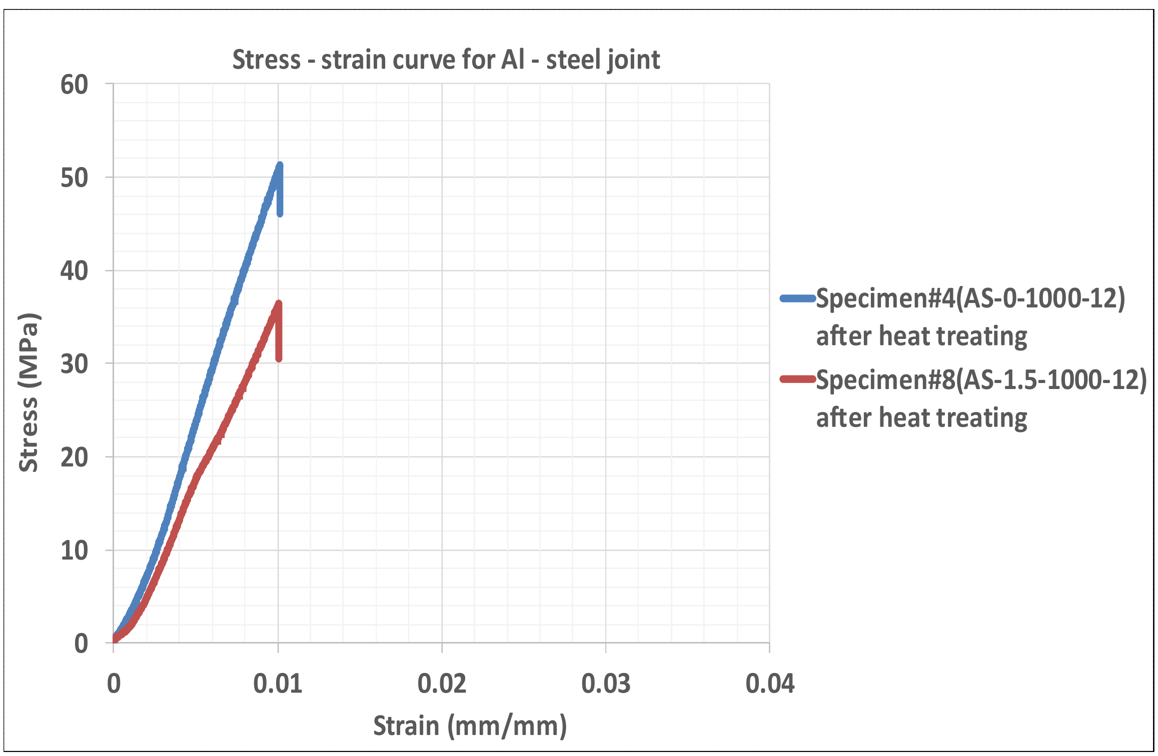


Figure (4.74) Stress – strain curves for tension test after heat trading

Figures (4.73 and 4.74) compare the variation in strength for specimens #1, #4, #5, and #8. The specimens were welded using the same rotation and travel speeds, but specimens #1and #4 were welded with a tilt angle of 0º and specimens #5 and #8 were welded with a tilt angle of 1.5º. According to the graphs, the effect of tilt angle on the strength of the specimen during the tension test was random. This means there is a substantial difference between the two strength profiles, indicating the variation in tilt angle over the range of 0º to 1.5º has significant effect on the tension strength of the welded specimens. In Figure 4.73, the comparison result corresponds with the literature review results, which means the specimen at a tilt angle equal to 1.5º is stronger than the specimen at a tilt angle equal to 0º. However, Figure 4.74 shows a contrary result, which means that the specimen that has a tilt angle equal to 0º is stronger than the specimen at a tilt angle equal to 1.5º. This is because of the thermal cycles of friction stir welding and because the atoms for aluminum and steel do not accept each other in the joint area. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied as shown in the appendix.

4.15.5 Effect of Varying Travel Speed after Heat Treatment

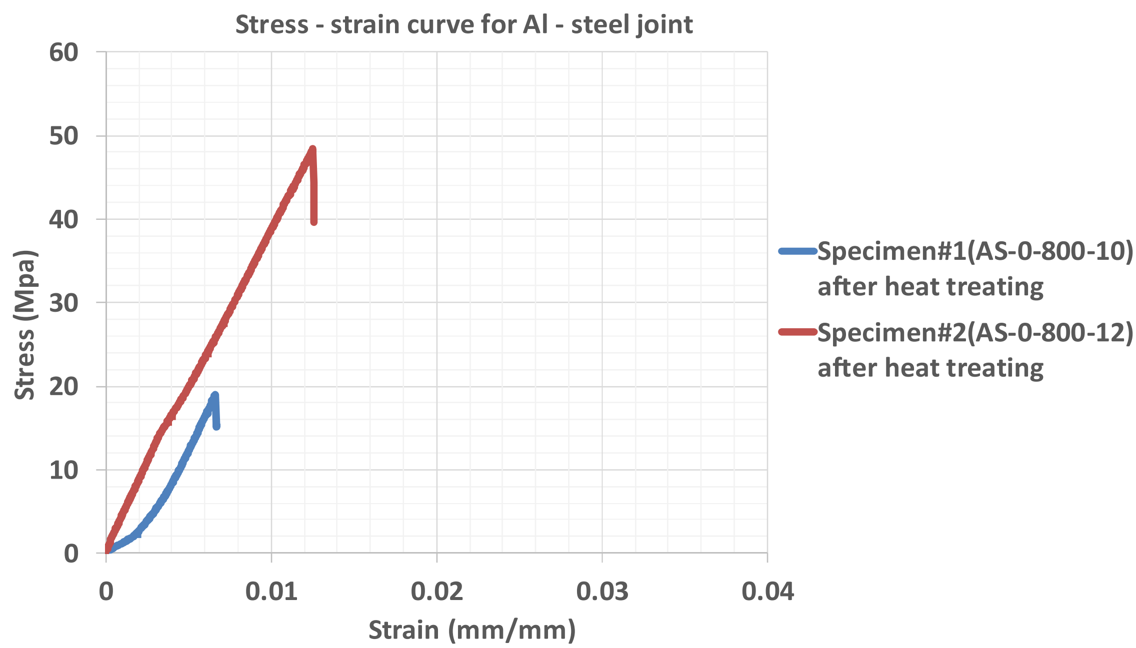


Figure (4.75) Stress – strain curves for tension test after heat trading

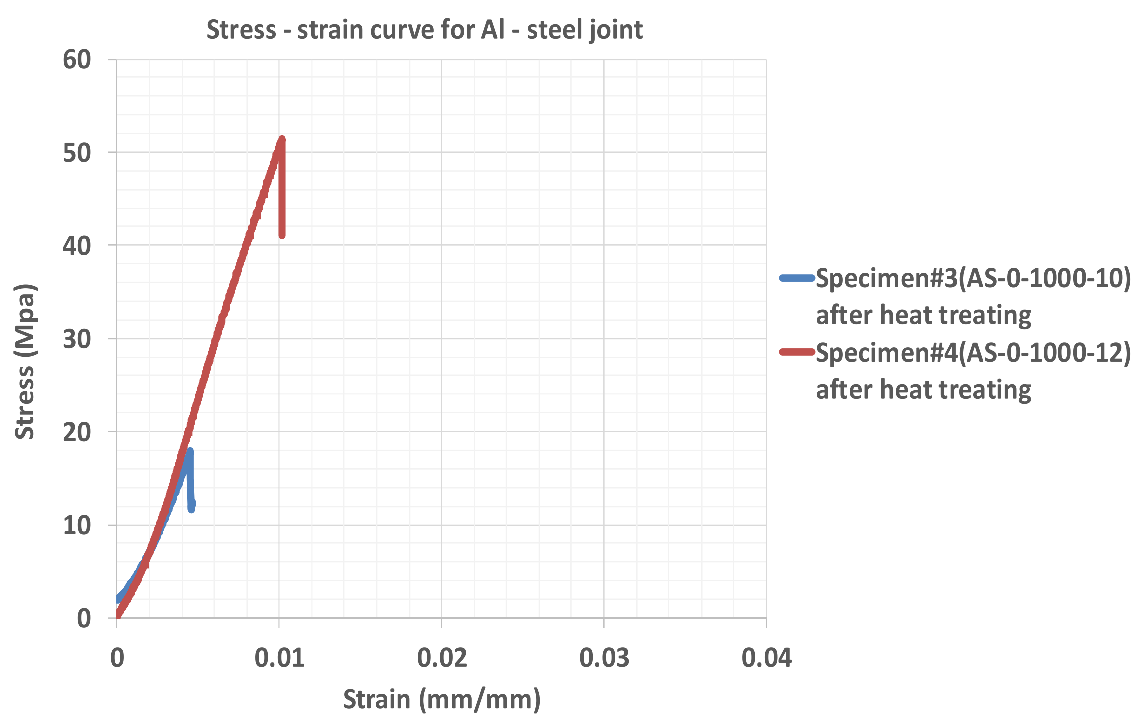


Figure (4.76) Stress – strain curves for tension test after heat trading

Figures (4.75 and 4.76) compare the variation in tension strength for specimens #1, #2, #3, and #4. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #1 and #3 was 10 mm/min and when welding specimens #2 and #4 was 12 mm/min. There is a substantial difference between the two strength profiles, indicating the variation in travel speed over the range of 10 to 12 mm/min has a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. According to the figures, the comparison took place when the tilt angle and rotation speed were constant for each of the two specimens while the travel speed was variable. The graphs show that the specimens with a higher travel speed were stronger than the specimens with a lower travel speed after the heat treating process. As mentioned before, this result does not mimic the literature review results where the literature review results show that the increase in travel speed decreases the mechanical properties such as the strength of the joint.

4.15.6 Effect of Varying Rotation Speed after Heat Treatment

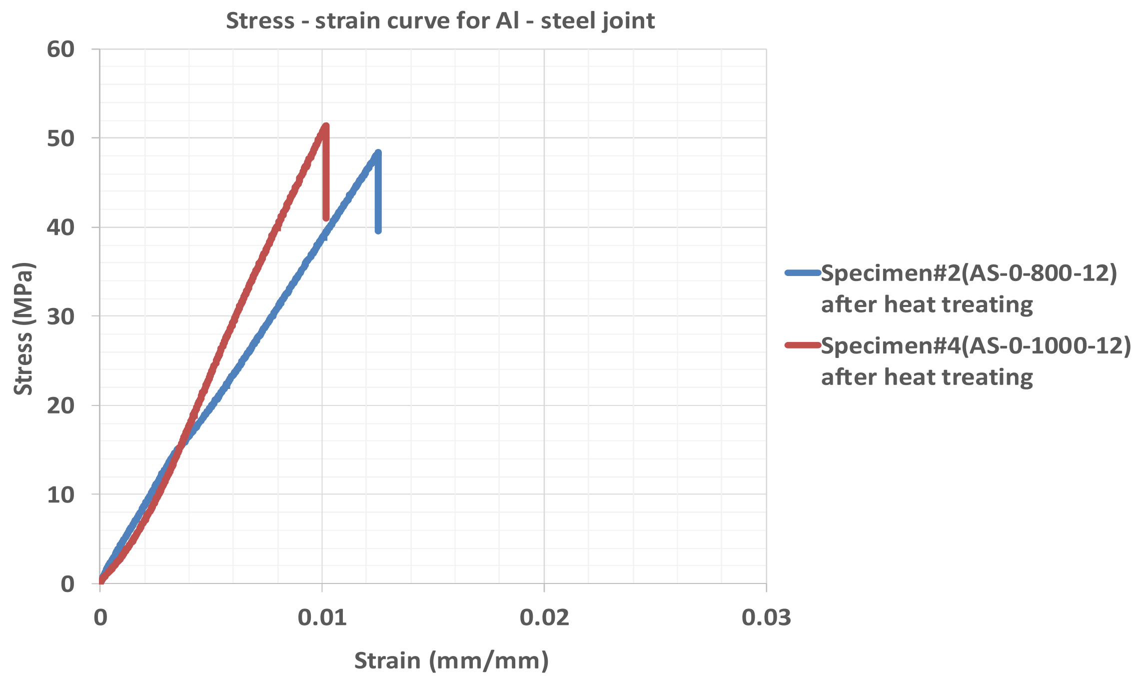


Figure (4.77) Stress – strain curves for tension test after heat treating

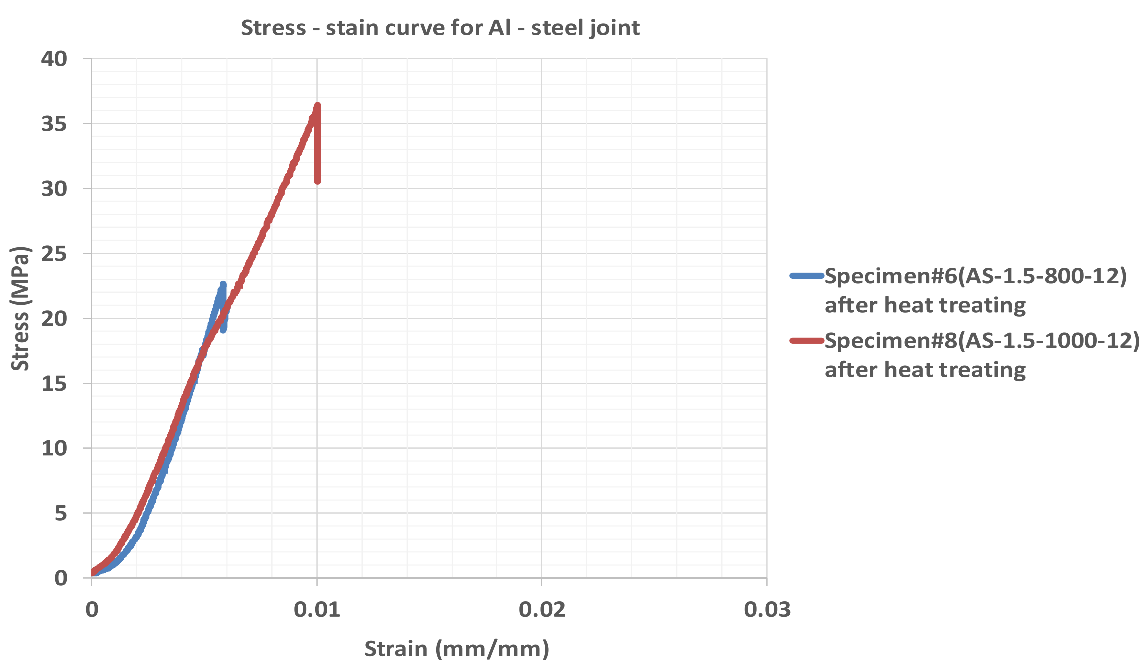


Figure (4.78) Stress – strain curves for tension test after heat treating

Figures (4.77 and 4.78) show the variation in tension strength for specimens #2, #4, #6, and #8. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #2 and #6 was 800 rpm and when welding specimens #4 and #8 was 1000 rpm. There is a substantial difference between the two strength profiles, indicating the variation in rotation speed over the range of 800 to 1000 rpm has a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix. According to the figures, the specimens that have a higher rotation speed were stronger than the specimens with a lower rotation speed after the heat treating process. This means that the rotation speed has an influence on the mechanical properties, such as the tensile strength, after the heat treating process. The result of this comparison corresponds with the literature review results.

4.16 Bending Test

4.16.1 Bending Comparison before and after Heat Treatment

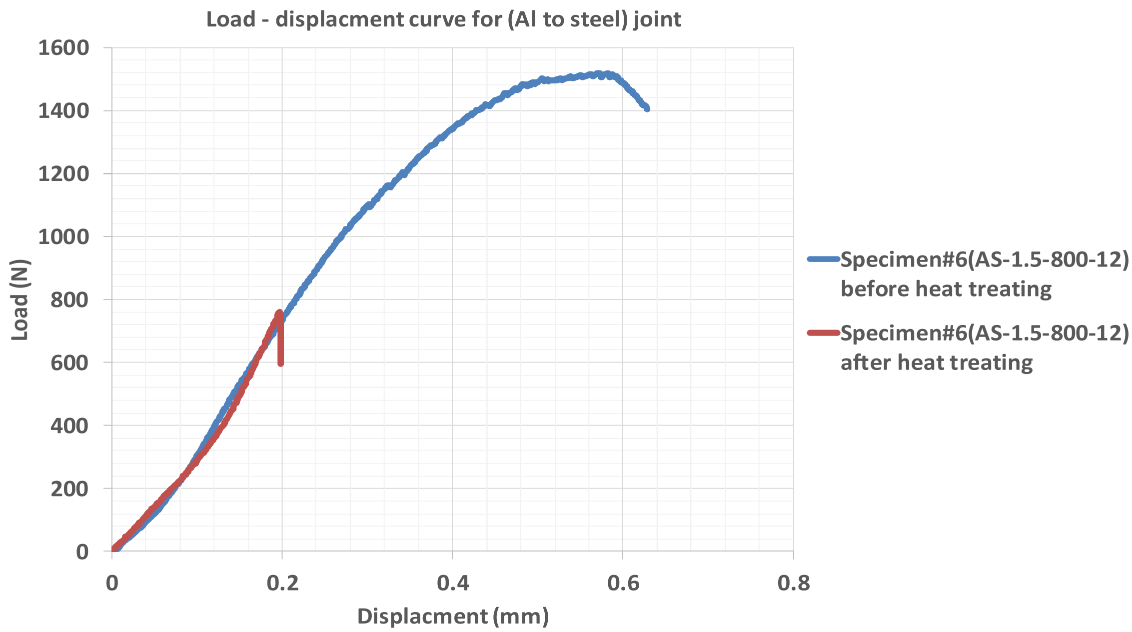


Figure (4.79) Load – displacement curves before and after heat treating

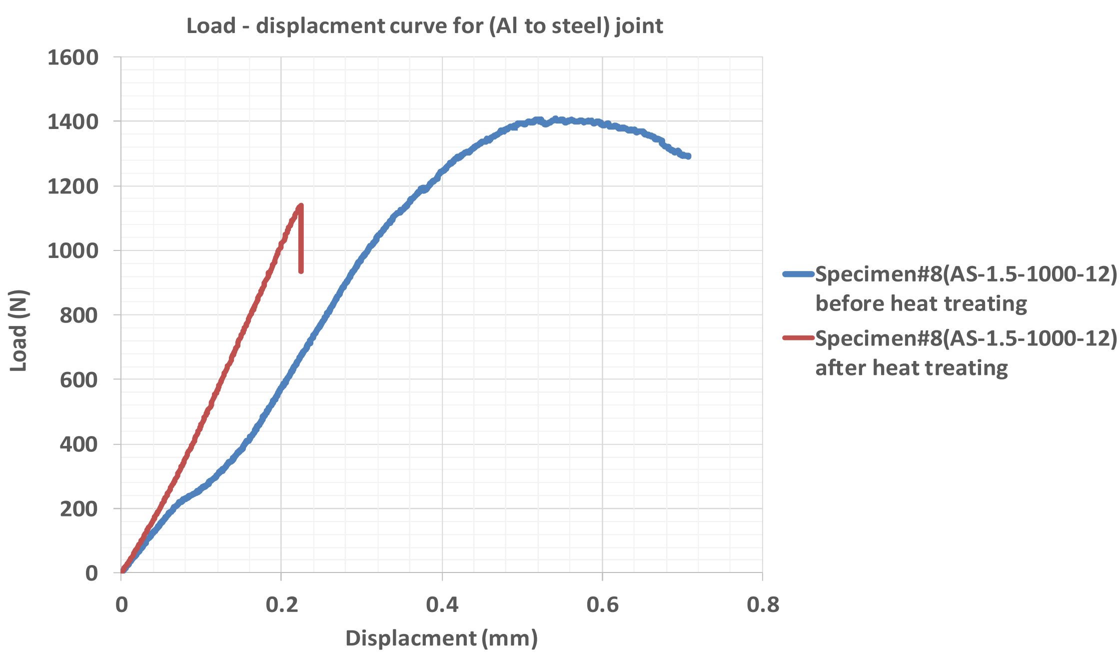


Figure (4.80) Load – displacement curves before and after heat treating

Bending tests were conducted on both the as-welded and the heat-treated conditions. Figures (4.79 and 4.80) show typical variations in strength over the friction stir welded zone. These figures show the load – displacement curves of the bending test for Al (6061-T6) to (1018 steel) joints before and after the heat treating process. All the graphs show that the specimens before the heat treating process were stronger than after the heat treating process when welding parameters for each of the two specimens were constant. This was because the atoms of both the aluminum and steel alloys in the joint area did not accept each other during the heat treating process. The specimens before the heat treating process had more deformation than the specimens after the heat treating process. So, the fracture time that was needed of those specimens was too long. However, the specimens behavior after heat treatment is brittle, which means fracture occurred without any indication. A similar observation was made for other combinations of welding conditions before and after the heat treating process as shown in the appendix part.

4.17 Effect of Welding Parameters on Properties before and after Heat Treatment

4.17.1 Effect of Varying Tilt Angle before Heat Treatment

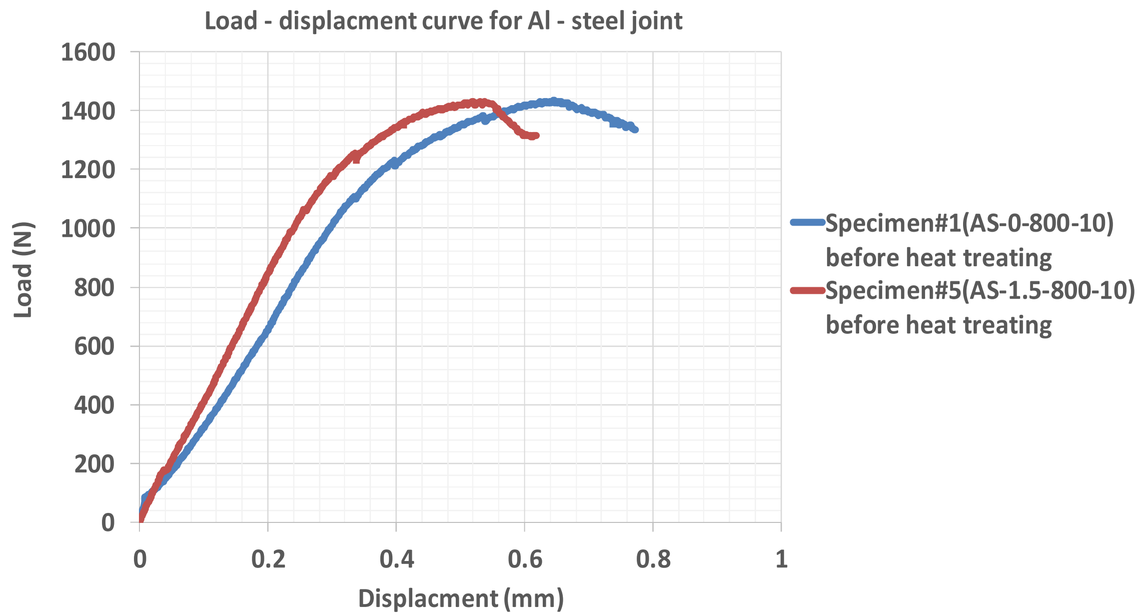


Figure (4.81) Load – displacement curves for bending test before heat treating

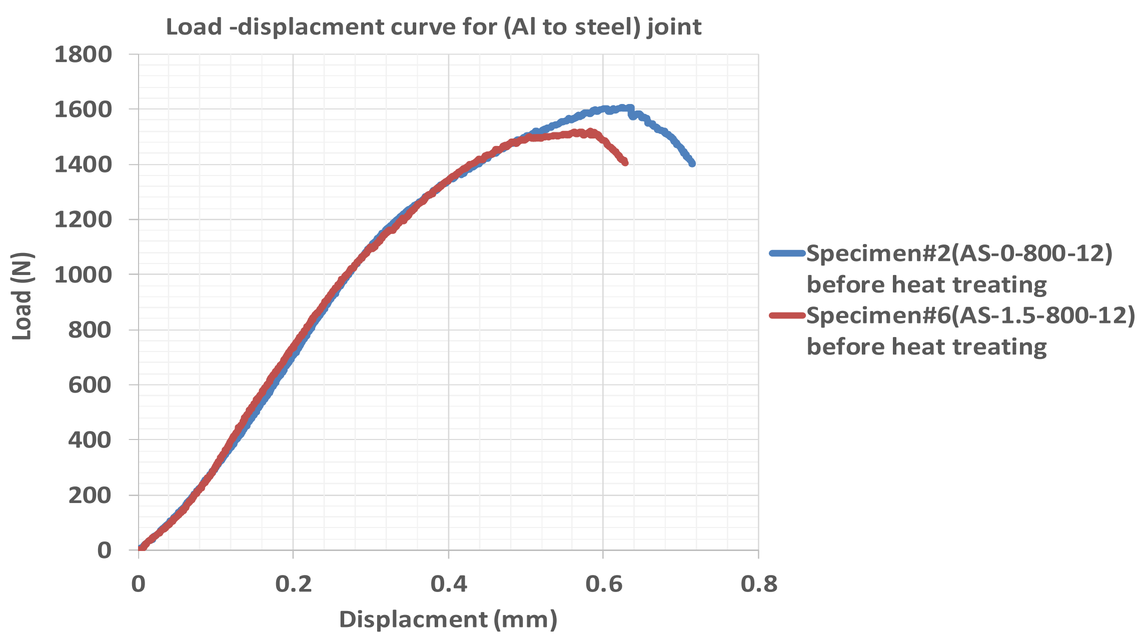


Figure (4.82) Load – displacement curves for bending test before heat treating

According to Figures (4.81 and 4.82), the comparison took place when the rotation and travel speeds were constant and the tilt angle was variable. The comparison was conducted on load – displacement curves between each of the two specimens before the heat treating process. Figure (4.81) shows that the specimen's strength was exactly the same value, equal to 1440 N. However, Figure (4.82) show the specimen that had a tilt angle equal to 0º was stronger than the specimen with a tilt angle equal to 1.5º. This means that the effect of tilt angle on the mechanical properties, such as strength, is random. In other words, the effect of tilt angle on the mechanical properties before the heat treating process is not constant.

4.17.2 Effect of Varying Travel Speed before Heat Treatment

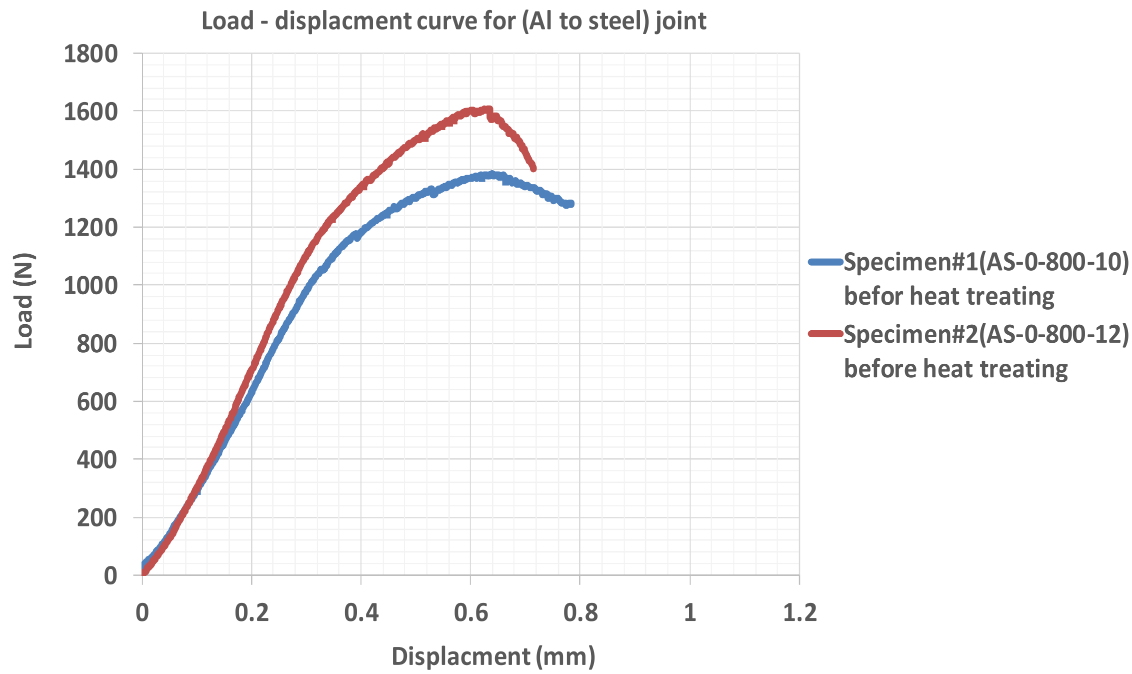


Figure (4.83) Load – displacement curves for bending test before heat treating

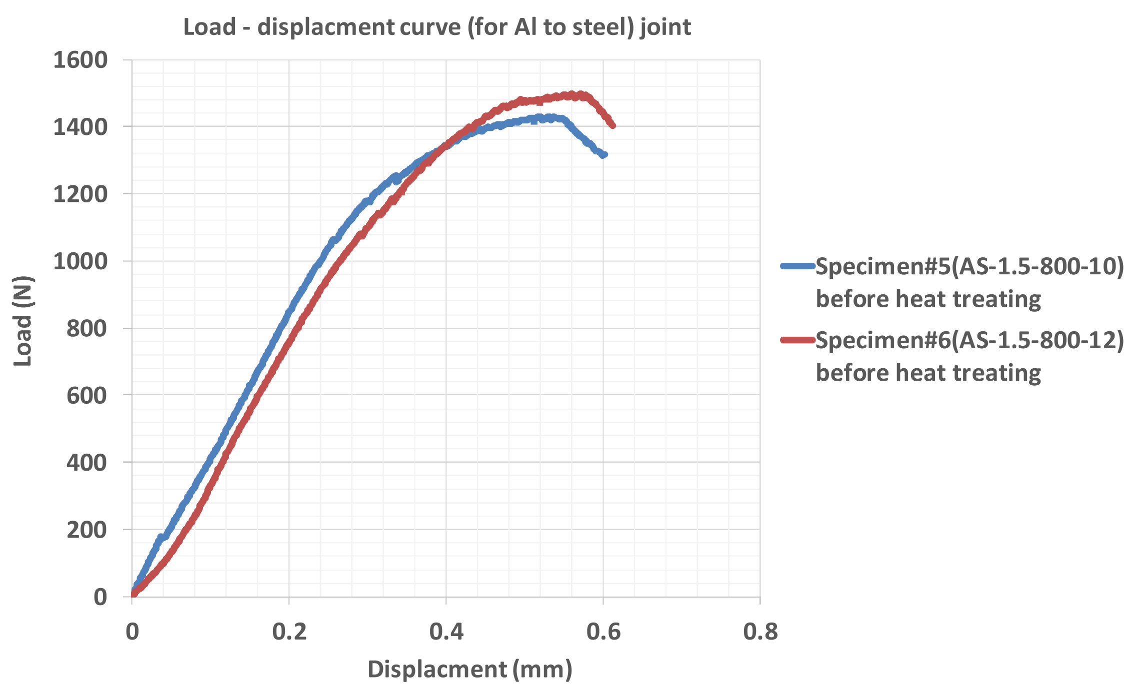


Figure (4.84) Load – displacement curves for bending test before heat treating

Figures (4.83 and 4.84) compare the variation in bending strength for specimens #1, #2, #5, and #6. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #1 and #5 was 10 mm/min and when welding the specimens #2 and #6 was 12 m/min. According to the graphs, there was a substantial difference between the two strength profiles, indicating the variation in travel speed over the range of 10 to 12 mm/min has a significant effect on the bending strength of the welded samples. The specimens that have a higher travel speed were stronger than the specimens at a lower travel speed before the heat treating process. This result is incompatible with the literature review results, where the literature review showed that the increase in travel speed affects the mechanical properties negatively. The reason is the effect of travel speed before the heat treating process is small or almost non-existent.

4.17.3 Effect of Varying Rotation Speed before Heat Treatment

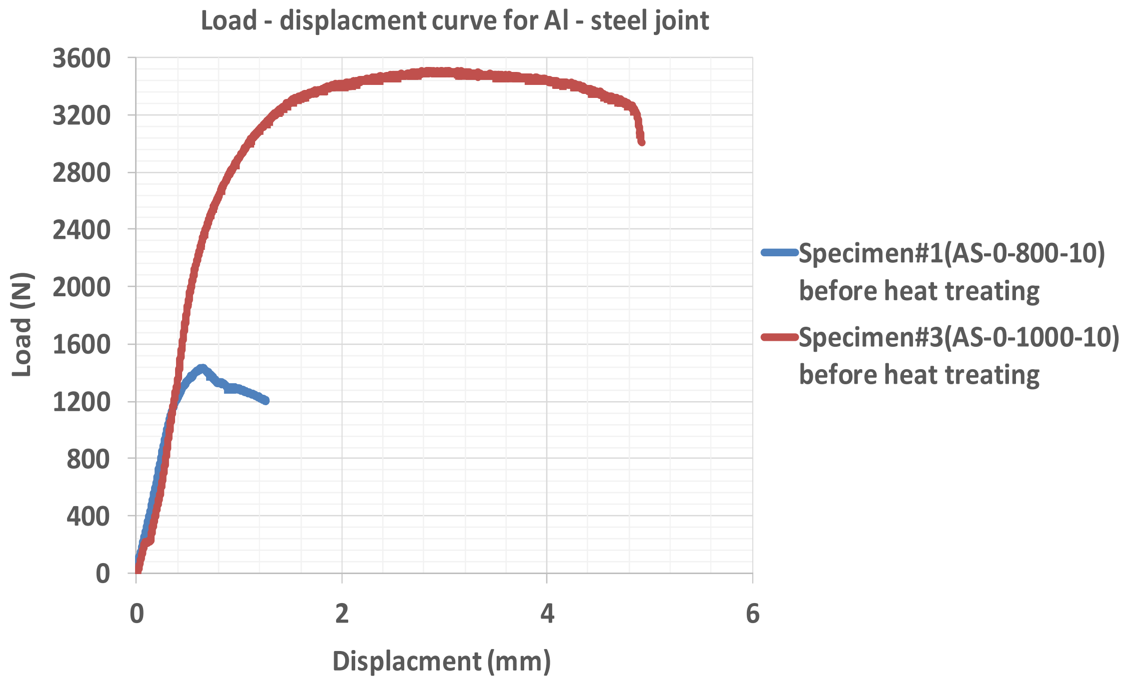


Figure (4.85) Load - displacement curves for bending test before heat treating

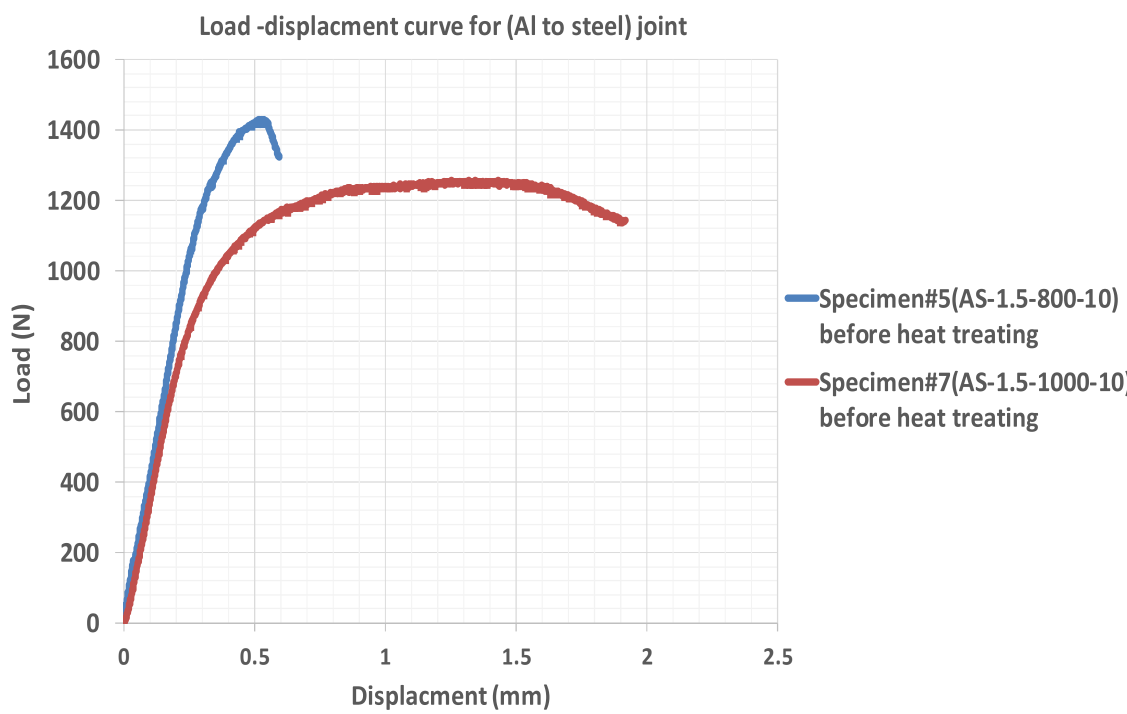


Figure (4.86) Load - displacement curves for bending test before heat treating

Figures (4.85 and 4.86) compare the variation in bending strength for four specimens. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimens #1 and #5 was 800 rpm and when welding specimens #3 and #7 was 1000 rpm. There is a substantial difference between the two strength profiles, indicating the variation in rotation speed over the range of 800 to 1000 rpm has a significant effect on the bending strength of the welded samples. According to the figure (4.85), the specimen that had a rotation speed equal to 1000 rpm is stronger than the specimen with a rotation speed equal to 800 rpm before the heat treating process. However, figure (4.86) shows that the specimen with lower rotation speed is stronger than the specimen with higher rotation speed. This means that the effect of rotation speed on mechanical properties such as strength is random effect.

4.17.4 Effect of Varying Tilt Angle after Heat Treatment

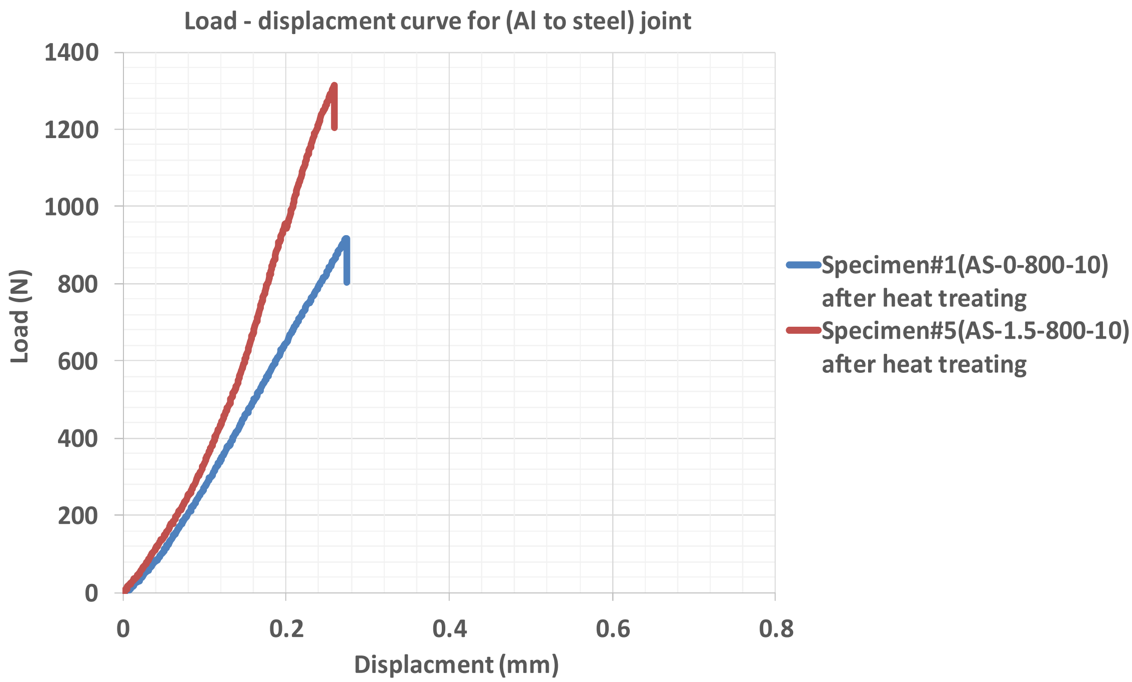


Figure (4.87) Load – displacement curves for bending test after heat treating

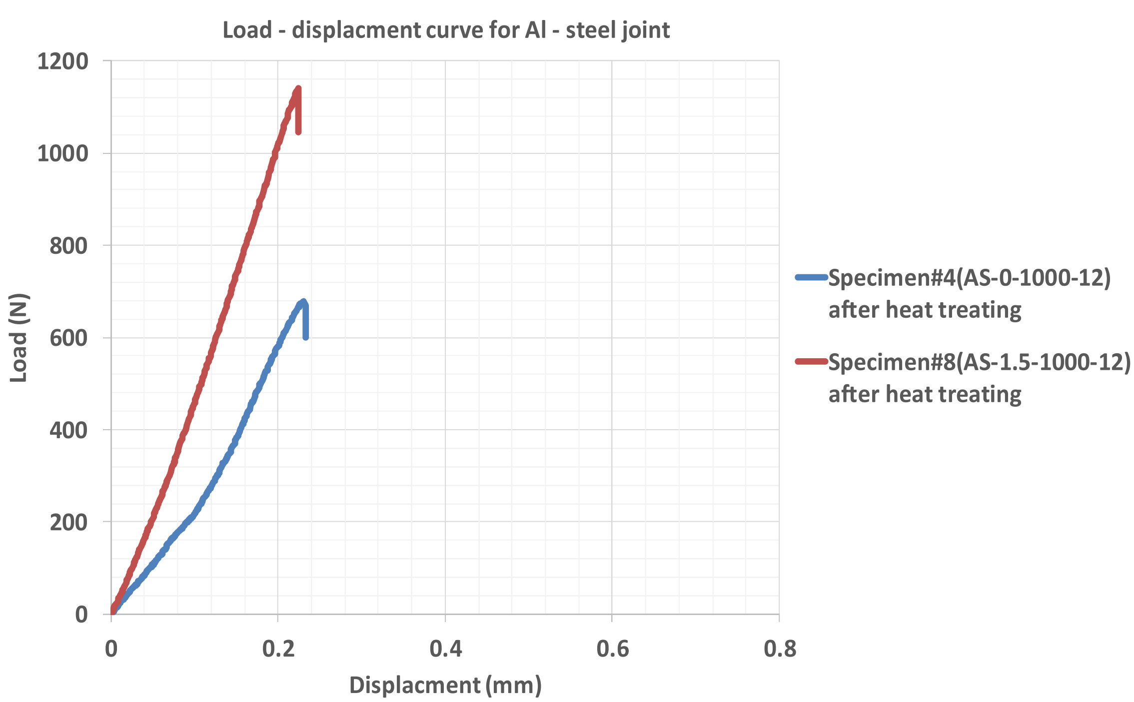


Figure (4.88) Load – displacement curves for bending test after heat treating

Figures (4.87 and 4.88) compare the variation in bending strength for specimens #1, #4, #5, and #8 according to the varying in tilt angle after heat treatment. The specimens were welded using the same rotation and travel speeds, but specimens #1 and #4 were welded with a tilt angle of 0º and specimens #5 and #8 were welded with a tilt angle of 1.5º. There is substantial difference between the two strength profiles, indicating the variation in tilt angle over the range of 0º to 1.5º has a significant effect on the bending strength of the welded samples. According to Figures (4.87 and 4.88), the specimens that have a higher tilt angle are stronger than the specimens with a lower tilt angle after the heat treating process. The result of this comparison corresponds with the literature review results. So, the tilt angle parameter has a positive effect on the mechanical properties, such as the strength, after the heat treating process. A similar observation was made for other combinations of welding conditions in which only the tilt angle was varied.

4.17.5 Effect of Varying Travel Speed after Heat Treatment

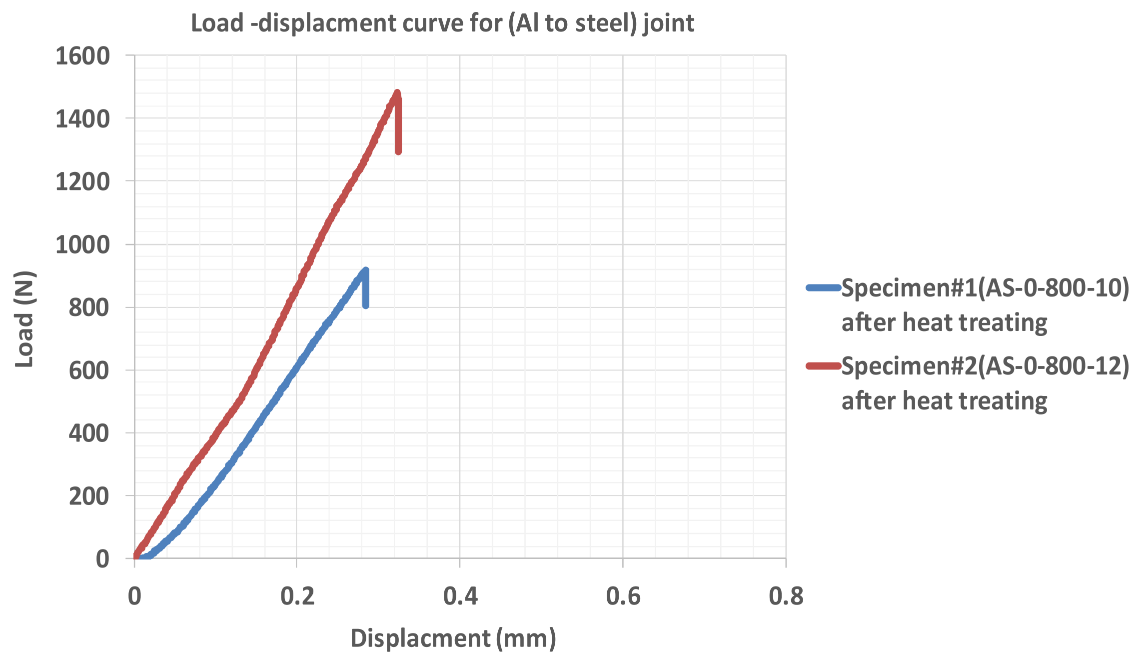


Figure (4.89) Load – displacement curves for bending test after heat treating

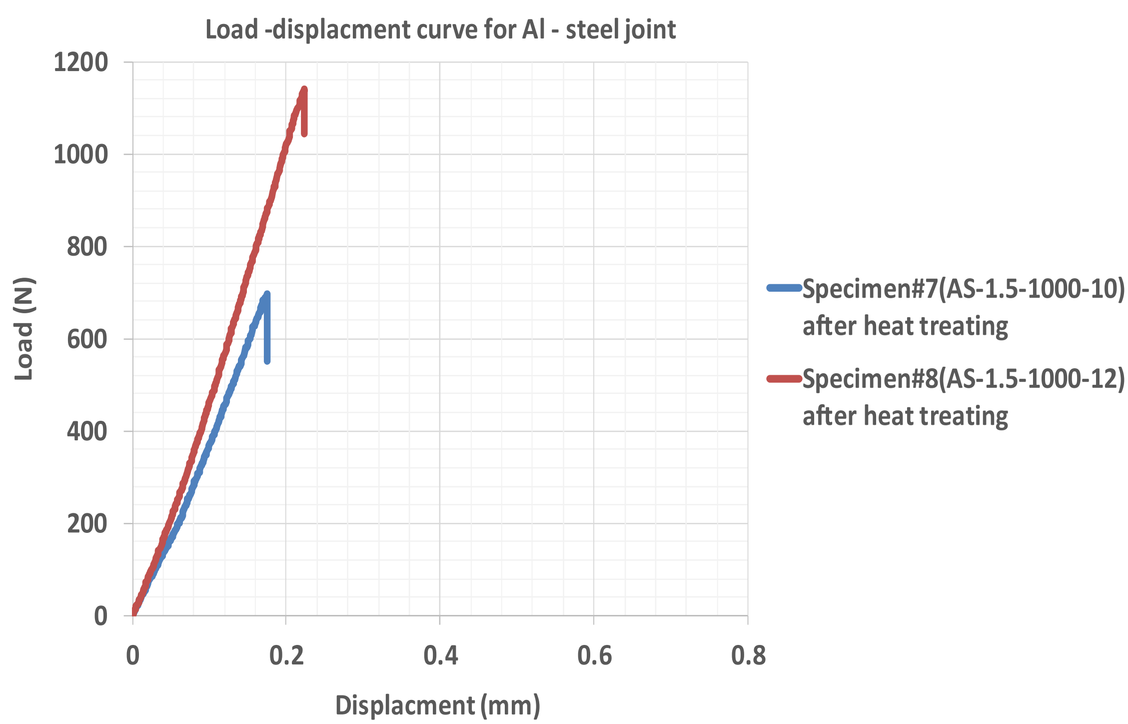


Figure (4.90) Load – displacement curves for bending test after heat treating

Figures (4.89 and 4.90) compare the variation in bending strength for specimens #1, #2, #7, and #8. The specimens were welded using the same rotation speed and tilt angle. The difference was that the travel speed when welding specimens #1 and #7 was 10 mm/min and when welding specimens #2 and #8 was 12 mm/min. There is a substantial difference between the two strength profiles, indicating the variation in travel speed over the range of 10 to 12 mm/min has a significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the travel speed was varied as shown in the appendix. The figures show that the specimens which have a higher travel speed were stronger than the specimens with a lower travel speed. So, the effect of travel speed on mechanical properties, such as the strength, after heat treatment is positive. All the comparisons that took place between Al to steel joints are different overall from the comparisons between Al to Al joints, where the first one behaved randomly and the second one was almost constant. The main reason for this is that different atoms of aluminum and steel which existed in the joint area were undesirable during the heat treating process. Therefore, each type of atoms try to revert to its original alloy, which means there was no attraction between the different atoms.

4.17.6 Effect of Varying Rotation Speed after Heat Treatment

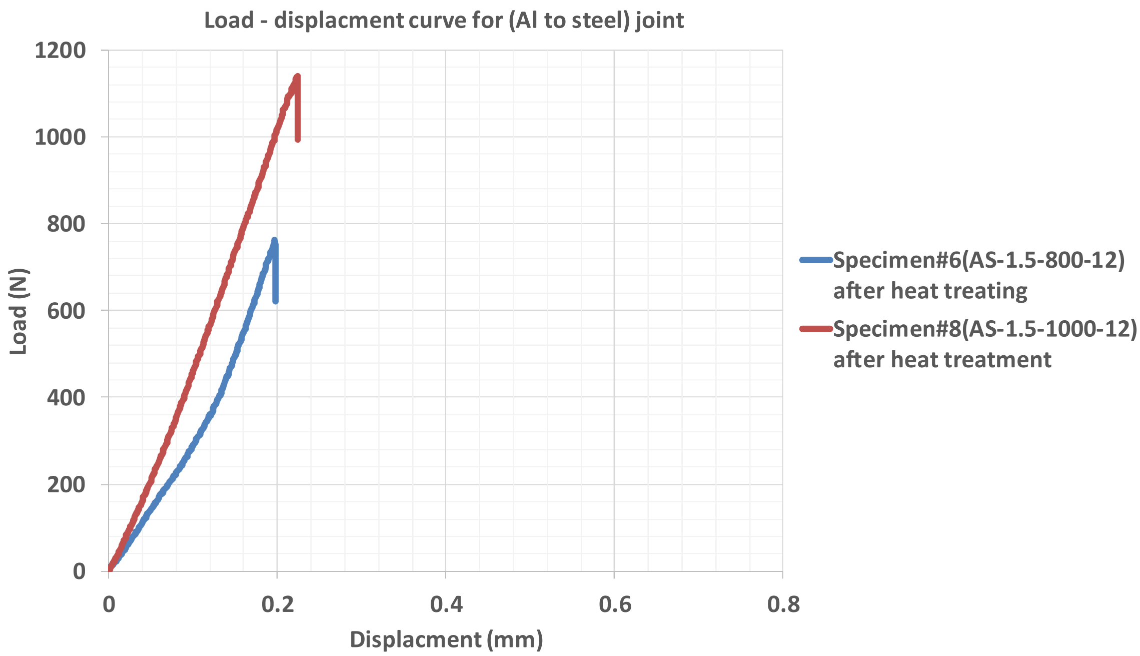


Figure (4.91) Load – displacement curves for bending test after heat treating

Figure (4.91) compare the variation in bending strength for specimens #6 and #8. The specimens were welded using the same travel speed and tilt angle. The difference was that the rotation speed when welding specimen #6 was 800 rpm and when welding specimen #8 was 1000 rpm. There is a substantial difference between the two strength profiles, indicating the variation in rotation speed over the range of 800 to 1000 rpm has significant effect on the strength of the welded samples. A similar observation was made for other combinations of welding conditions in which only the rotation speed was varied as shown in the appendix part. The figure also show that the specimen that has a higher rotation speed was stronger than the specimen with a lower rotation speed when the tilt angle and travel speed are constant. This result matches the literature review results.

Table (4.4) Summary of the mechanical properties of aluminum to steel joints

Al (6061-T6) to 1018 steel				**Tensile test (UTS) MPa**		**Tensile test (Elongation %)**		**Joint hardness (HRF)**		**Standard deviation**		**Bending test (Fracture stress) MPa**	
Samples #	A	R	T	Before	After	Before	After	Before	After	Before	After	Before	After
1	0	800	10	134.8	19.05	3.6	0.7	46.5	80.2	12.3	7.3	411.5	165.5
2	0	800	12	110.3	48.3	3.8	1.3	53.1	76.9	7.8	6.3	274.8	271.8
3	0	1000	10	93.2	18	2.8	0.7	52.3	85.04	7.02	9.3	267.2	244
4	0	1000	12	98	51.3	2.8	1.5	47.2	86.8	6.3	3.7	264.4	156.84
5	1.5	800	10	175.5	50.5	3.9	1	44.7	80.4	0.82	9.3	430.3	164.7
6	1.5	800	12	157.9	22.6	3.9	0.8	49.4	77.6	5.8	5.8	219.4	123.3
7	1.5	1000	10	137.3	35.4	3.8	1.2	48.5	81	2.8	6.7	228.9	133.4
8	1.5	1000	12	108.5	36.4	3.06	1.2	57.8	88	6.03	5.5	282.5	152.9

4.18 Microstructure Test

4.18.1 Optical Micrograph for AL to Steel Joints before and after Heat Treatment

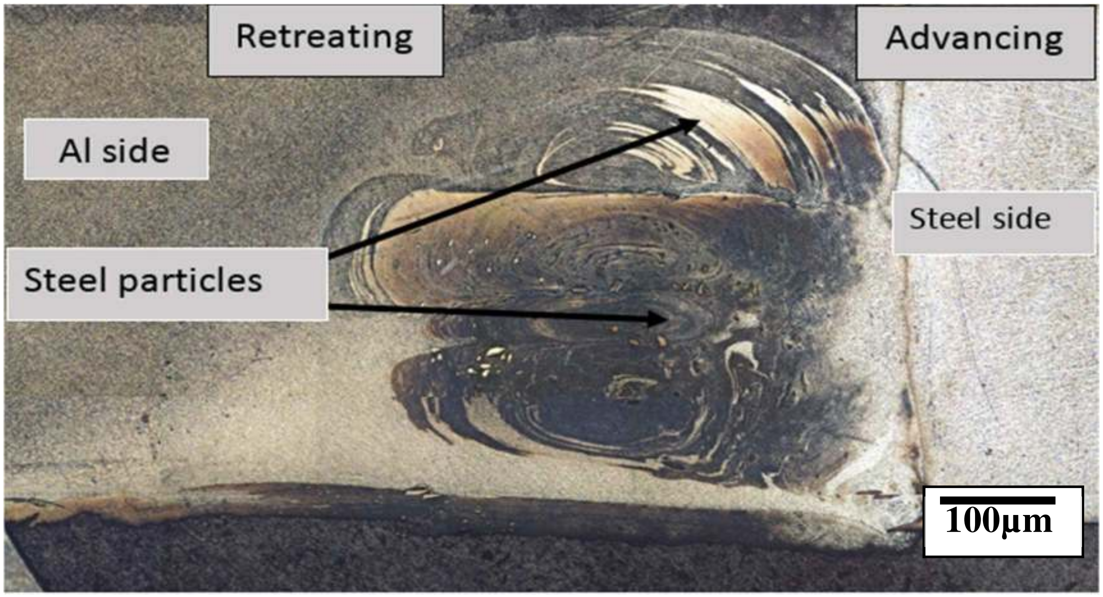


Figure (4.92) Optical micrograph for (Al-steel) joint at the conditions (AS-1.5-800-10) before heat treating

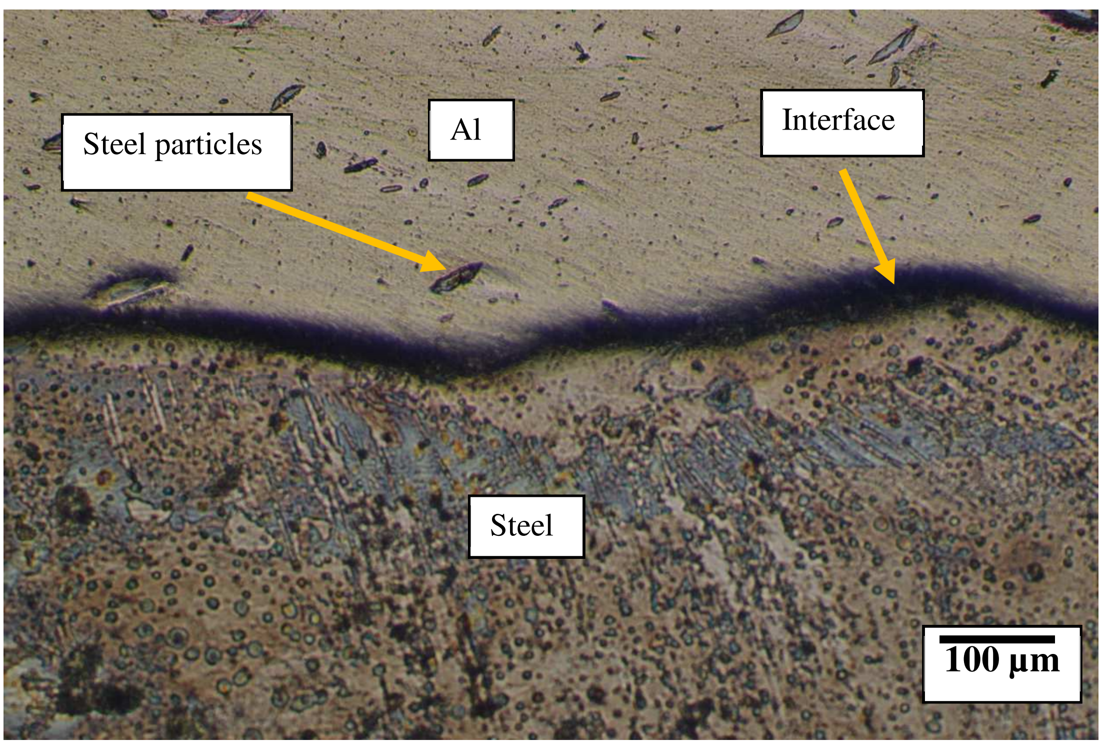


Figure (4.93) Optical micrograph for (Al-steel) joint at the conditions (AS-1.5-800-10) before heat treating

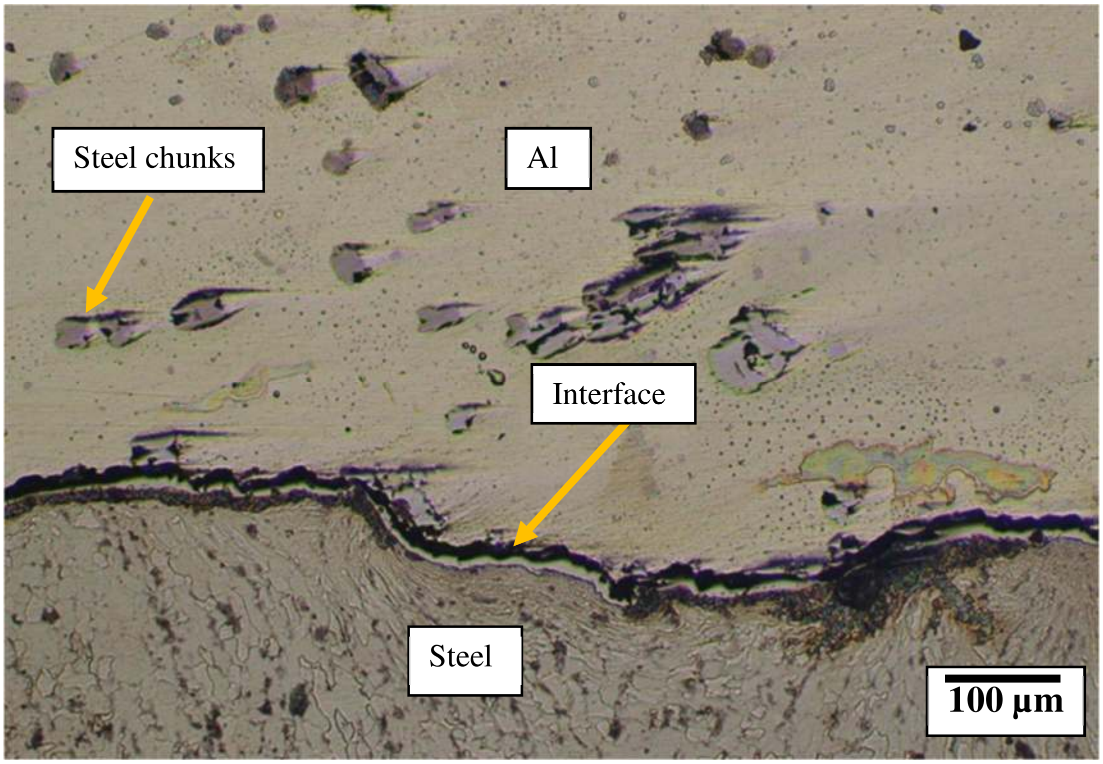


Figure (4.94) Optical micrograph for (Al-steel) joint at the conditions (AS-1.5-800-10) after heat treating

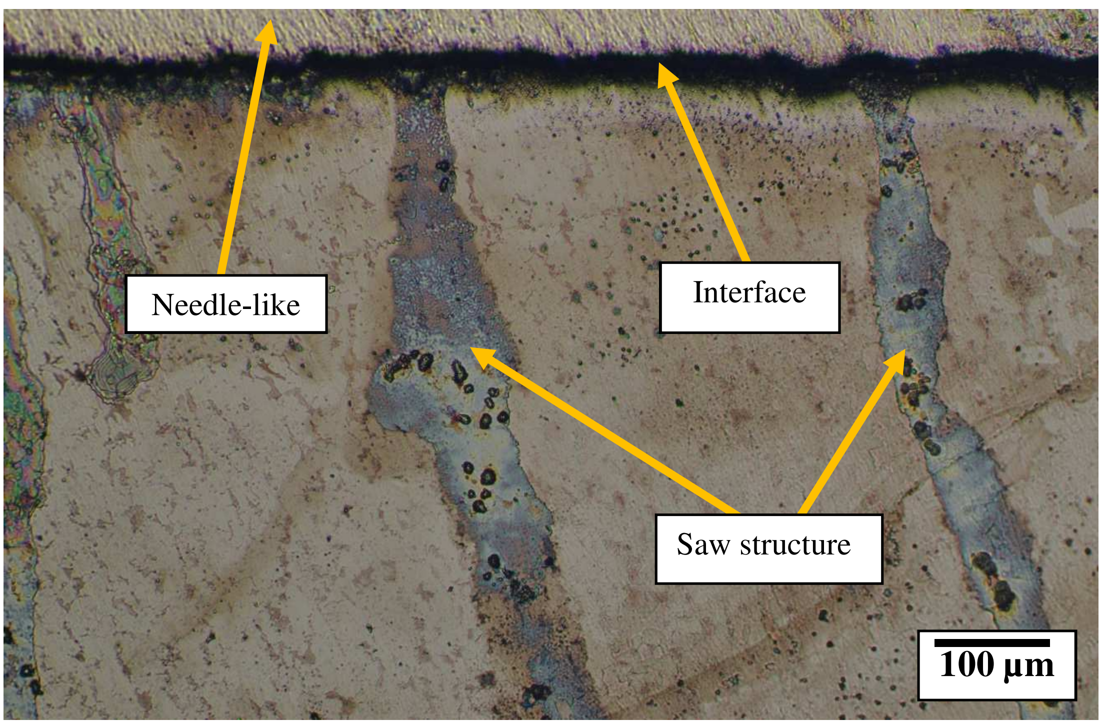


Figure (4.95) Optical micrograph for (Al-steel) joint at the conditions (AS-1.5-800-10) after heat treating

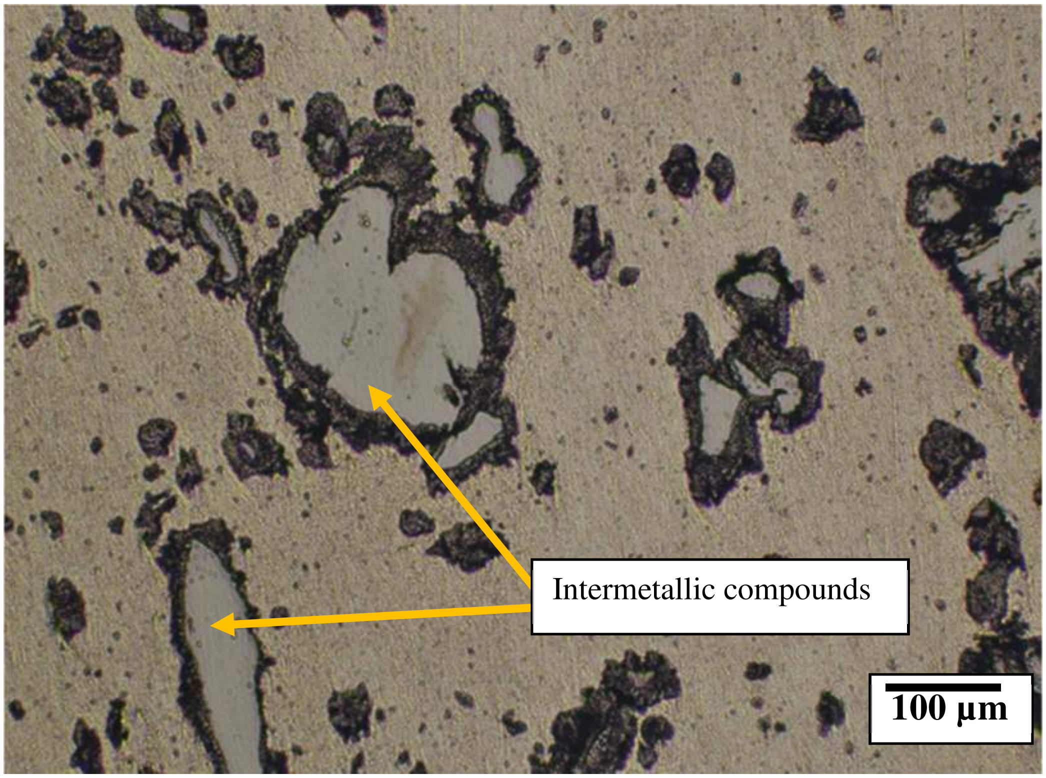


Figure (4.96) Optical micrograph for (Al-steel) joint at the conditions (AS-1.5-800-10) after heat treating

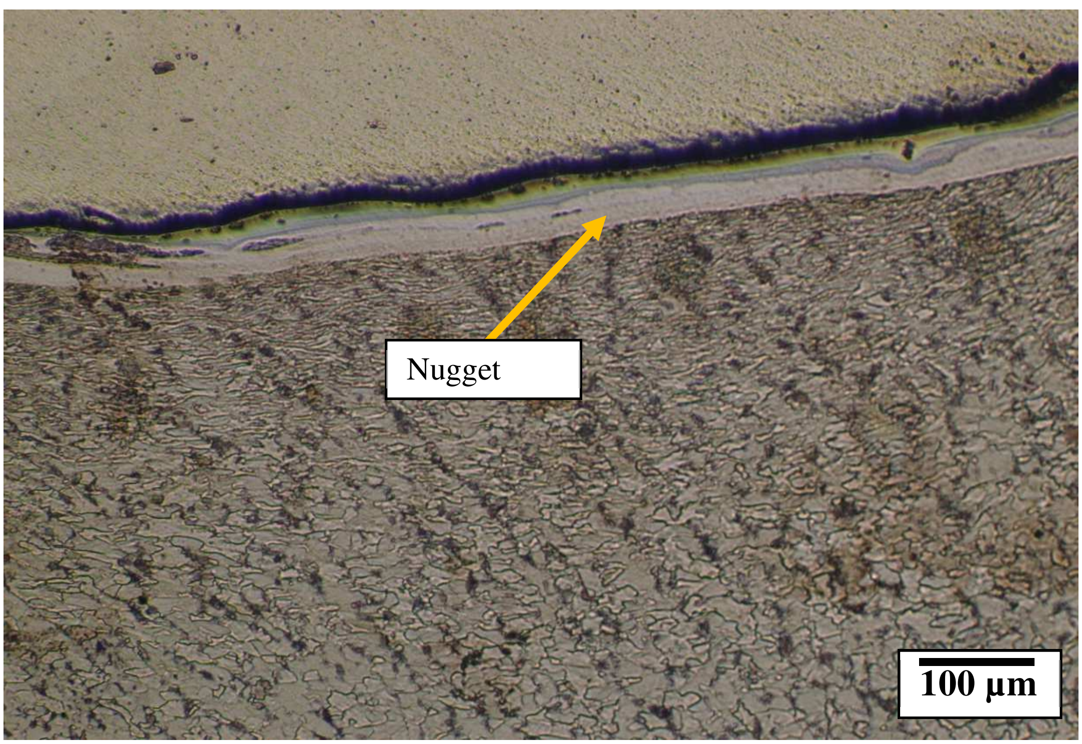


Figure (4.97) Optical micrograph for (Al-steel) joint at the conditions (AS-1.5-800-12) before heat treating

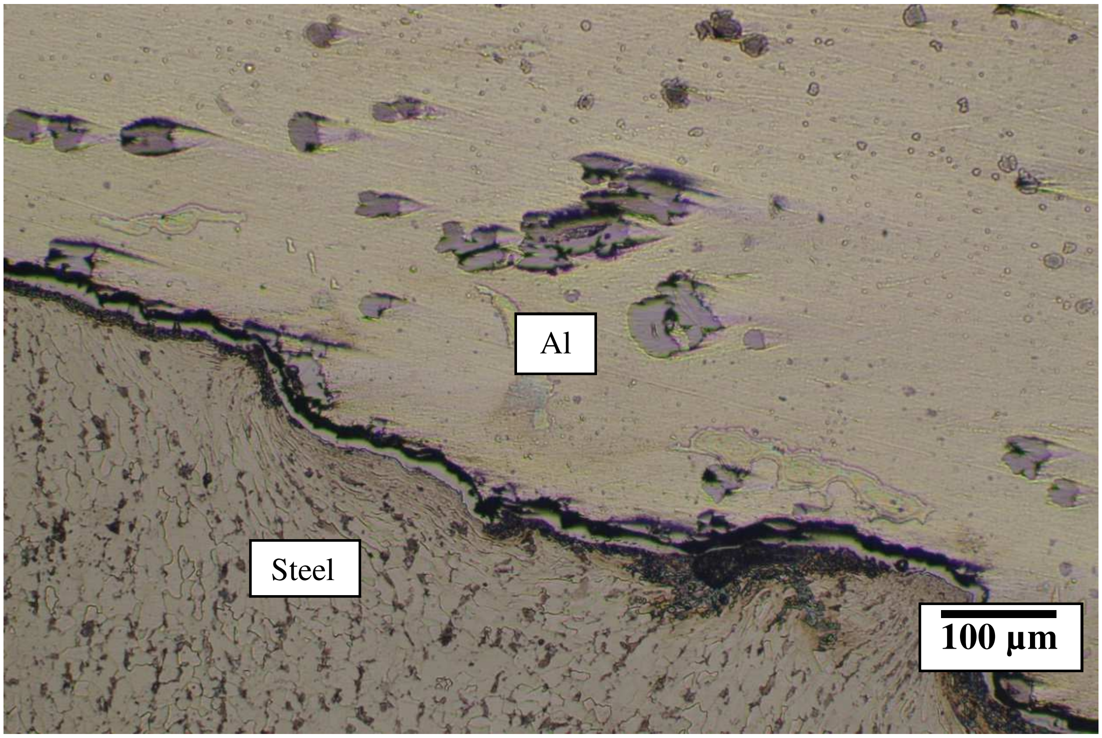


Figure (4.98) Optical micrograph for (Al-steel) joint at the conditions (AS-1.5-800-12) after heat treating

Figures (4.92, 4.93, 4.94, 4.95, 4.96, 4.97, 4.98, 4.99, 4.100, 4.101, 4.102, and 4.103) show the microstructure for an Al (6061-T6) and (1018 steel) joints. The images show that the base metal of steel has small equiaxed grains which include both Perlite and Ferrite. This fine structure in steel side adjacent to the nugget zone results due to the dynamic recrystallization. According to the images, the welding interface between an aluminum and steel joint is clearer than between an aluminum to aluminum joint. The microstructure shows some steel chunks in aluminum side which have different colors, these colures are dark and gray. The figures show the microstructure of Al (6061-T6) to 1018 steel joints before and after the heat treating process. The interface between both the aluminum and steel looks like a zigzag line. Some of the intermetallic compounds that are black and gray form during welding because this method of welding is a solid state method, as seen in figure (4.98). Another important feature that forms is the "saw" structure which exists in the steel zone and close to the nugget zone. Saw structure forms as a result of the shear force by the friction tool, especially by the sharp edge of the shoulder. Figure (4.97) shows the needle – like compounds that take place in the aluminum side which are segregated from the other intermetallic compounds because of the maximum stirring in the NZ. Figure (4.100) illustrate the width of the nugget zone and the position of the pin. One quarter of the pin diameter was at the steel side while the other three quarters were at the aluminum side. So, the joint floor looks like aluminum instead of the steel, which means the joint lies on the aluminum side more than on the steel side. This means that the friction stir welding joint between Al (6061-T6) and (1018 steel) seems heterogeneous. In other words, the friction stir welding zones such as NZ, TMAZ, HAZ, and BM, are different in strength. The tension fracture occurred at the boundary between the thermos mechanically affected zone and the nugget zone, which means the nugget zone has higher strength. The finer grains structure take place during welding in the aluminum side, these grains result because of the high cooling rate. However, coarse grains form after the fine grains region because of the low cooling rate. Some defects form during friction stir welding process due to the variation in the temperatures. These defects include cracks, voids, and porosity. The steel grains that exist in the thermos mechanically affected zone are smaller than the grains in the base metal. However, the grains for the aluminum alloy which exist in both the base metal and thermos mechanically affected zone are identical.

CHAPTER 5 : CONCLUSION

5.1 Summary

Friction stir welding between similar and dissimilar materials was done by using a milling machine. The joints were investigated under tension and bending tests rather than hardness and microstructure. A comparison took place in this work before and after heat treating process. Friction stir welding between (Ti-6Al-4V) alloy and (304 SS) was not successful. The main important reason was the high hardness for the titanium alloy. There was an attempt to weld copper (110) with Al (6061-T6), but it was not successful. The lack of was success due to the high conductivity of the copper metal which made the heat generated during the friction stir welding insufficient. Friction stir welding between Al (6061-T6) as a similar material was done with high degree of success. All the joint types between the similar and dissimilar materials were butt joints. Friction stir welding for Al (6061-T6) alloy was done in a counter clockwise direction. The last materials welded using the friction stir welding method were (1018 steel) and Al (6061-T6). The welding was successful, but the strength of the joint was less than the aluminum to aluminum joint. For all specimens, the steel was in advancing side while the aluminum in retreating side during friction stir welding. Eight specimens of both aluminum to aluminum and aluminum to steel joints were investigated before and after heat treating.

The heat treating process involved both the solid solution and aging step for all samples. The main purpose of this process was to return each alloy to its original properties and for comparison to take place. A hardness testing machine was used using the HRF scale for each specimen before and after heat treating. Hardness – position curves were plotted for comparison before and after heat treating process and for the base metals. For the tension test, load – displacement curves were converted to the stress- strain curves according to the definitions of both stress and strain. Two comparisons were conducted between the two specimens of both aluminum to aluminum and aluminum to steel joints. The first one was according to the change in one of the three welding parameters, those parameters were tilt angle, rotation speed, and travel speed. The second comparison was between the two specimens before and after the heat treating process.

5.2 Conclusions

The friction stir welding results for Al (6061-T6) and Al (6061-T6) to (1018 steel) joints were observed for all four different tests. It was concluded from the comparison in hardness before and after heat treating, all the joints after the heat treating process had higher hardness than the joints before heat treating. Also, the aluminum joints' shapes after the heat treating process were exactly straight lines, which means the hardness for both the base metal and the joint zone were the same and constant. It is concluded that the heat treating processes returned the alloy to its original properties. The joints' shapes before the heat treating processes were curved, which means the variations in temperature during friction stir welding make the joints softer. Because the hardness comparison before heat treating of each two specimens was identical after changing one of the three parameters, it was concluded that there is no effect of the welding parameters on the mechanical properties before heat treating process. Similarly, the specimens after heat treating process behaved in same the manner, so the welding parameters effect was almost nonexistent. For the aluminum to steel joint, the joint's shape was still curved, which means the hardness is still low before and after heat treating process. It is concluded that changing one of the three welding parameters is not effective on the mechanical properties, such as hardness, before or after heat treating process.

The tension test for the aluminum to aluminum joints showed that all the specimens after heat treating process had higher stress than the specimens before heat treating. It is concluded that the specimens after the heat treating process were stronger than the specimens before the heat treating process. Stress-strain curves of some aluminum joints had ultimate tensile strength higher than the base metal. This means that the friction stir welding process for aluminum to aluminum and the test procedures were more reliable. However, the tension test for the aluminum to steel joint showed that all the specimens before the heat treating process were stronger than the specimens after the heat treating process. It is concluded that during the heat treating process, the different atoms that exist in the joint area could return to its original alloy, such as aluminum to aluminum and steel to steel. For all types of joints, the effects of changing one of the three welding parameters behaved randomly, before and after heat treating. The conclusion concerning this point is that the milling machine used for this research was very old and not perfect.

Load – displacement curves of the bending test for the aluminum joint showed that all the specimens after the heat treating process were stronger than the specimens before the heat treating process. In conclusion, the heat treating process which included solution heat treating and aging returned the alloy properties to its nature. On the other hand, all the aluminum to steel joints before the heat treating process were stronger than after the heat treating process. As it was previously concluded, the different atoms could not unite in the joint area, so each type of atoms was returned to its original alloy, such as steel to steel and aluminum to aluminum. Changing one of the three welding parameters for both the aluminum and the aluminum to steel joints affected the weld in a random manner. It is concluded that adjusting the welding parameters, such the travel speed, of friction stir welding machine was not easy because it is an old machine.

5.3 Recommendations for future work

The most important recommendation is that the milling machine be modified so that the welding parameters can be adjusted easily. My research used three of welding parameters, those parameters were tilt angle, rotation speed, and travel speed, and adjusting all of those parameters was very difficult. The machine was not capable of continuous welding because the overload, especially for aluminum to steel joint. So, my recommendation is to replace that machine with a new one or at least to replace the control part.

It is also recommended to modify the universal testing machine which used for the tension test. The Instron 5500 R should have a maximum load capacity equal to150000 N. However, it was not able to apply more than 35000 N for strong specimens, and then it showed an error message. Repairing that machine would make the researcher able to test the specimens in right way, even if some welding joint exceeds the base metal load.

The last recommendation is that the hardness variation at the microstructure level be measured using a microhardness tester. The indentations using the Rockwell hardness testing machine are too large to observe the differences in hardness that would occur between the NZ, TMAZ, and the HAZ in the welded region. This would give additional insight into the microstructure resulting from FSW and subsequent heat treatment.

REFERENCES

[1] S. Malopheyev, I. Vysotskiy, V. Kulitskiy, S. Mironov, and R. Kaibyshev, "Optimization of processing-microstructure-properties relationship in friction-stir welded 6061-T6 aluminum alloy," *Mater. Sci. Eng. A*, vol. 662, pp. 136–143, 2016.

[2] W.-B. Lee and S.-B. Jung, "Effect of Microstructure on Mechanical Properties of Friction-Welded Joints between Ti and AISI 321 Stainless Steel," *Mater. Trans.*, vol. 45, no. 9, pp. 2805–2811, 2004.

[3] S. Ravi and R. Ramadoss, "A Study on Mechanical and Metallurgical Properties of Friction Welded Dissimilar Materials," vol. 3, no. June, pp. 32–38, 2015.

[4] Y. N. Zhang, X. Cao, S. Larose, and P. Wanjara, "Review of tools for friction stir welding and processing," *Can. Metall. Q.*, vol. 51, no. 3, pp. 250–261, 2012.

[5] B. A. Halkier, "Chapter One – General Introduction to Glucosinolates," *Adv. Bot. Res.*, vol. 80, pp. 1–14, 2016.

[6] A. Farias, G. F. Batalha, E. F. Prados, R. Magnabosco, and S. Delijaicov, "Tool wear evaluations in friction stir processing of commercial titanium Ti-6Al-4V," *Wear*, vol. 302, no. 1–2, pp. 1327–1333, 2013.

[7] X. K. Zhu and Y. J. Chao, "Numerical simulation of transient temperature and residual stresses in friction stir welding of 304L stainless steel," *J. Mater. Process. Technol.*, vol. 146, no. 2, pp. 263–272, 2004.

[8] S. S. Sengar and J. Kumar, "A study of recent trends in friction stir welding," pp.

646–649, 2012.

[9] S. Pervaiz, A. Rashid, I. Deiab, and M. Nicolescu, "Influence of Tool Materials on Machinability of Titanium- and Nickel-Based Alloys: A Review," *Mater. Manuf. Process.*, vol. 29, no. 3, pp. 219–252, 2014.

[10] K. S. CH Muralimohan, "Properties of Friction Welding Titanium-stainless Steel Joints with a Nickel Interlayer," *Procedia Mater. Sci.*, vol. 5, pp. 1120–1129, 2014.

[11] M. S. Sidhu and S. S. Chatha, "Friction Stir Welding – Process and its Variables : A Review," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 2, no. 12, pp. 275–279, 2012.

[12] M. Kimura, T. Iijima, M. Kusaka, K. Kaizu, and A. Fuji, "Joining phenomena and tensile strength of friction welded joint between pure titanium and low carbon steel," *J. Mater.*, vol. 55, pp. 152–164, 2014.

[13] M. P. Meshram, B. K. Kodli, and S. R. Dey, "Friction Stir Welding of Austenitic Stainless Steel by PCBN Tool and its Joint Analyses," *Procedia Mater. Sci.*, vol. 6, no. Icmpc, pp. 135–139, 2014.

[14] Y. Gao, T. Tsumura, and K. Nakata, "Dissimilar welding of titanium alloys to steels," *Trans. JWRI*, vol. 41, no. 2, pp. 7–12, 2012.

[15] "Joining of CP-Ti to 304 stainless steel using friction stir welding technique," *Mater. Des.*, vol. 31, no. 10, pp. 4800–4807, 2010.

[16] K. Ishida, Y. Gao, K. Nagatsuka, M. Takahashi, and K. Nakata, "Microstructures and mechanical properties of friction stir welded lap joints of commercially pure titanium and 304 stainless steel," *J. Alloys Compd.*, vol. 630, pp. 172–177, 2015.

[17] F. Shahid, "Mechanical and Microstuctural Analysis of Dissimilar," vol. 25, no. October, pp. 6–14, 2015.

[18] S. K. Selvam and T. Parameshwaran Pillai, "Analysis of heavy alloy tool in friction stir welding," *Int. J. ChemTech Res.*, vol. 5, no. 3, pp. 1346–1358, 2013.

[19] K. Chiteka, "Friction Stir Welding/Processing Tool Materials and Selection," vol. 2, no. 11, pp. 8–18, 2013.

[20] R. Rai, A. De, H. K. D. H. Bhadeshia, and T. DebRoy, "Review: friction stir welding tools," *Sci. Technol. Weld. Join.*, vol. 16, no. 4, pp. 325–342, 2011.

[21] R. S. Mishra and Z. Y. Ma, "Friction stir welding and processing," *Mater. Sci. Eng. R Reports*, vol. 50, no. 1–2, pp. 1–78, 2005.

[22] X. He, F. Gu, and A. Ball, "Progress in Materials Science A review of numerical analysis of friction stir welding," *Prog. Mater. Sci.*, vol. 65, pp. 1–66, 2014.

[23] M. Mehta, G. M. Reddy, A. V. Rao, and A. De, "Numerical modeling of friction stir welding using the tools with polygonal pins," *Def. Technol.*, vol. 11, no. 3, pp. 229–236, 2015.

[24] M. H. Tolephih, K. M. Mashloosh, and Z. Waheed, "Comparative Study of the Mechanical Properties of (FS) and MIG Welded Joint in (AA7020-T6) Aluminum Alloy," *Al-Khwarizmi Eng. J.*, vol. 7, no. 2, pp. 22–35, 2011.

[25] H. Liu, K. Nakata, N. Yamamoto, and J. Liao, "Grain Orientation and Texture Evolution in Pure Titanium Lap Joint Produced by Friction Stir Welding," vol. 51, no. 11, pp. 2063–2068, 2010.

[26] Y. Zhang, Y. S. Sato, H. Kokawa, S. H. C. Park, and S. Hirano, "Microstructural characteristics and mechanical properties of Ti-6Al-4V friction stir welds," *Mater. Sci. Eng. A*, vol. 485, no. 1–2, pp. 448–455, 2008.

[27] C. M. Chen and R. Kovacevic, "Finite element modeling of friction stir welding - Thermal and thermomechanical analysis," *Int. J. Mach. Tools Manuf.*, vol. 43, no. 13, pp. 1319–1326, 2003.

[28] H. J. Liu, L. Zhou, and Q. W. Liu, "Microstructural characteristics and mechanical properties of friction stir welded joints of Ti-6Al-4V titanium alloy," *Mater. Des.*, vol. 31, no. 3, pp. 1650–1655, 2010.

[29] L. Zhou, H. J. Liu, P. Liu, and Q. W. Liu, "The stir zone microstructure and its formation mechanism in Ti-6Al-4V friction stir welds," *Scr. Mater.*, vol. 61, no. 6, pp. 596–599, 2009.

[30] J. Su, J. Wang, R. S. Mishra, R. Xu, and J. A. Baumann, "Microstructure and mechanical properties of a friction stir processed Ti-6Al-4V alloy," *Mater. Sci. Eng. A*, vol. 573, pp. 67–74, 2013.

[31] M. Jafarzadegan, A. Abdollah-zadeh, A. H. Feng, T. Saeid, J. Shen, and H. Assadi, "Microstructure and Mechanical Properties of a Dissimilar Friction Stir Weld between Austenitic Stainless Steel and Low Carbon Steel," *J. Mater. Sci. Technol.*, vol. 29, no. 4, pp. 367–372, 2013.

[32] A. P. Reynolds, W. Tang, T. Gnaupel-Herold, and H. Prask, "Structure, properties, and residual stress of 304L stainless steel friction stir welds," *Scr. Mater.*, vol. 48, no. 9, pp. 1289–1294, 2003.

[33] R. Nandan, T. DebRoy, and H. K. D. H. Bhadeshia, "Recent advances in friction-stir welding - Process, weldment structure and properties," *Prog. Mater. Sci.*, vol. 53, no. 6, pp. 980–1023, 2008.

[34] A. Fall, M. Fesharaki, A. Khodabandeh, and M. Jahazi, "Tool Wear Characteristics and Effect on Microstructure in Ti-6Al-4V Friction Stir Welded Joints," *Metals (Basel).*, vol. 6, no. 11, p. 275, 2016.

[35] M. Balasubramanian, "Development of processing windows for diffusion bonding of Ti-6Al-4V titanium alloy and 304 stainless steel with silver as intermediate layer," *Trans. Nonferrous Met. Soc. China (English Ed.*, vol. 25, no. 9, pp. 2932–2938, 2015.

[36] M. M. Cheepu, V. Muthupandi, and S. Loganathan, "Friction Welding of Titanium to 304 Stainless Steel with Electroplated Nickel Interlayer," *Mater. Sci. Forum*, vol. 710, pp. 620–625, 2012.

[37] H. C. Dey, M. Ashfaq, A. K. Bhaduri, and K. P. Rao, "Joining of titanium to 304L stainless steel by friction welding," *J. Mater. Process. Technol.*, vol. 209, no. 18–19, pp. 5862–5870, 2009.

[38] M. Fazel-Najafabadi, S. F. Kashani-Bozorg, and A. Zarei-Hanzaki, "Dissimilar lap joining of 304 stainless steel to CP-Ti employing friction stir welding," *Mater. Des.*, vol. 32, no. 4, pp. 1824–1832, 2011.

[39] M. KIMURA, M. KUSAKA, K. KAIZU, and A. FUJI, "Effect of Friction Welding Condition on Joining Phenomena and Tensile Strength of Friction Welded joint between Pure Copper and Low Carbon Steel," *J. Solid Mech. Mater. Eng.*, vol. 3,

no. 2, pp. 187–198, 2009.

[40] R. Kumar and M. Balasubramanian, “Experimental investigation of Ti–6Al–4V titanium alloy and 304L stainless steel friction welded with copper interlayer,” *Def. Technol.*, vol. 11, no. 1, pp. 65–75, 2015.

[41] W. Secietyt, “Friction Welding Austenitic Stainless Steel * ofTitaniumand Study Type 304L Words : Wetdinterface Rrpd,” vol. 21, no. April, pp. 58–65, 1990.

[42] A. Nallappan, “Joining of Ti-6Al-4V with SS304 by Friction welding.”

[43] N. Kumar, “Welding and,” .

[44] J. Ouyang, E. Yarrapareddy, and R. Kovacevic, “Microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper,” *J. Mater. Process. Technol.*, vol. 172, no. 1, pp. 110–122, 2006.

[45] P. Xue, B. L. Xiao, D. R. Ni, and Z. Y. Ma, “Enhanced mechanical properties of friction stir welded dissimilar Al-Cu joint by intermetallic compounds,” *Mater. Sci. Eng. A*, vol. 527, no. 21–22, pp. 5723–5727, 2010.

[46] I. Galvão, J. C. Oliveira, A. Loureiro, and D. M. Rodrigues, “Formation and distribution of brittle structures in friction stir welding of aluminium and copper: Influence of shoulder geometry,” *Intermetallics*, vol. 22, pp. 122–128, 2012.

[47] L. I. Xia-wei, Z. Da-tong, Q. I. U. Cheng, and Z. Wen, “Microstructure and mechanical properties of dissimilar pure copper / 1350 aluminum alloy butt joints by friction stir welding,” *Trans. Nonferrous Met. Soc. China*, vol. 22, no. 6, pp. 1298–1306, 2012.

[48] P. Copper, “Friction Stir Welding on Dissimilar Metals Aluminum 6061 & Pure Copper,” no. December, 2016.

[49] E. Taban, J. E. Gould, and J. C. Lippold, “Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel : Properties and microstructural characterization,” *Mater. Des.*, vol. 31, no. 5, pp. 2305–2311, 2010.

[50] C. M. Chen and R. Kovacevic, “Joining of Al 6061 alloy to AISI 1018 steel by combined effects of fusion and solid state welding,” *Int. J. Mach. Tools Manuf.*, vol. 44, no. 11, pp. 1205–1214, 2004.

[51] E. Taban, J. E. Gould, and J. C. Lippold, “Characterization of 6061-T6 aluminum alloy to AISI 1018 steel interfaces during joining and thermo-mechanical conditioning,” *Mater. Sci. Eng. A*, vol. 527, no. 7–8, pp. 1704–1708, 2010.

[52] M. Dehghani, A. Amadeh, and S. A. A. A. Mousavi, “Materia ls and Design Investigations on the effects of friction stir welding parameters on intermetallic and defect formation in joining aluminum alloy to mild steel,” *Mater. Des.*, vol. 49, pp. 433–441, 2013.

[53] S. Rajakumar, C. Muralidharan, and V. Balasubramanian, “Establishing empirical relationships to predict grain size and tensile strength of friction stir welded AA 6061-T6 aluminium alloy joints,” *Trans. Nonferrous Met. Soc. China*, vol. 20, no. 10, pp. 1863–1872, 2010.

[54] P. Engineering, T. Authors, and T. Authors, “Available online at www.sciencedirect.com,” vol. 64, pp. 862–867, 2013.

[55] K. Niitsu, L. Contri, L. Bergmann, and J. Fernandez, "Microstructure and interface characterization of dissimilar friction stir welded lap joints between Ti – 6Al – 4V and AISI 304," *J. Mater.*, vol. 56, pp. 139–145, 2014.

[56] C. W. Tan, Z. G. Jiang, L. Q. Li, Y. B. Chen, and X. Y. Chen, "Microstructural evolution and mechanical properties of dissimilar Al-Cu joints produced by friction stir welding," *Mater. Des.*, vol. 51, pp. 466–473, 2013.

[57] P. M. G. P. Moreira, A. M. P. de Jesus, A. S. Ribeiro, and P. M. S. T. de Castro, "Fatigue crack growth in friction stir welds of 6082-T6 and 6061-T6 aluminium alloys: A comparison," *Theor. Appl. Fract. Mech.*, vol. 50, no. 2, pp. 81–91, 2008.

[58] B. Richards, "Microstructure-Property Correlations in Friction Stir Welded Al6061-T6 Alloys," *Worcester Polytech. Inst.*, p. 67, 2010.

[59] Q. M. D. and B. A. Wahab1, "Experimental Study of Friction Stir Welding of 6061-T6 Aluminum Pipe," vol. 1, no. 3, 1991.

[60] A. Simar, Y. Br??chet, B. De Meester, A. Denquin, C. Gallais, and T. Pardoen, "Integrated modeling of friction stir welding of 6xxx series Al alloys: Process, microstructure and properties," *Prog. Mater. Sci.*, vol. 57, no. 1, pp. 95–183, 2012.

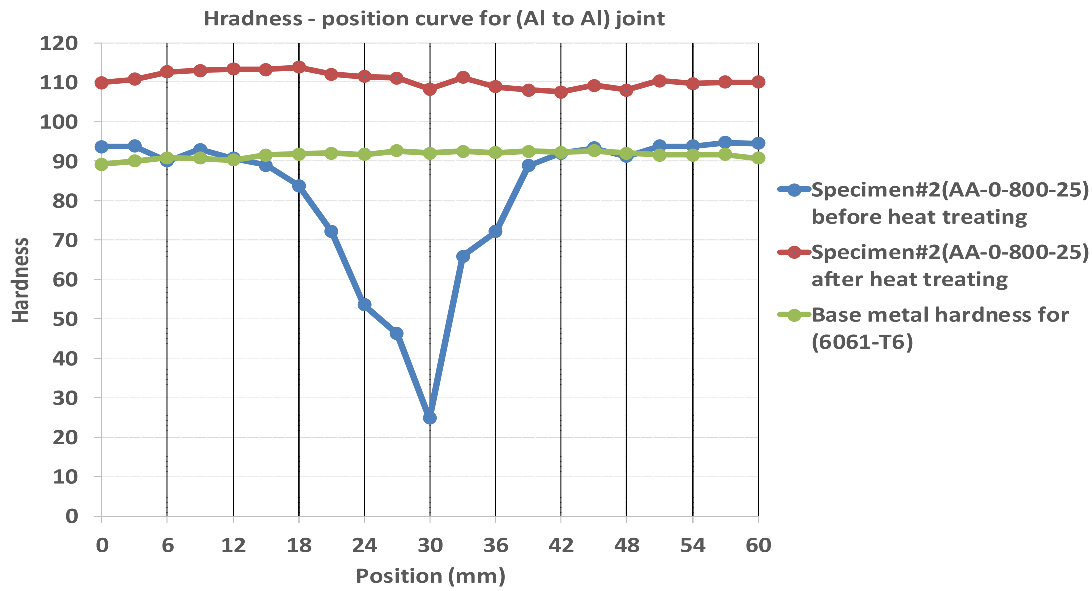
[61] W. H. Jiang and R. Kovacevic, "Feasibility study of friction stir welding of 6061-T6 aluminium alloy with AISI 1018 steel," *Proc. Inst. Mech. Eng. Part B-Journal Eng. Manuf.*, vol. 218, no. 10, pp. 1323–1331, 2004.

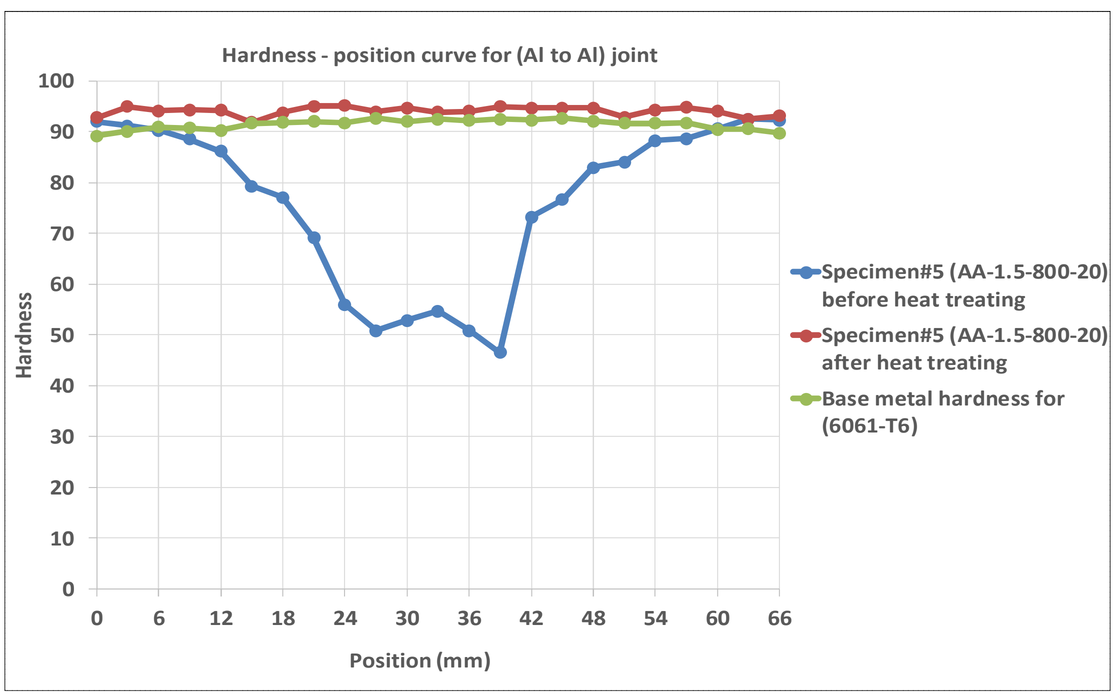
[62] W. B. Lee, M. Schmuecker, U. A. Mercardo, G. Biallas, and S. B. Jung, "Interfacial reaction in steel-aluminum joints made by friction stir welding," *Scr. Mater.*, vol.

55, no. 4, pp. 355–358, 2006.

Appendix

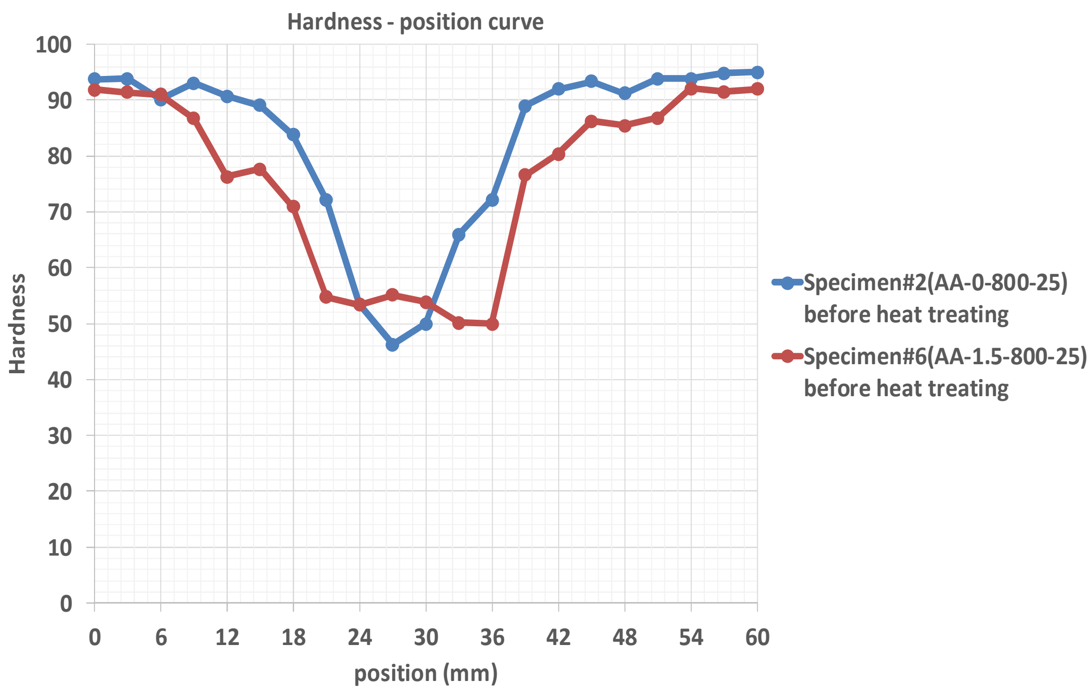
Hardness Test for Al (6061-T6) Joints before and after Heat Treatment

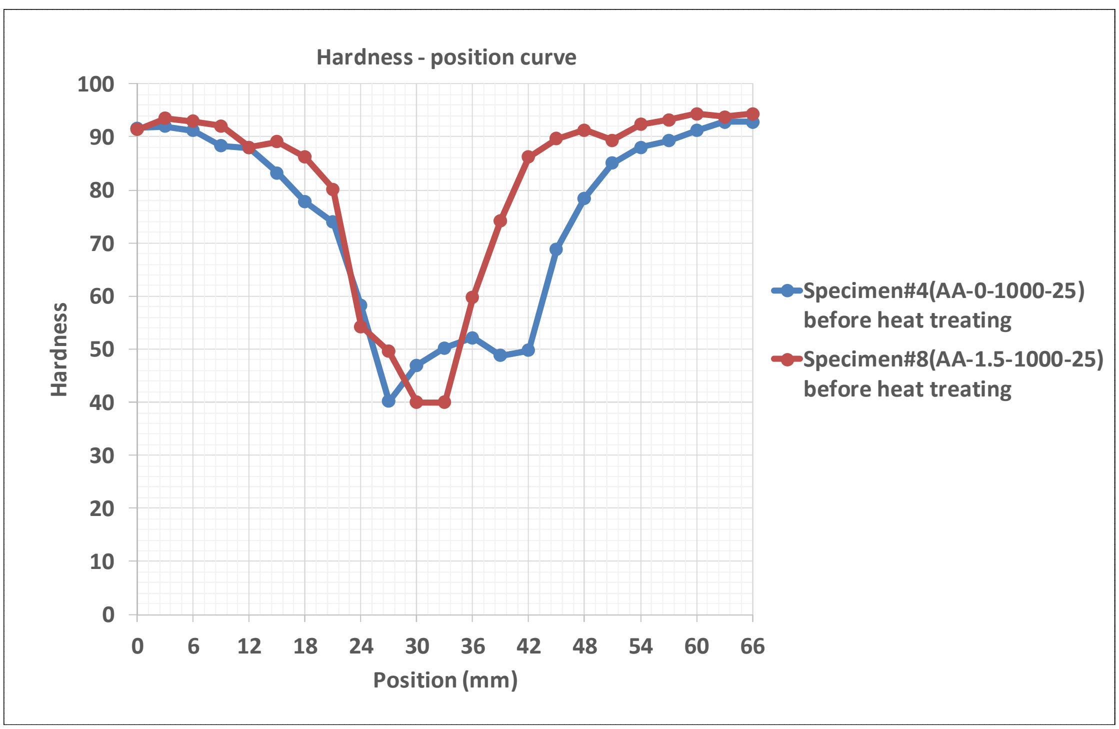




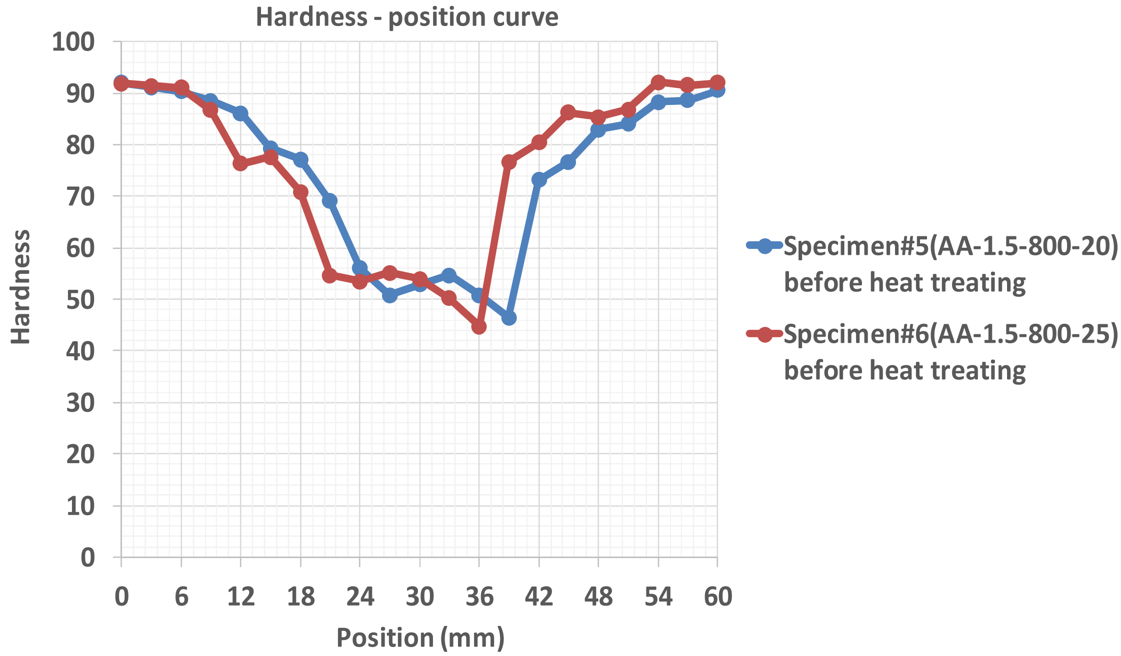
Effect of Welding Parameters on Properties before and after Heat Treatment

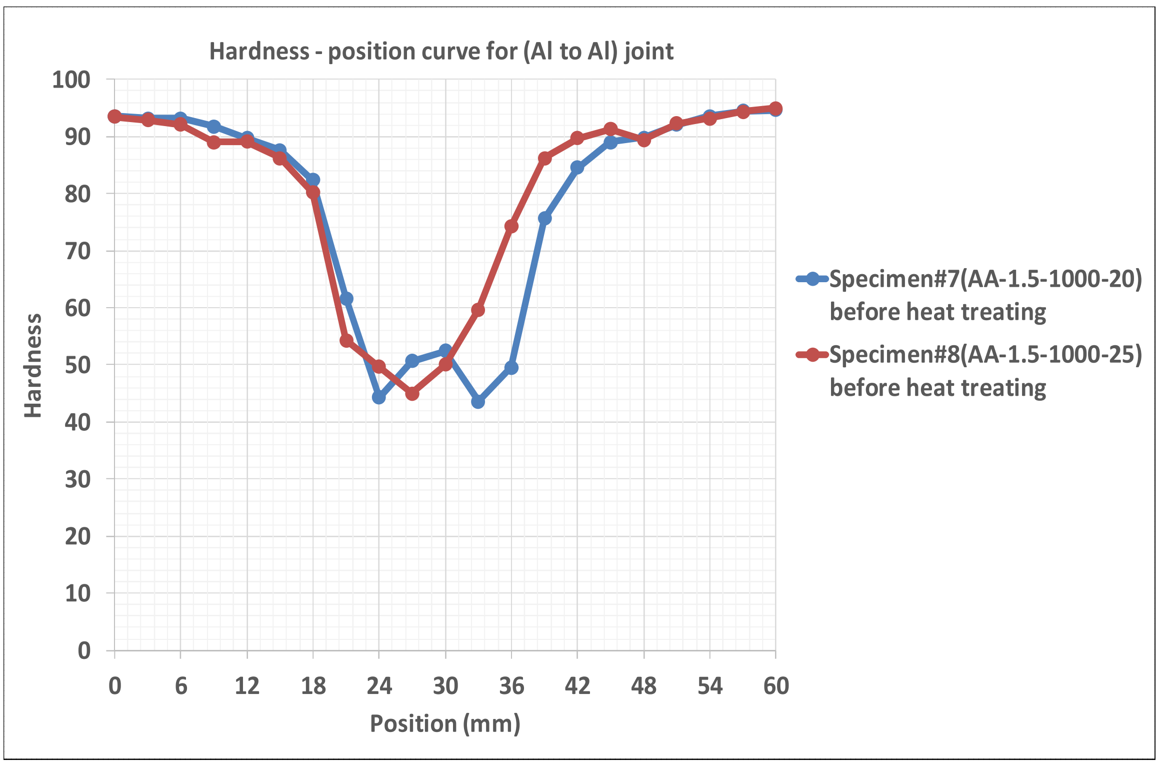
Effect of Varying Tilt Angle before Heat Treating Process





Effect of Varying Travel Speed before Heat Treatment





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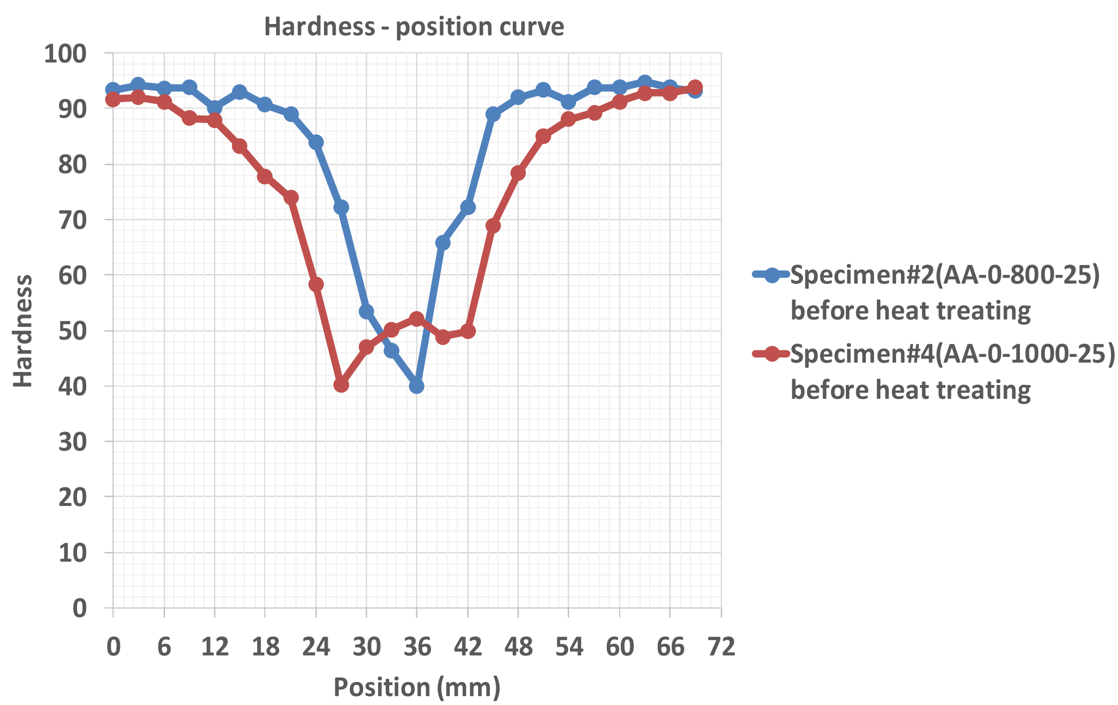

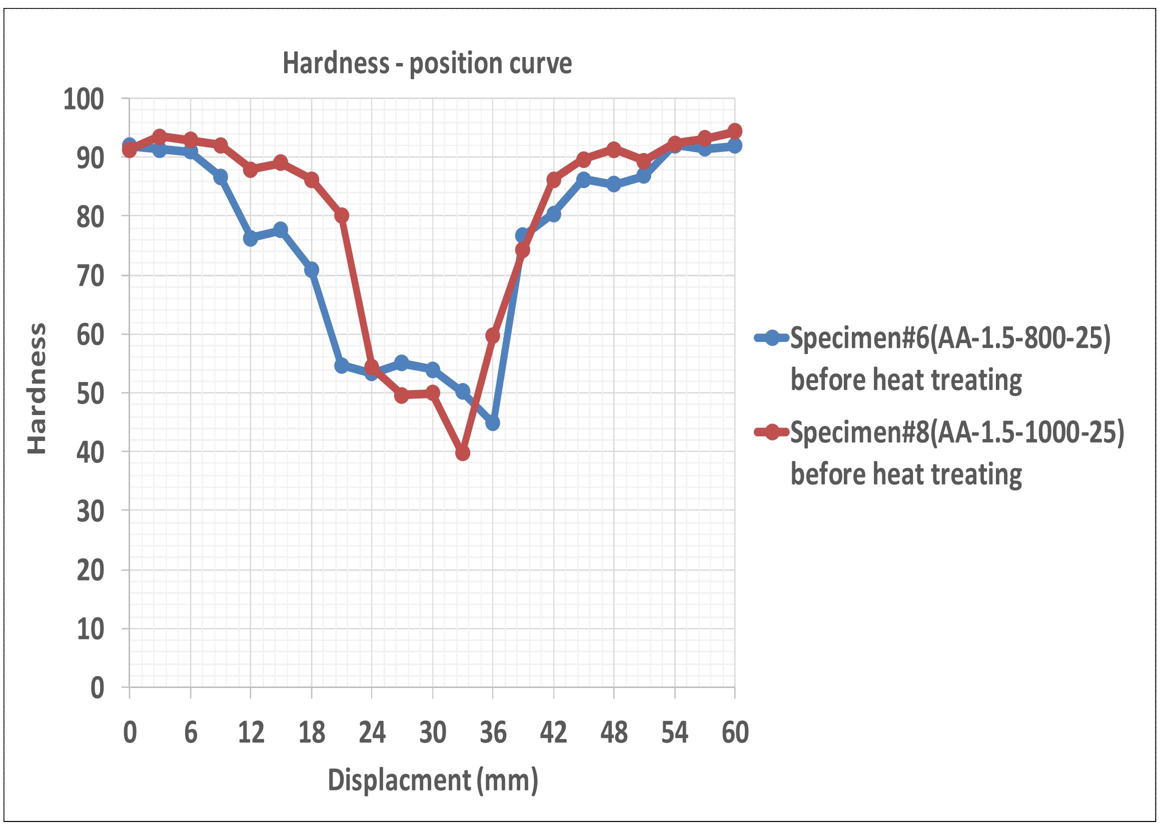

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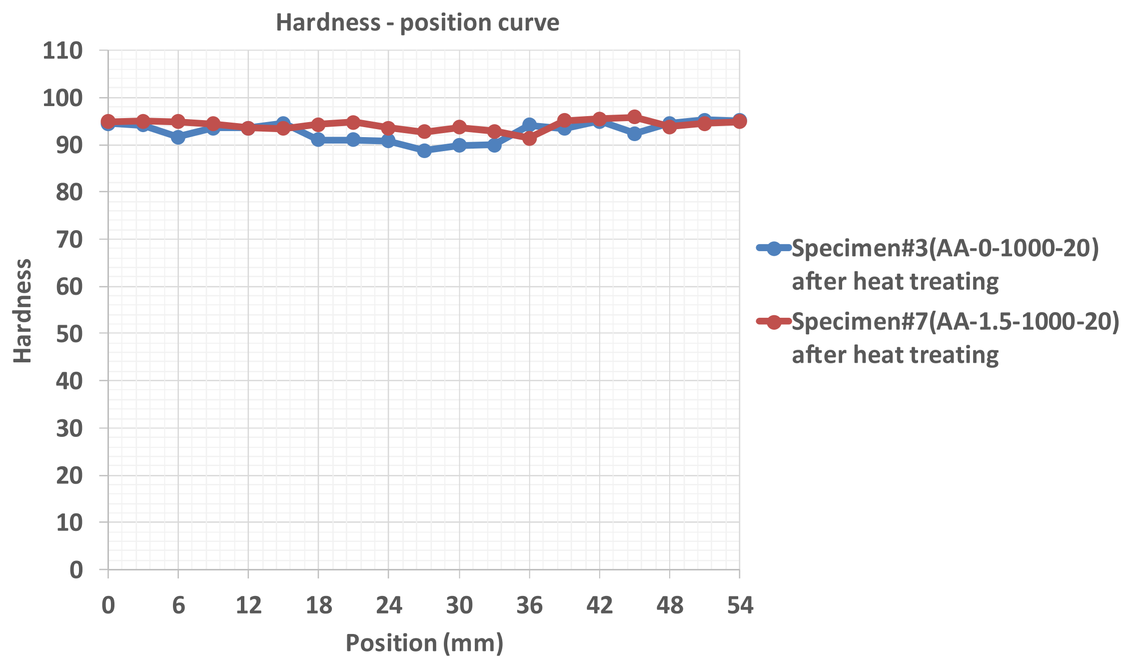

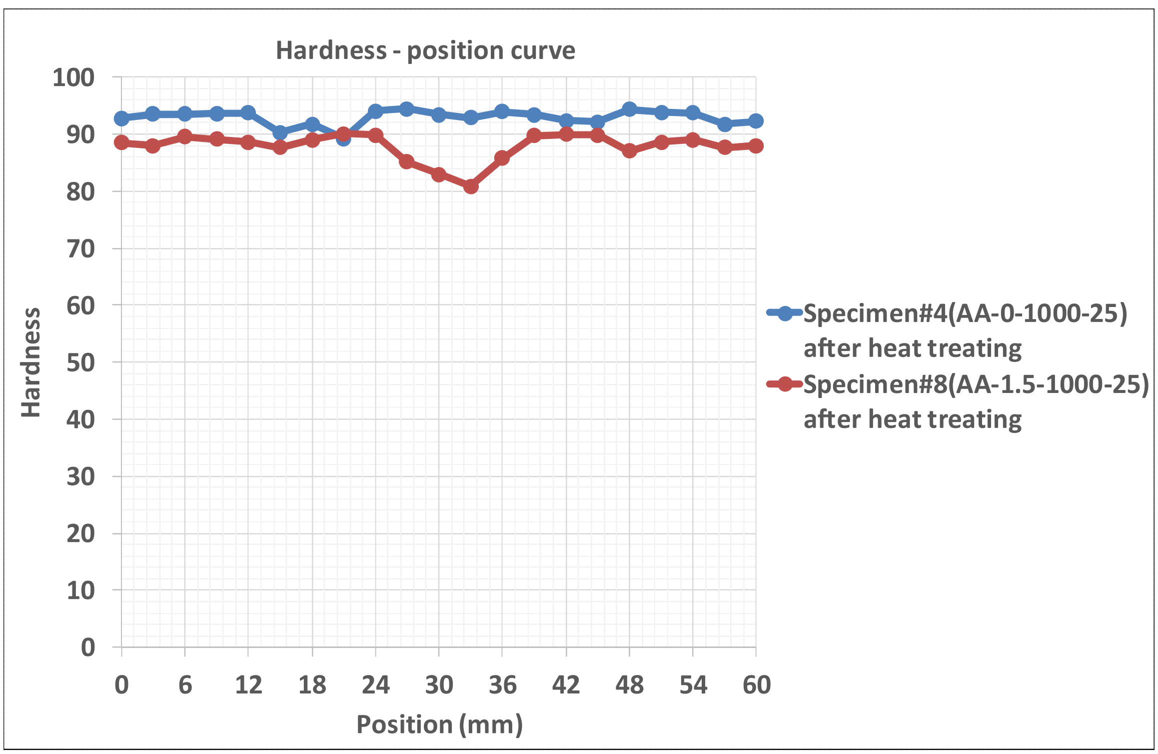

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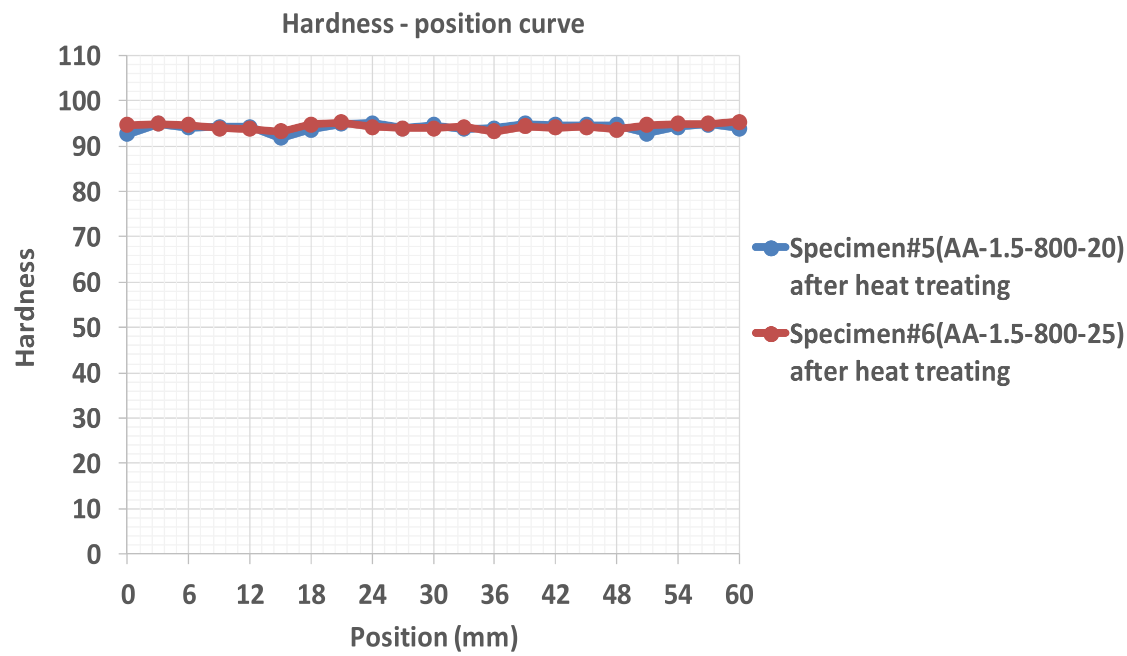

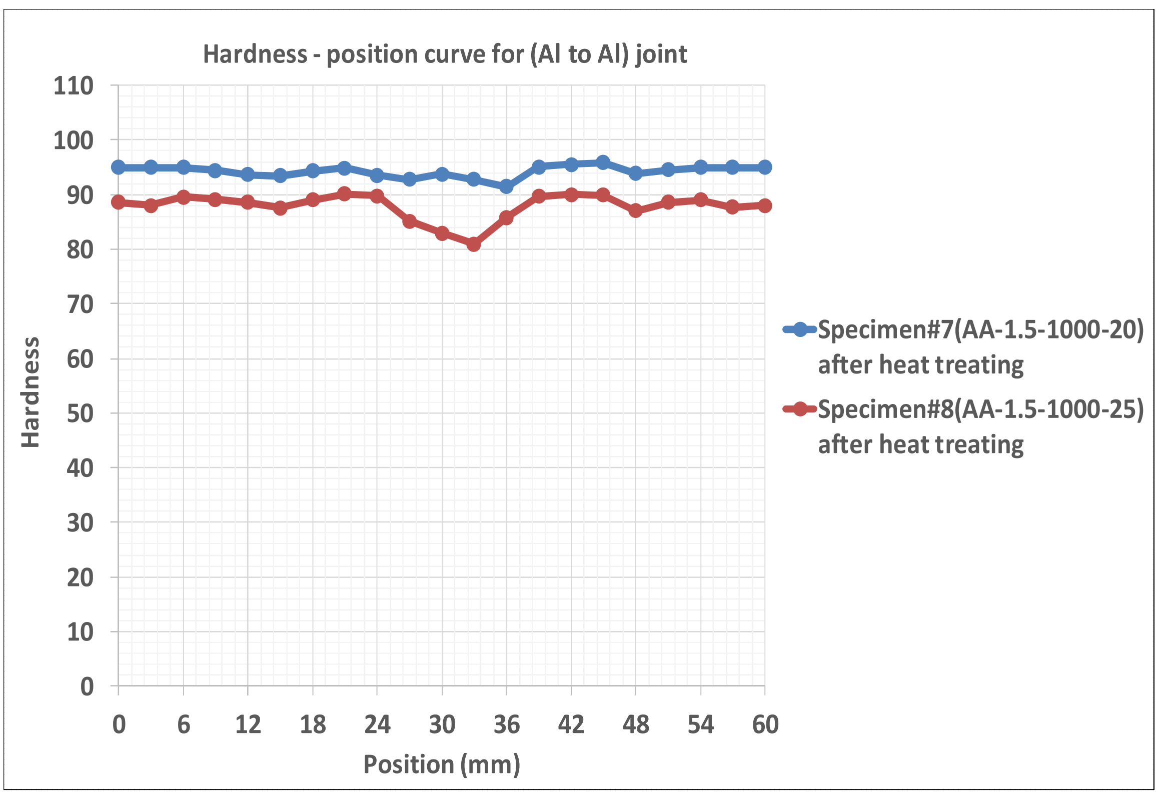

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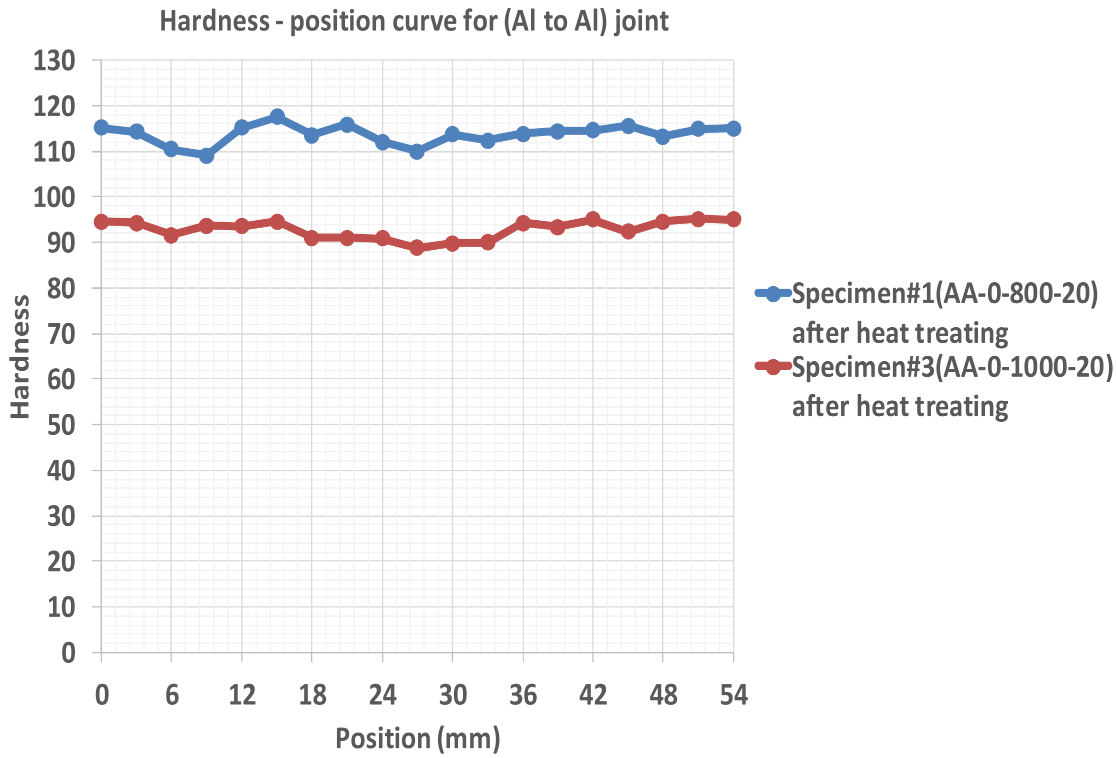
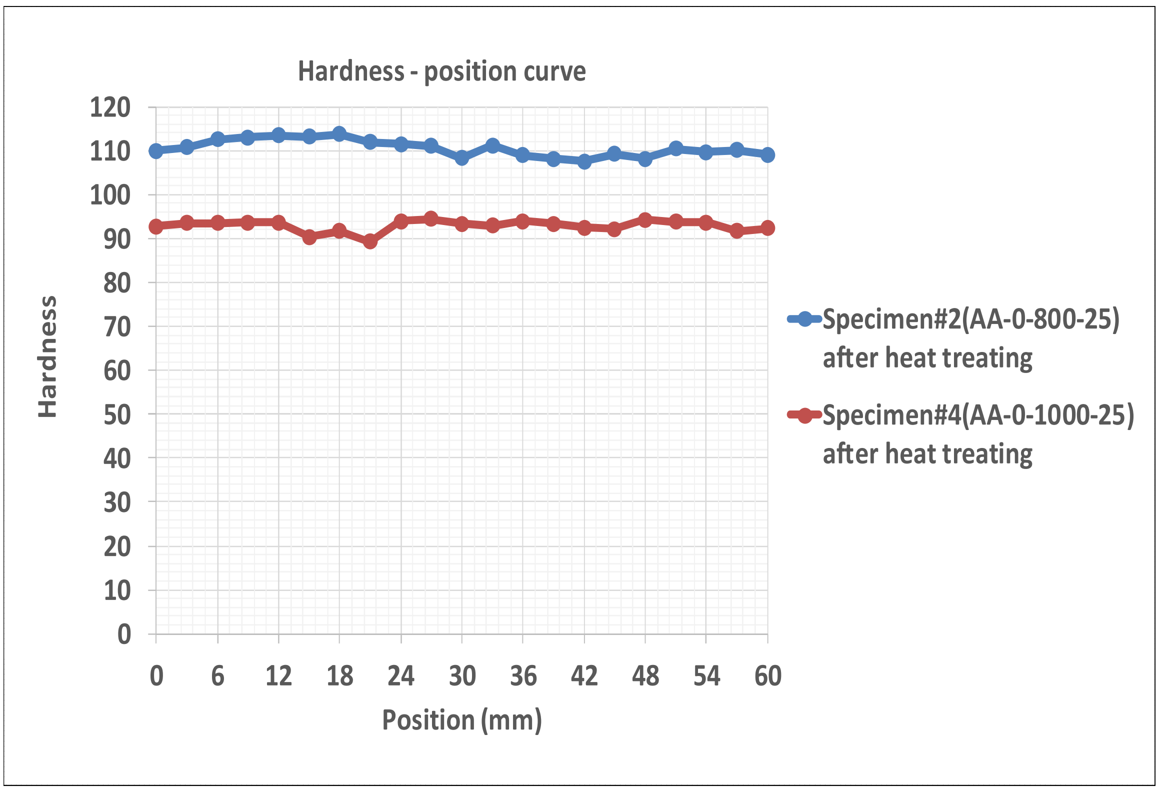
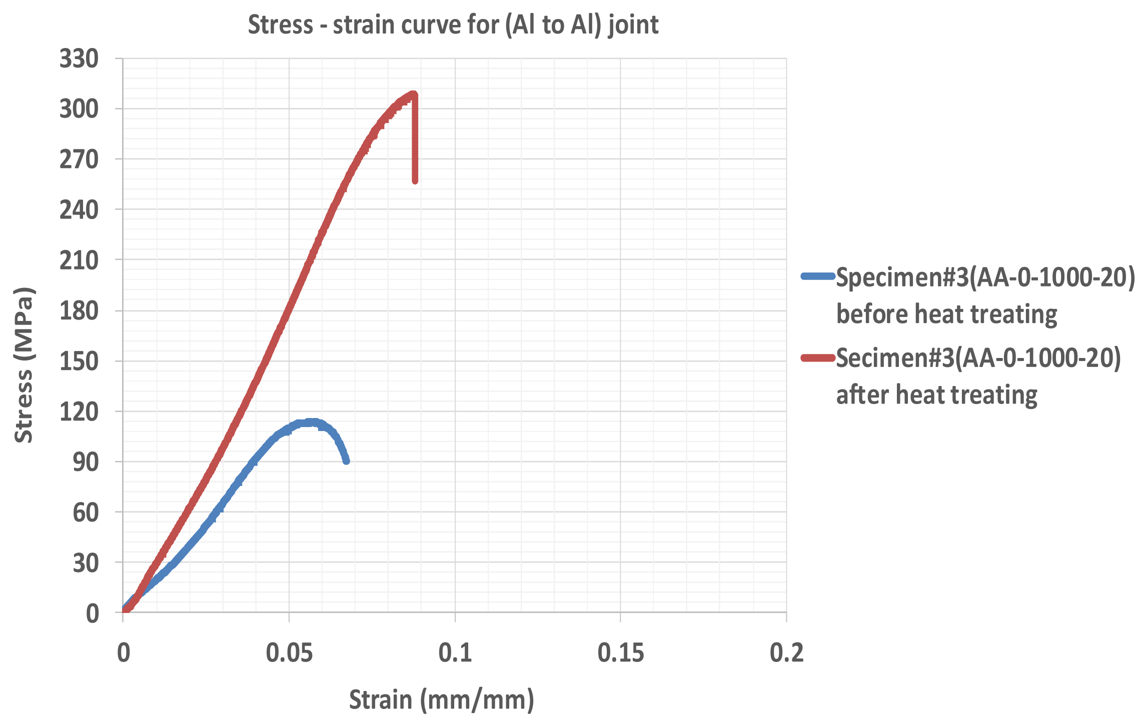
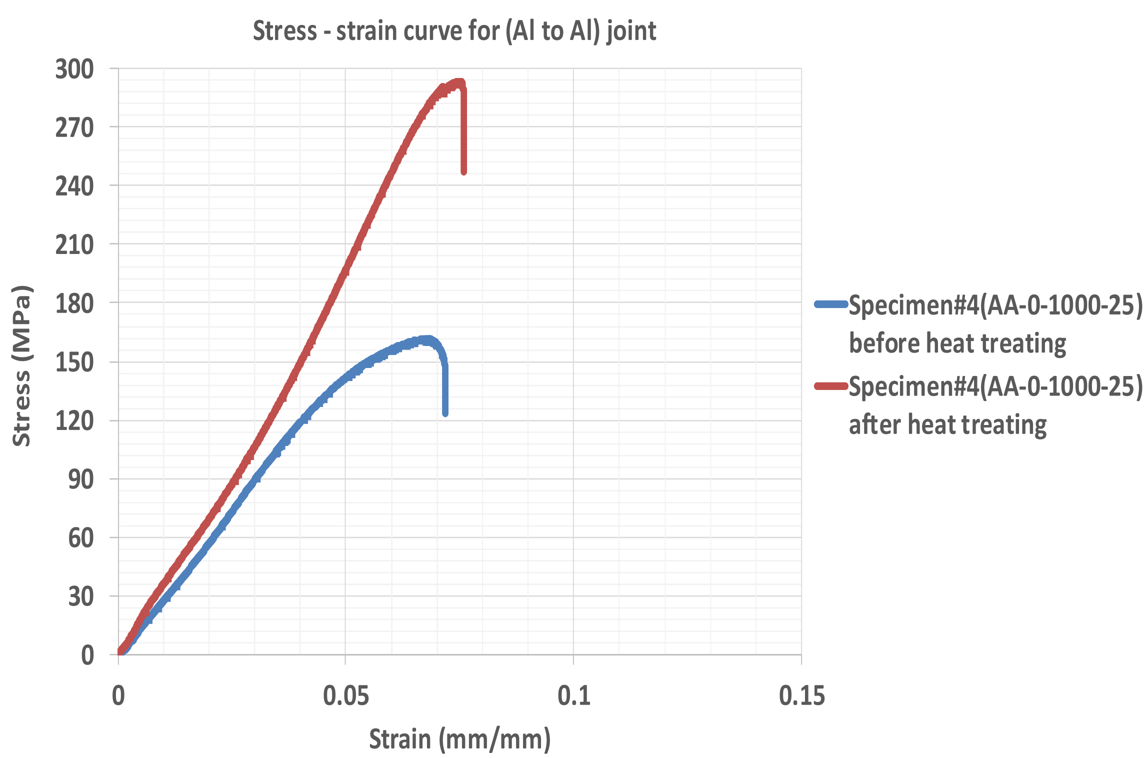




Tension Test Comparison for Al (6061-T6) Joints before and after Heat Treatment





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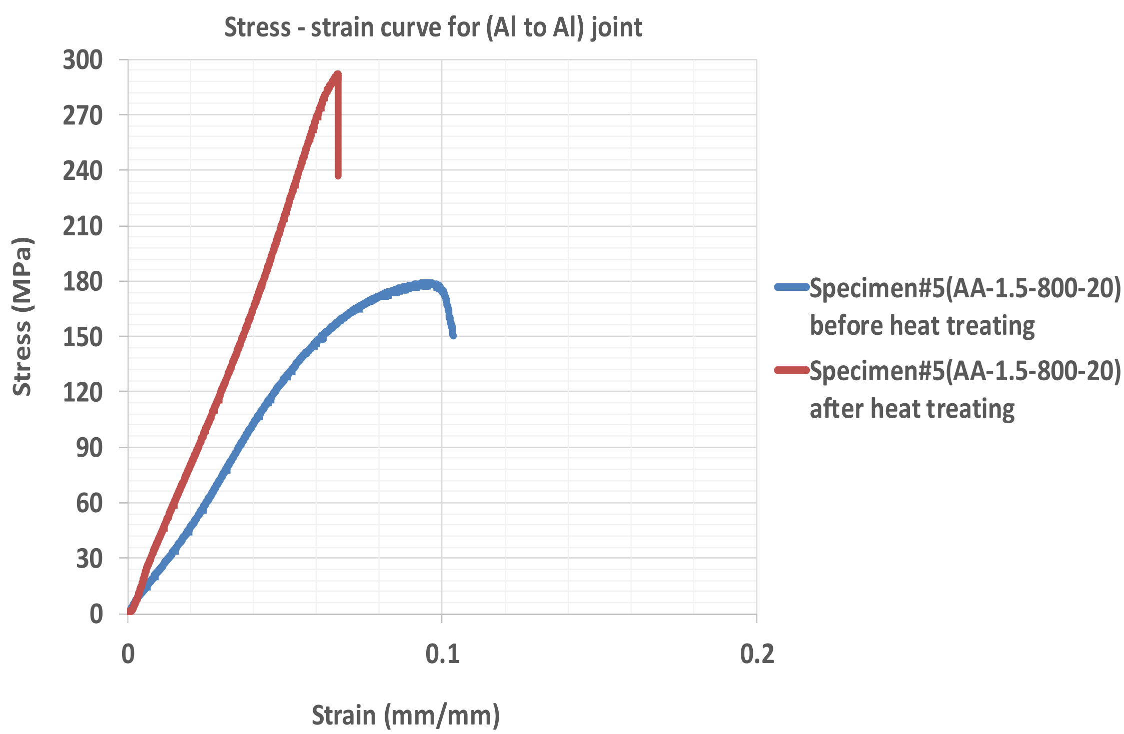
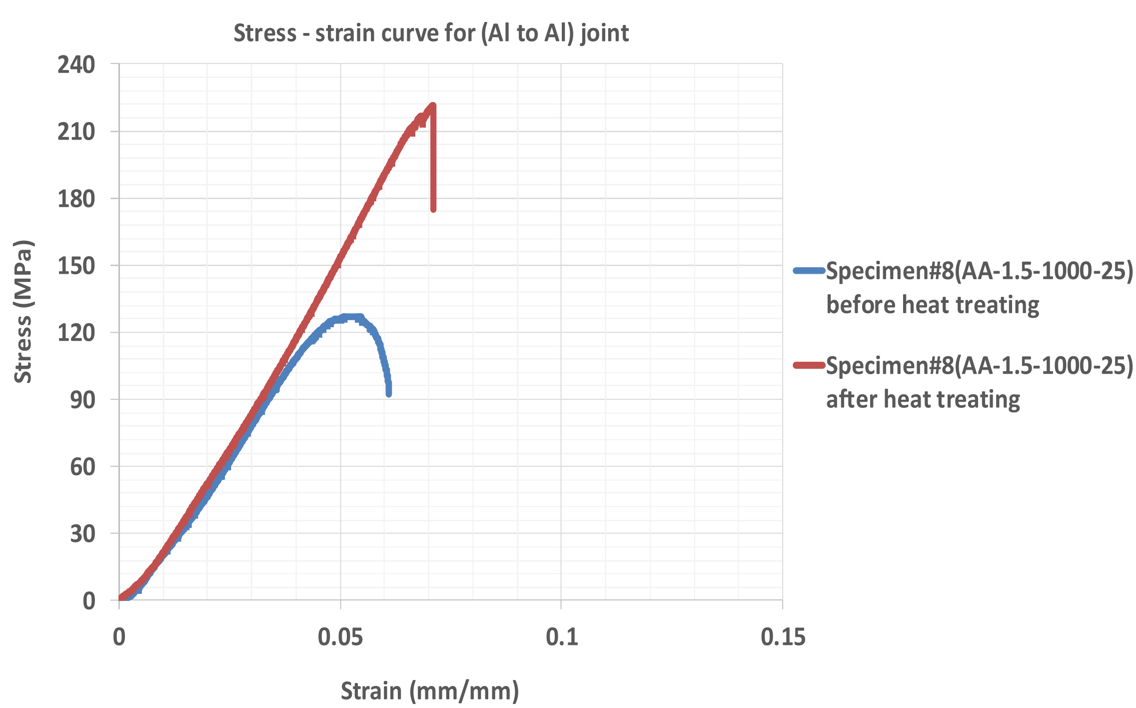
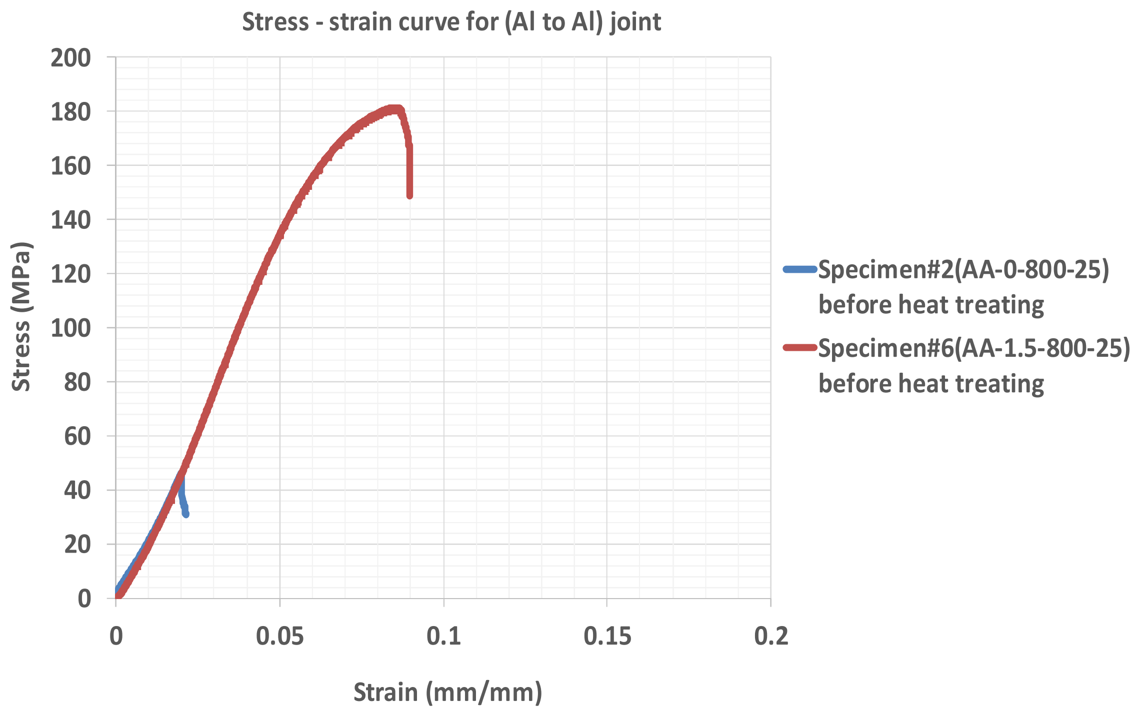
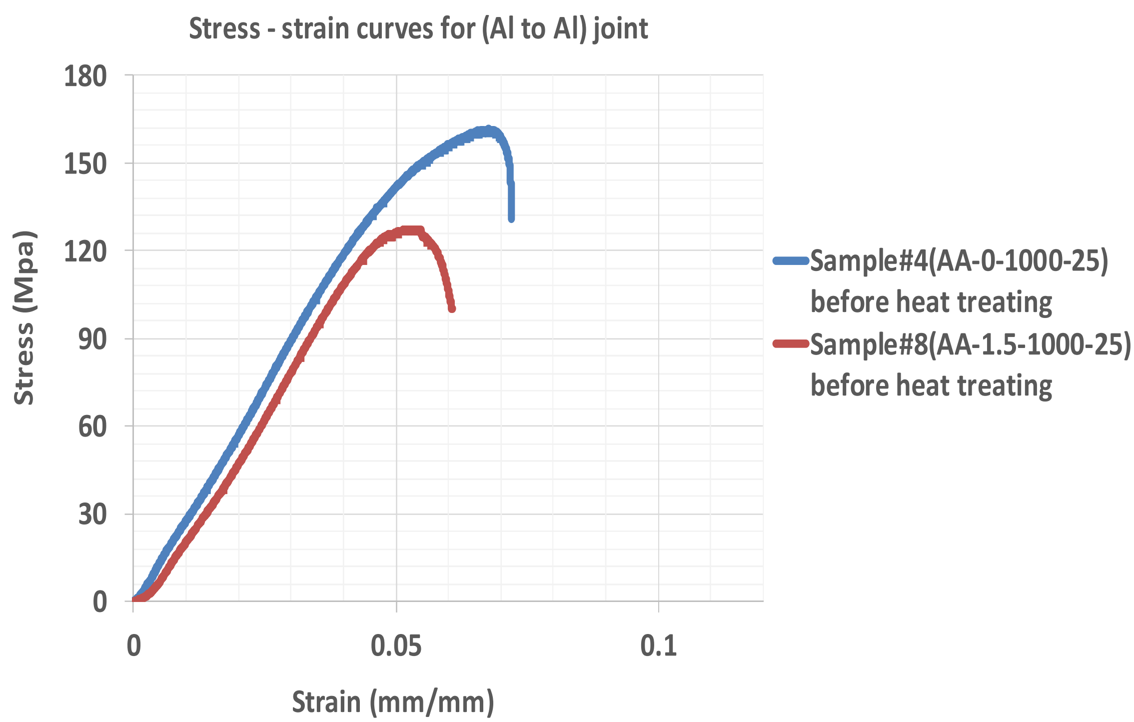




Effect of Varying Tilt Angle before Heat Treatment





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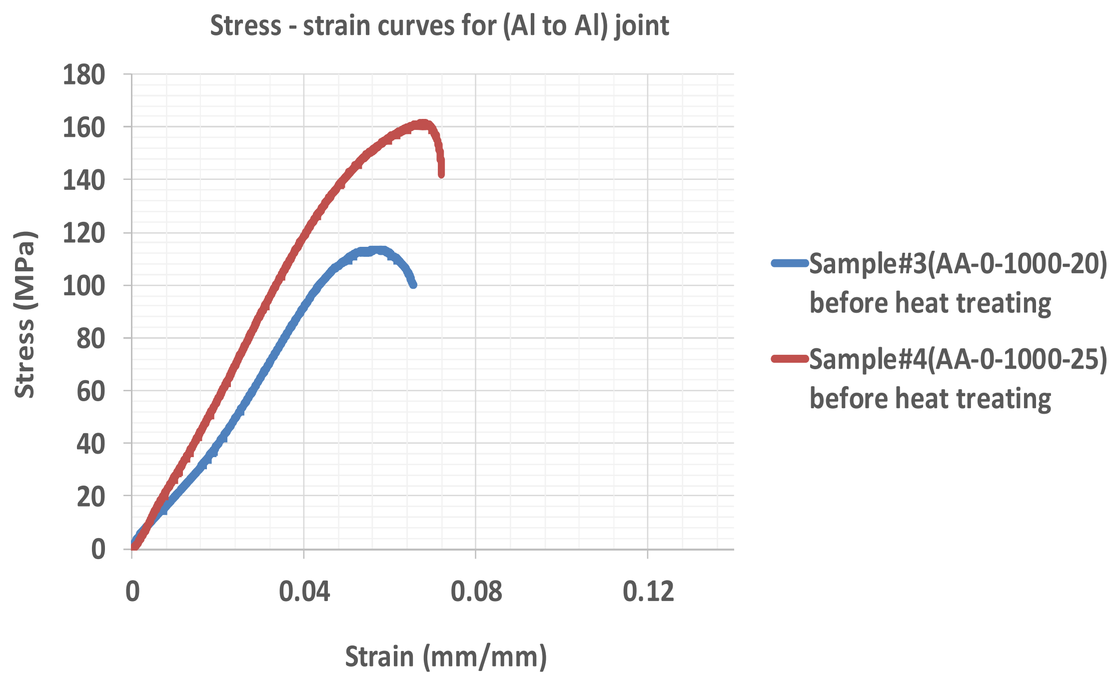

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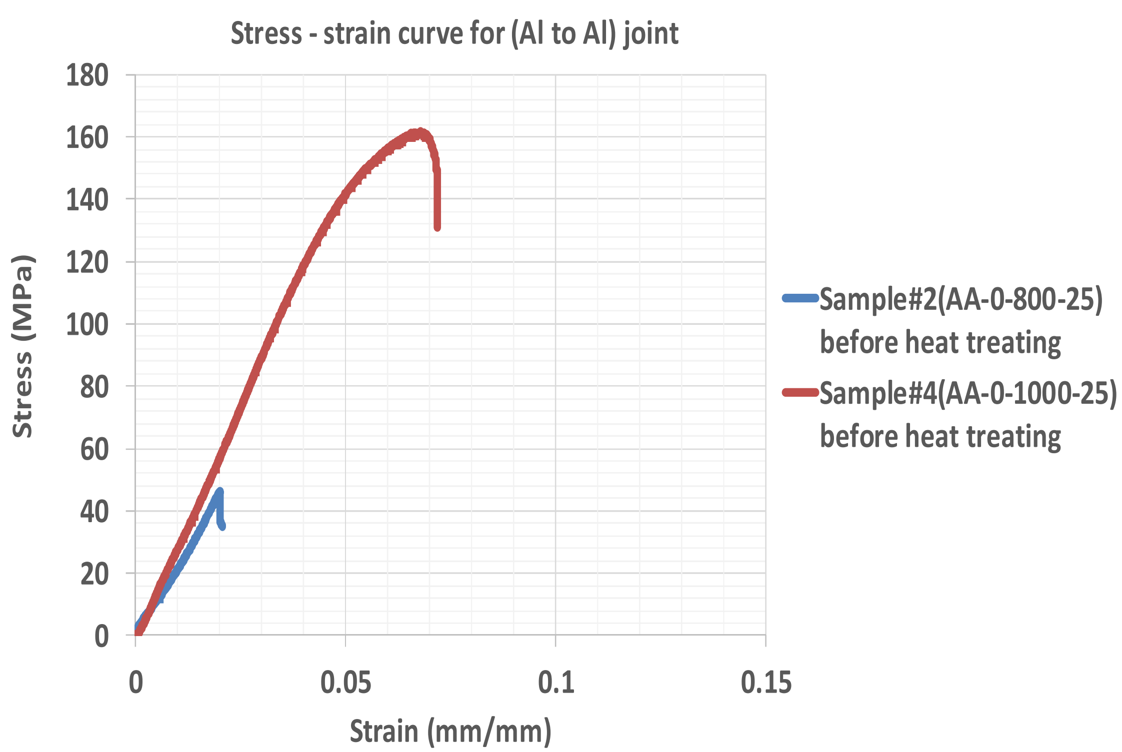

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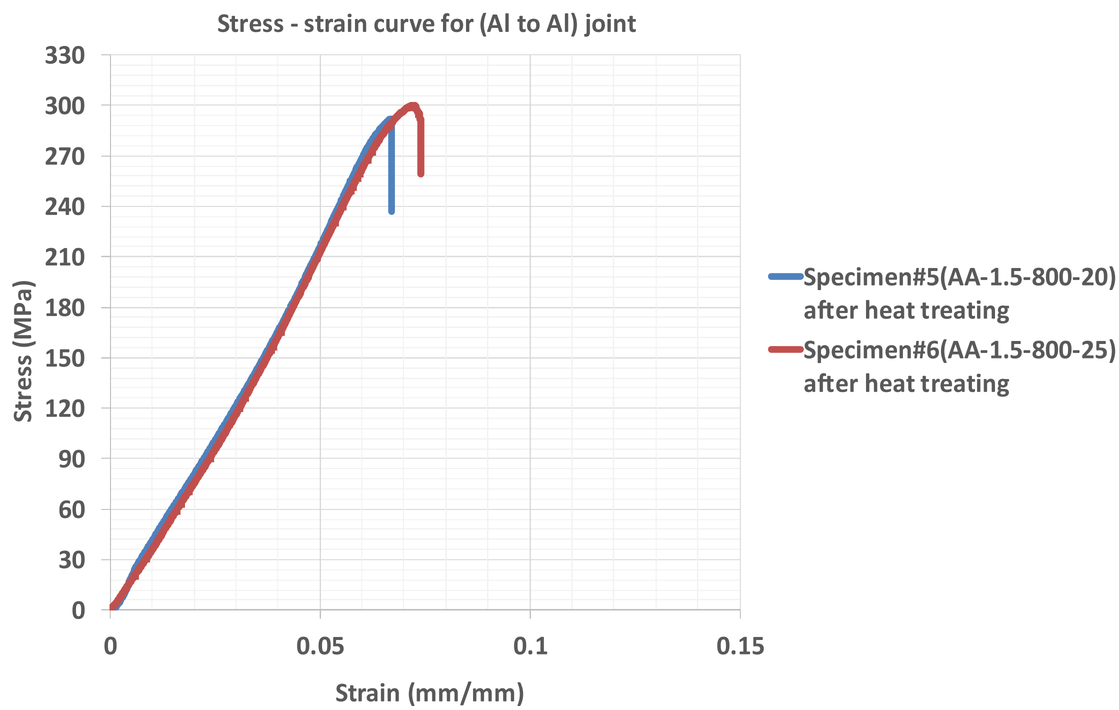

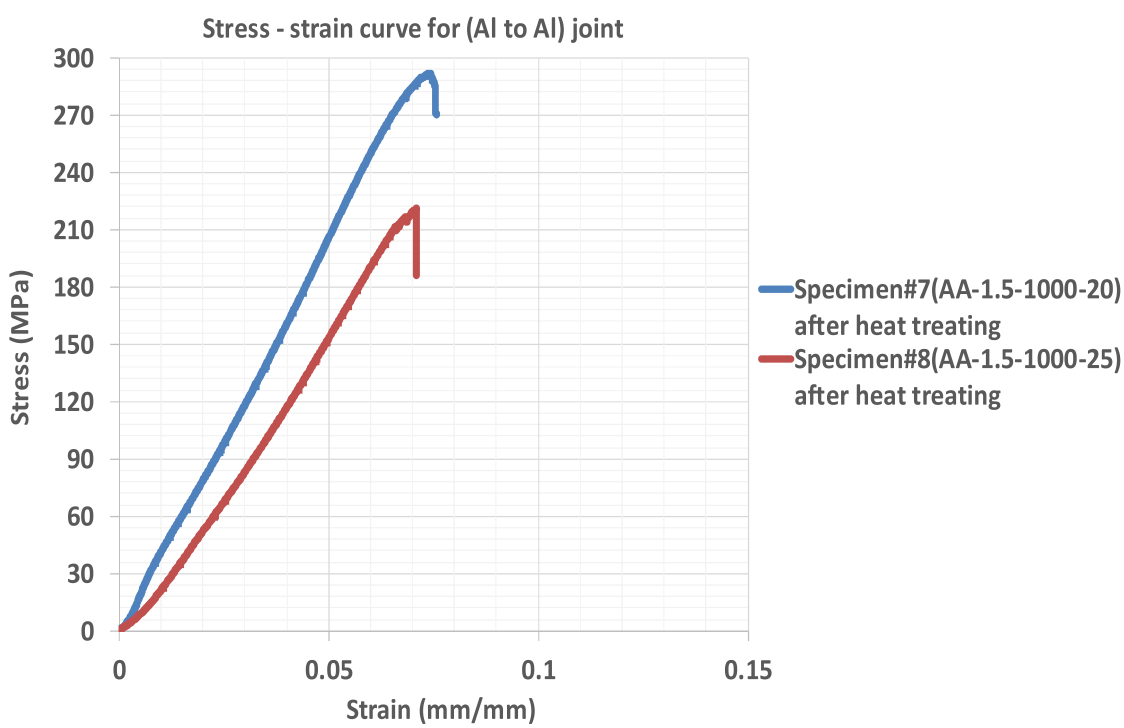

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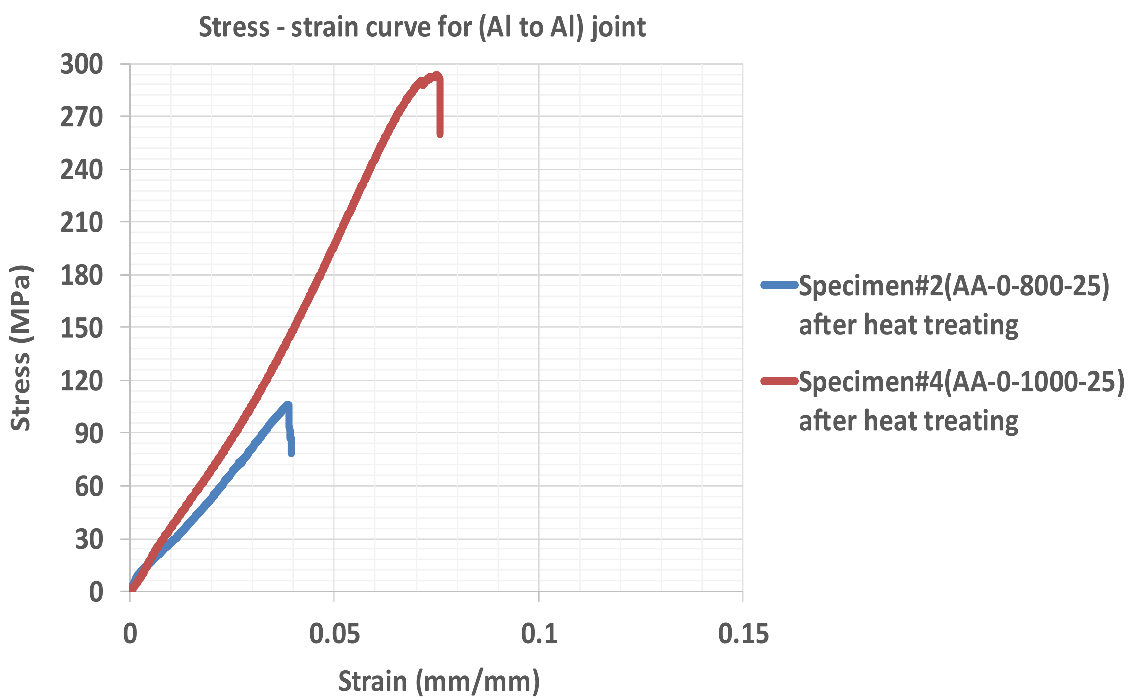
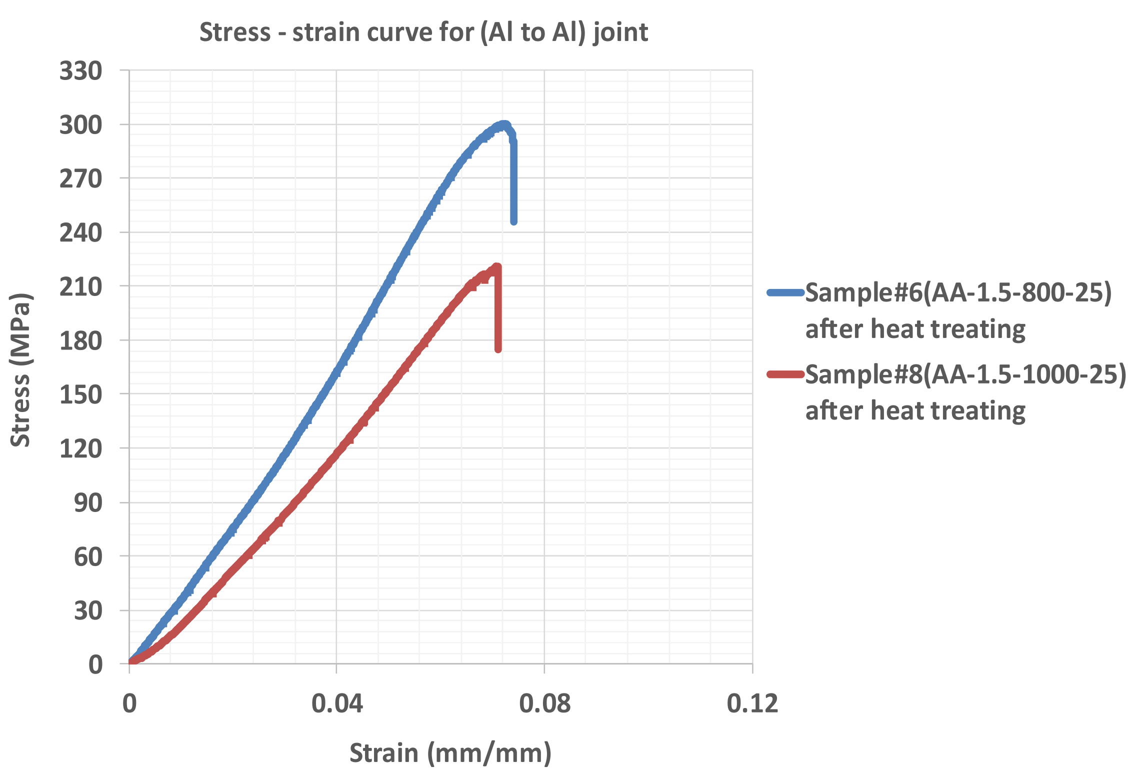
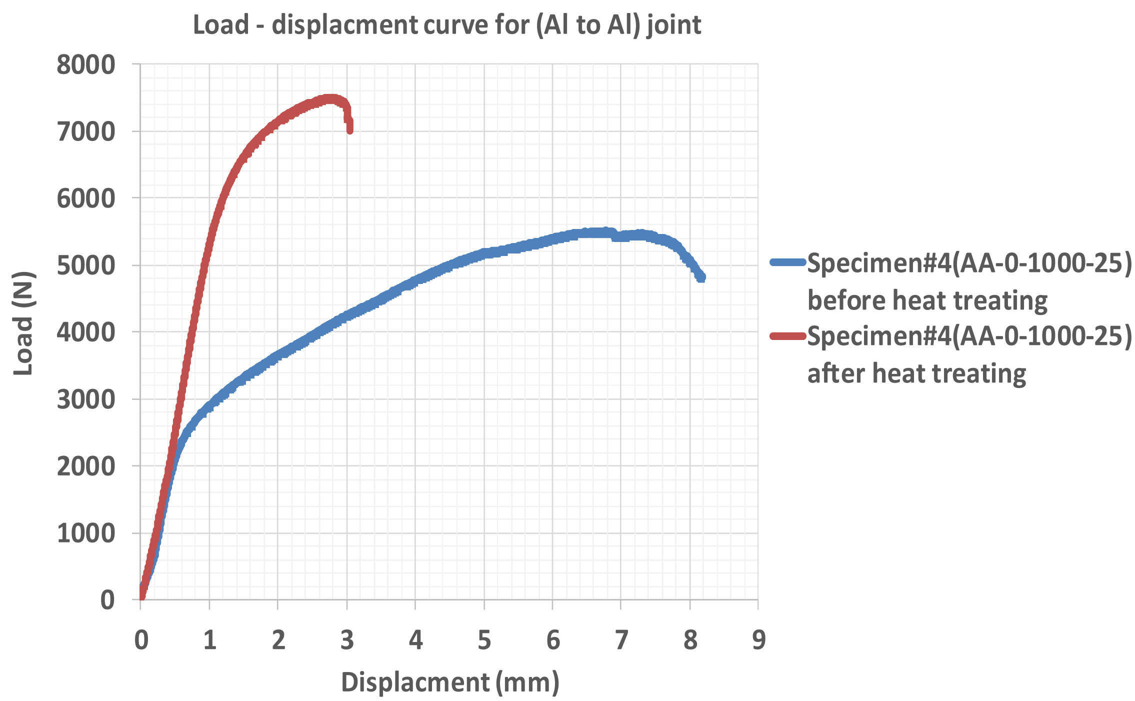
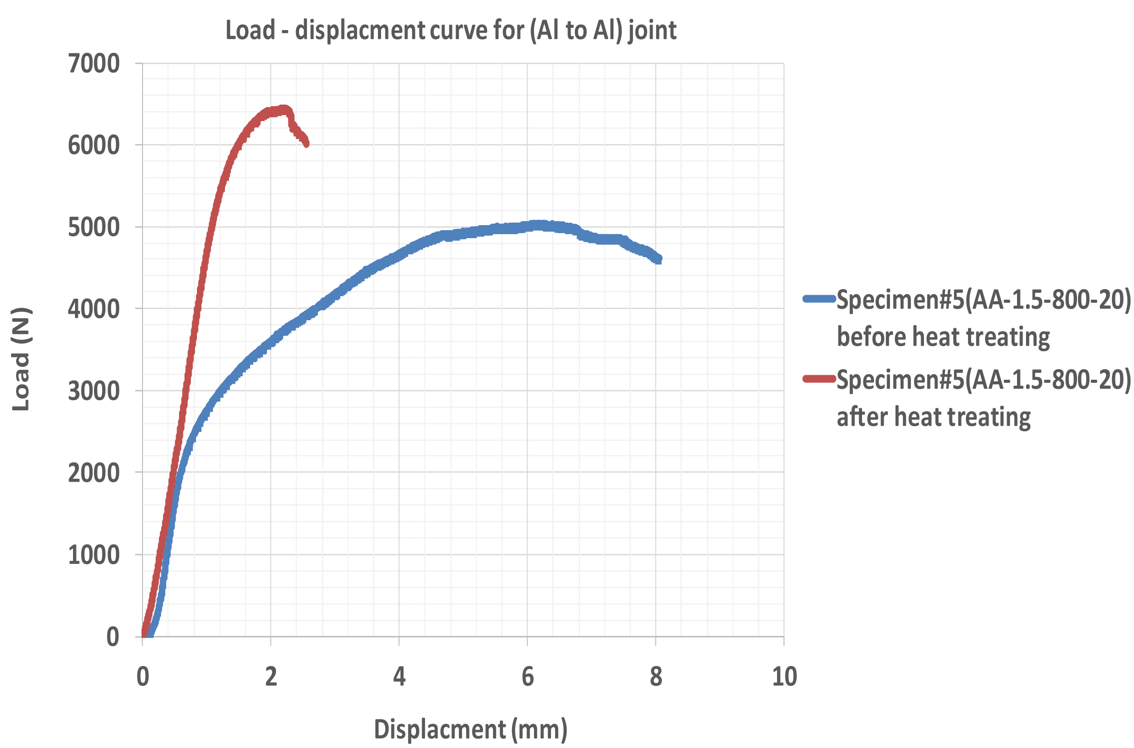




Bending Test Comparison before and after Heat Treatment





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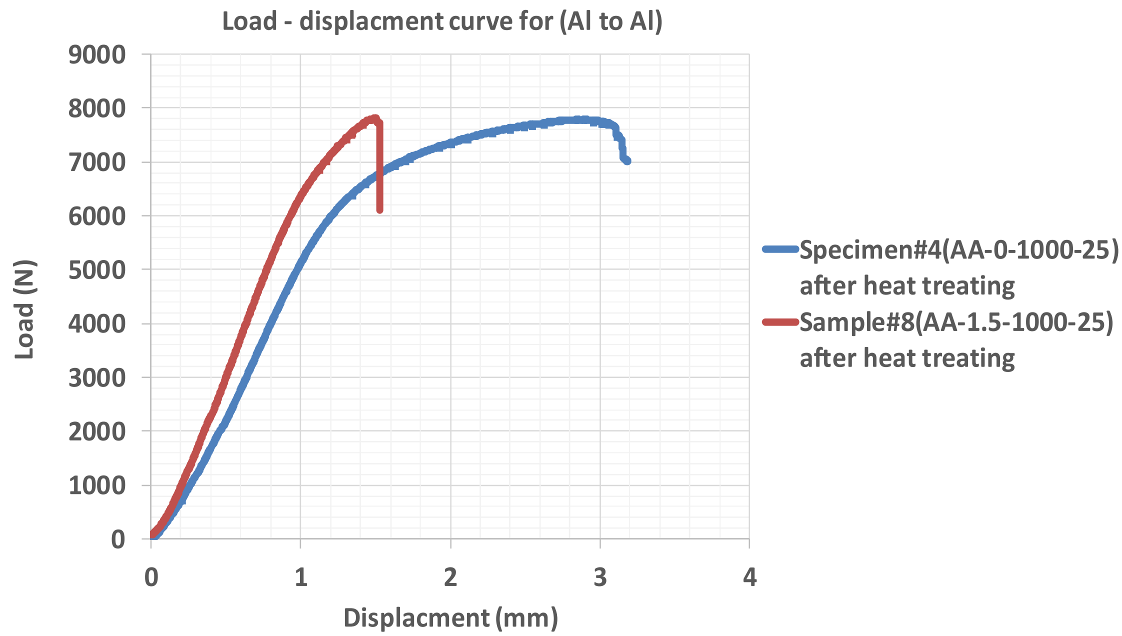

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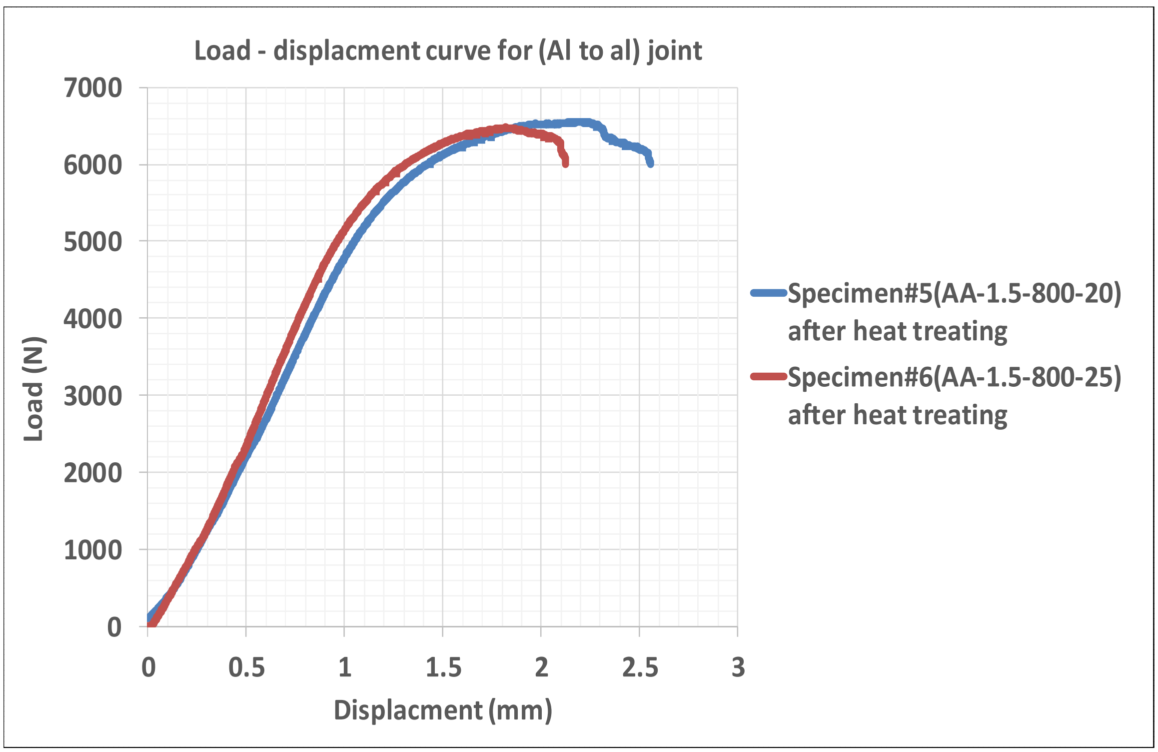
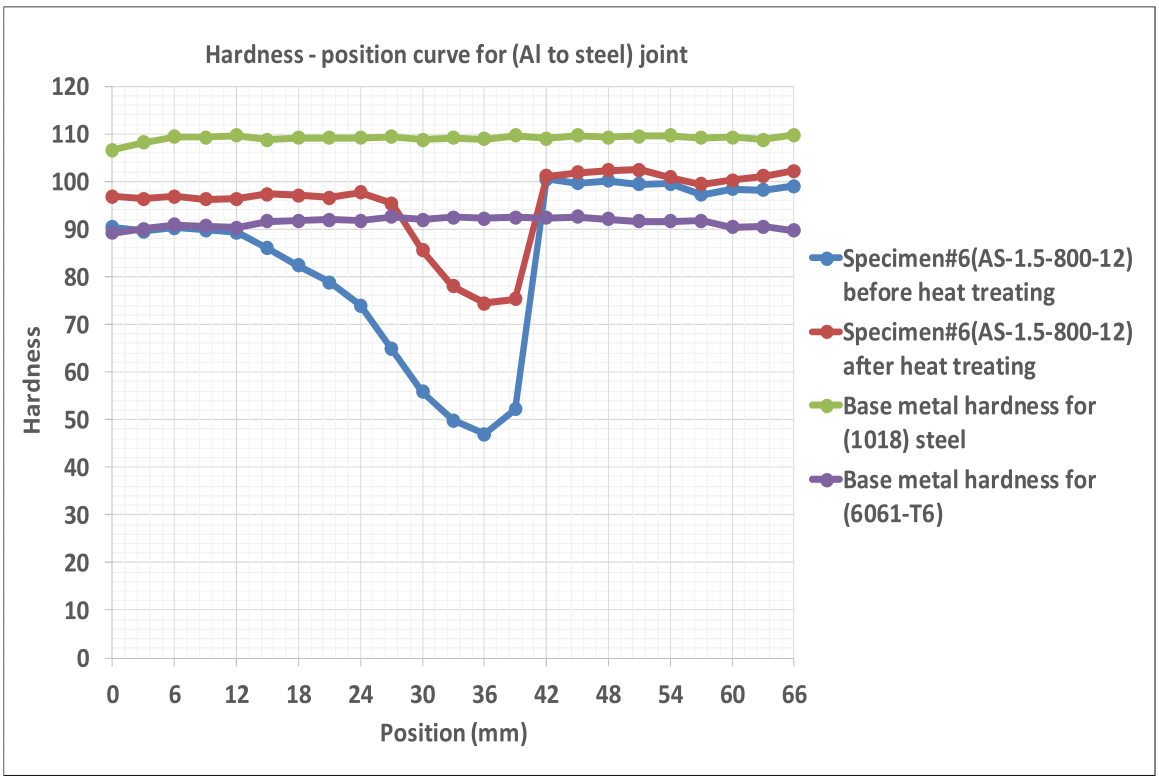


Hardness Test for aluminum to steel joints before and after Heat Treatment



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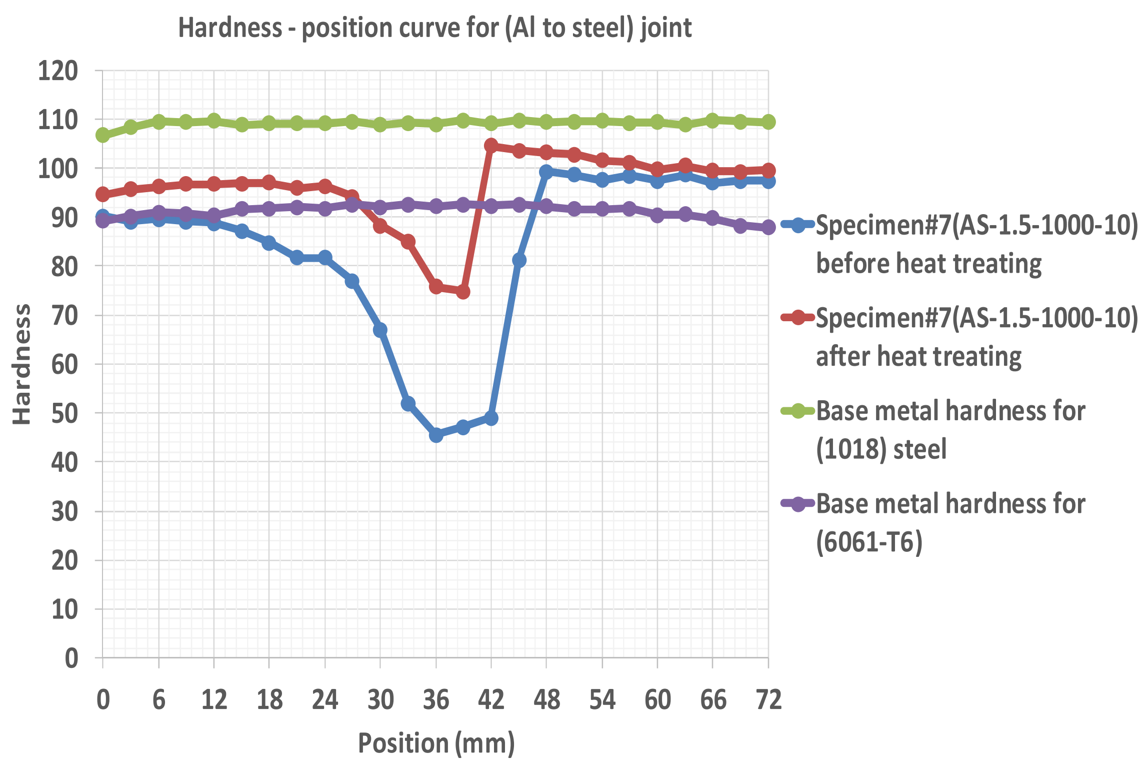

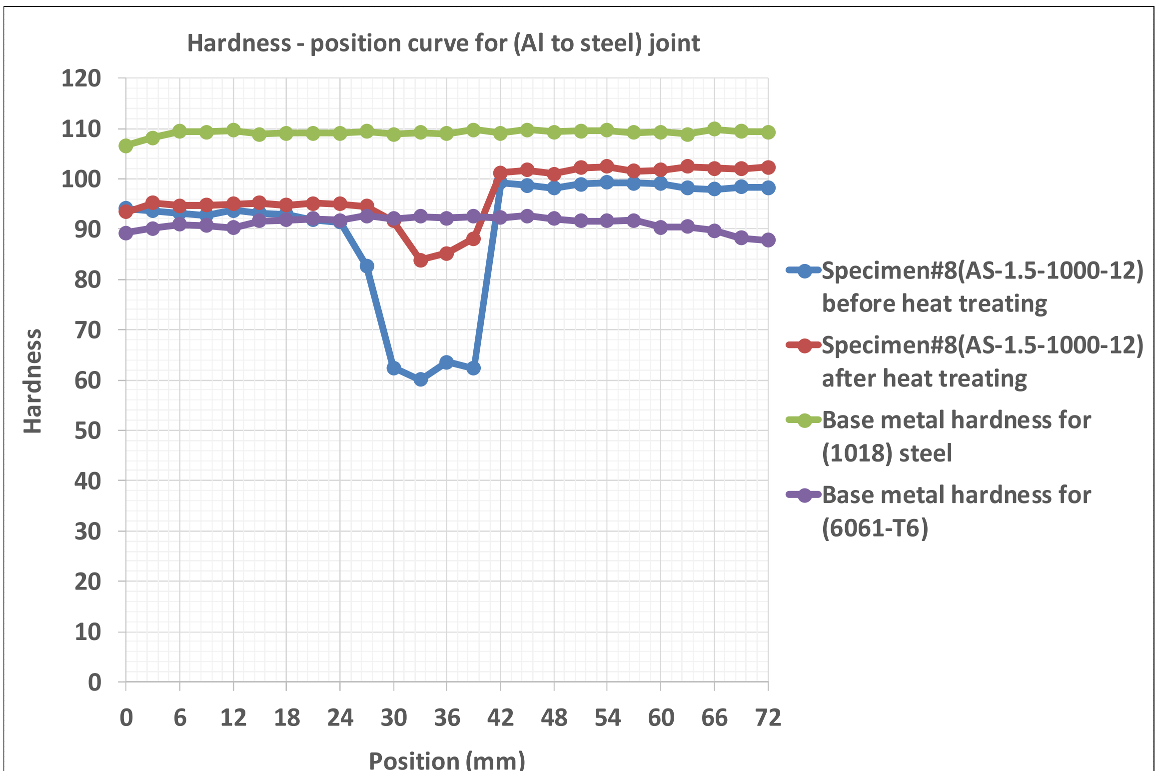

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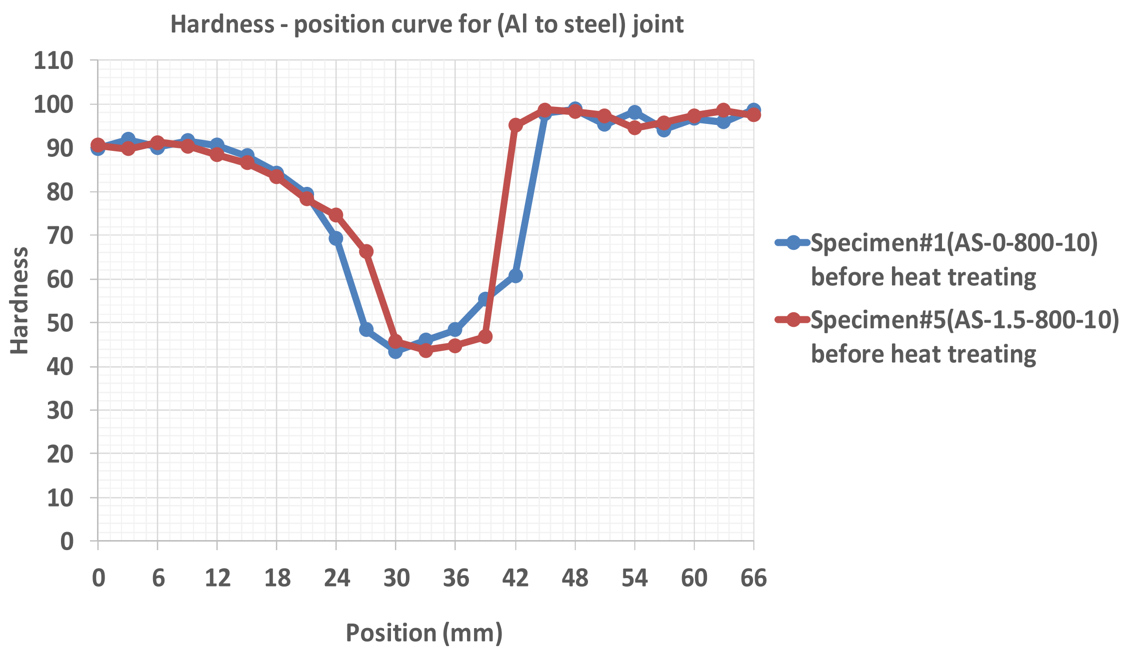

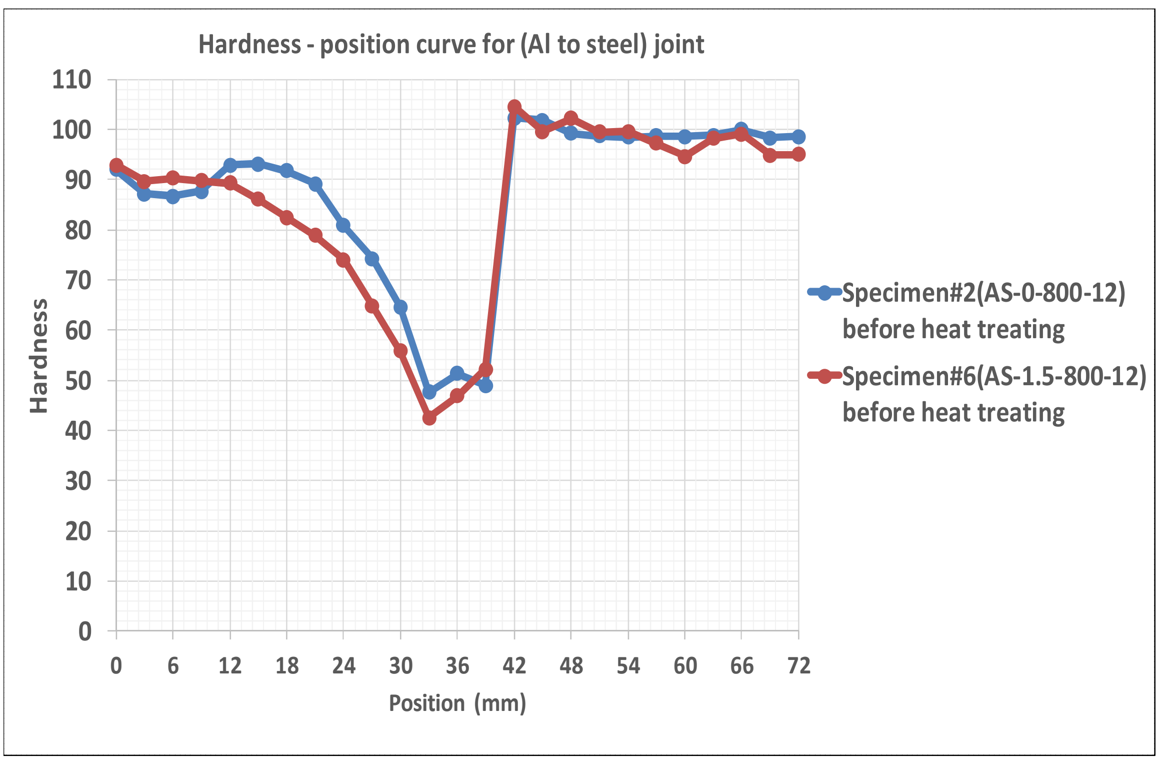

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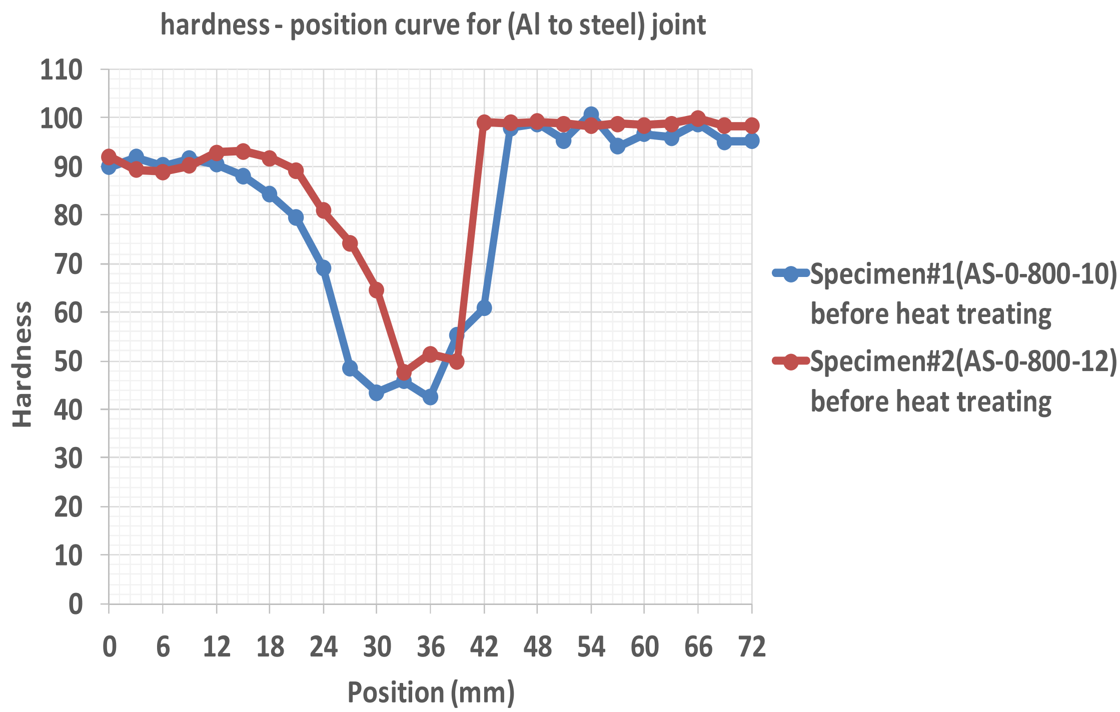

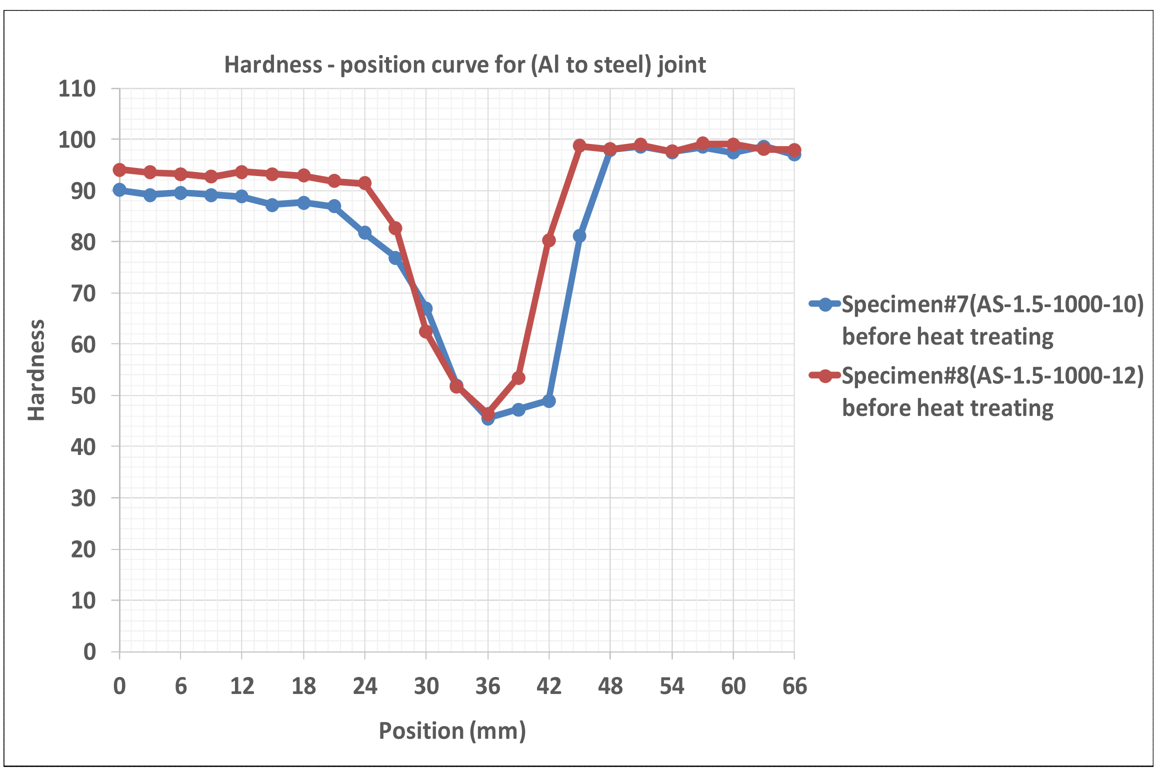

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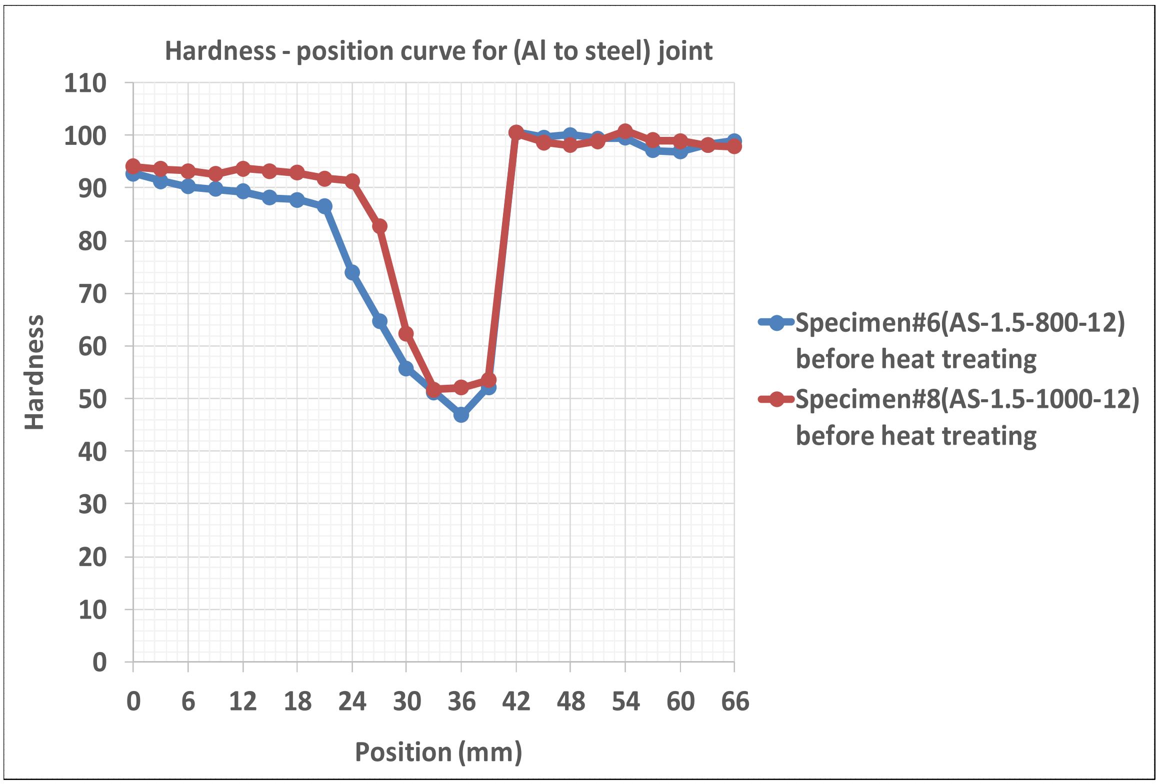
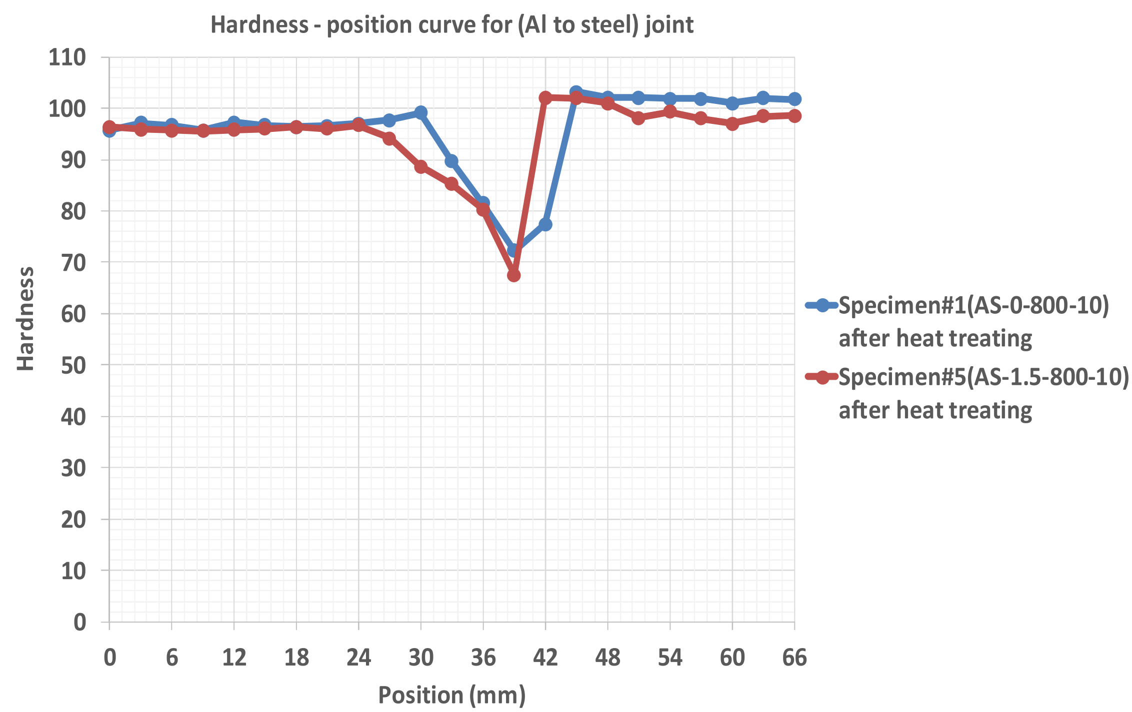
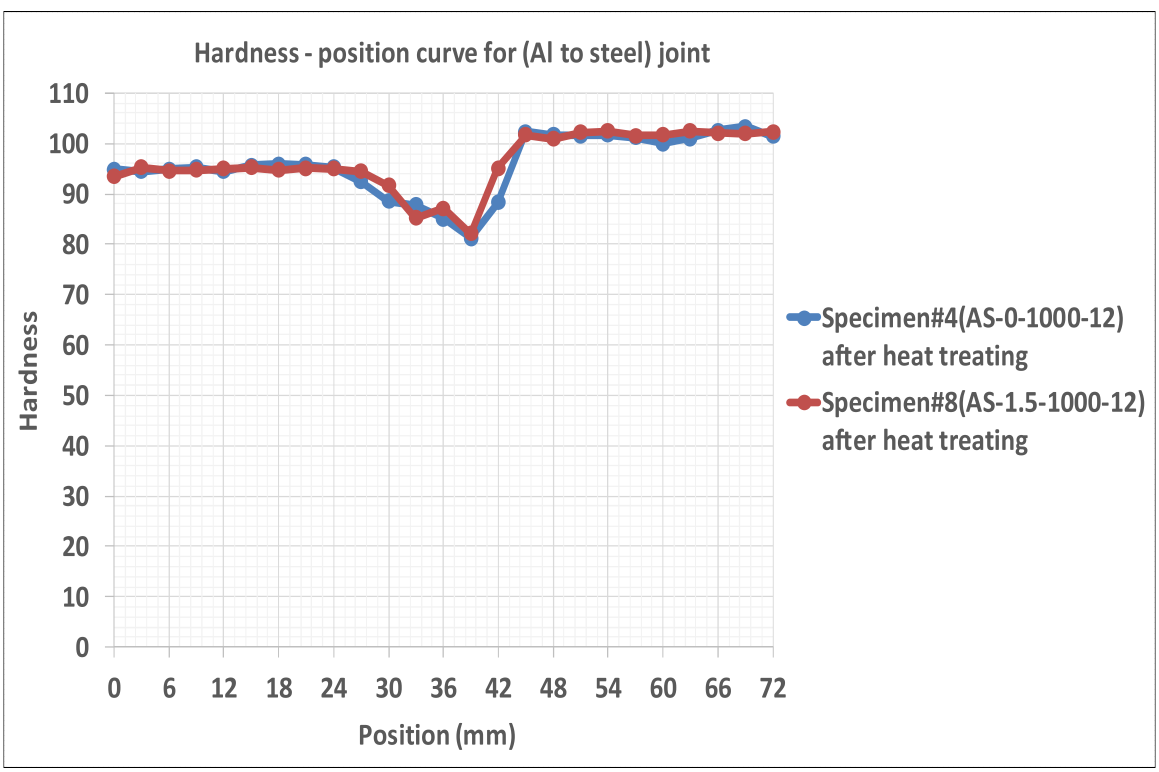
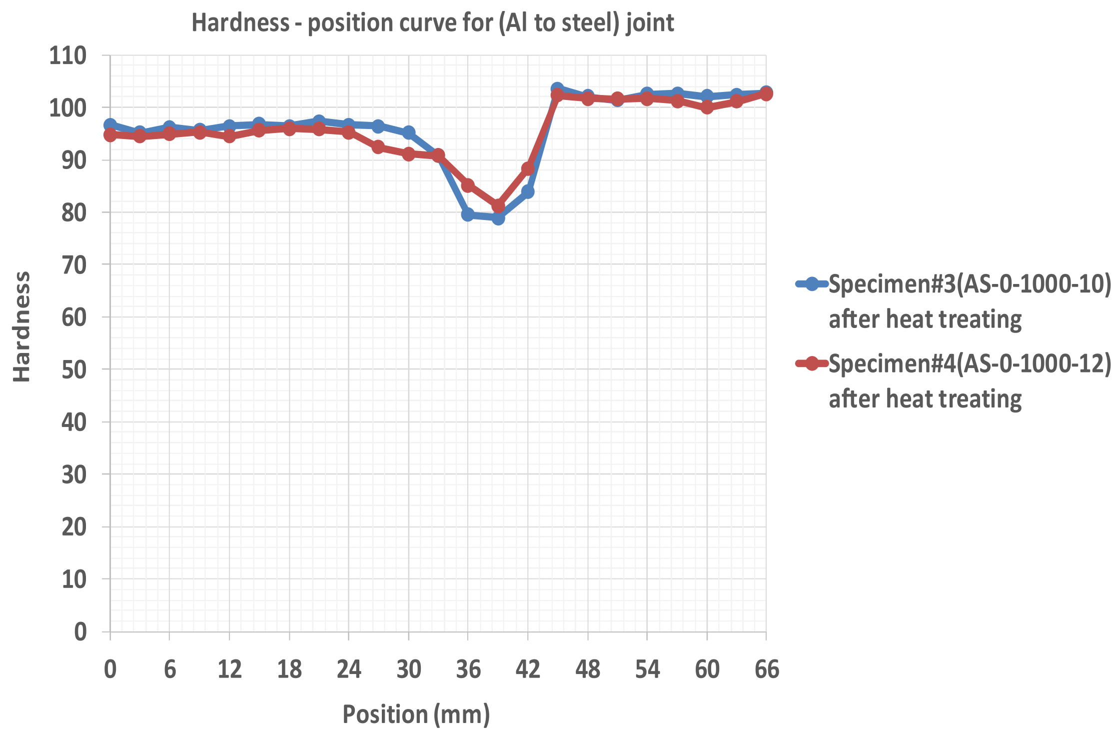


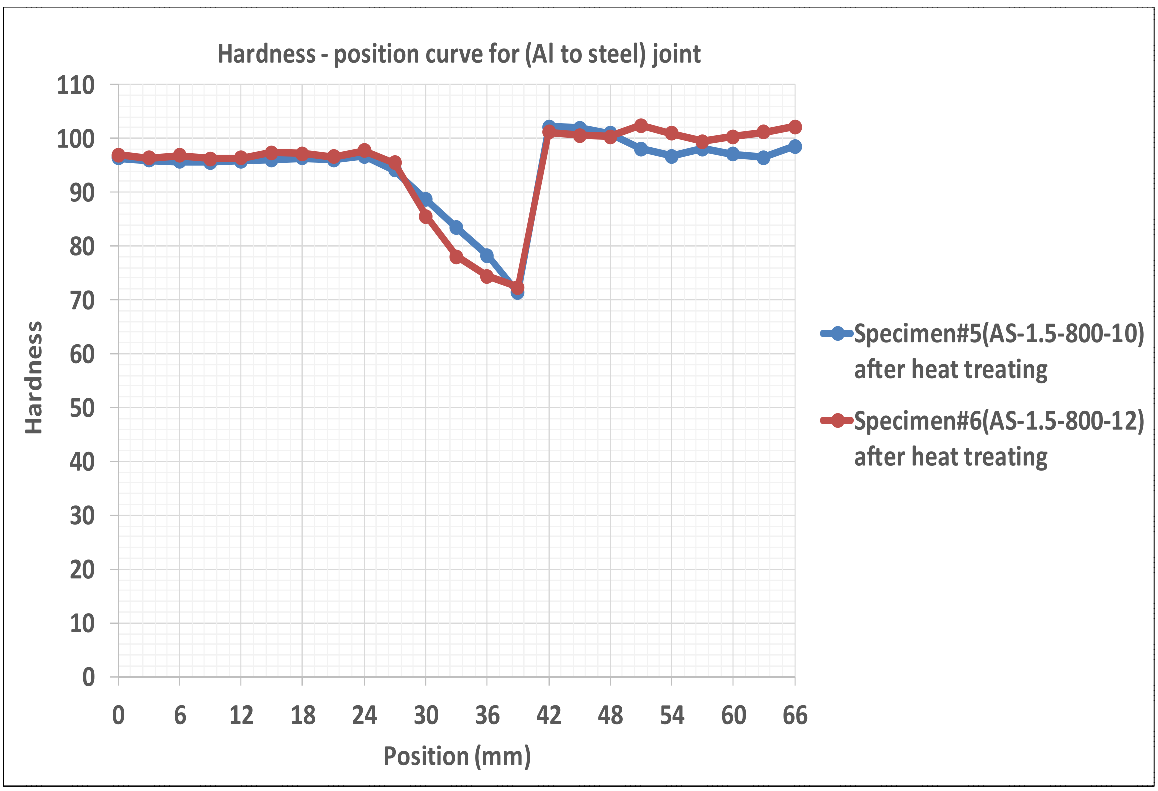
Effect of Varying Tilt Angle after Heat Treatment



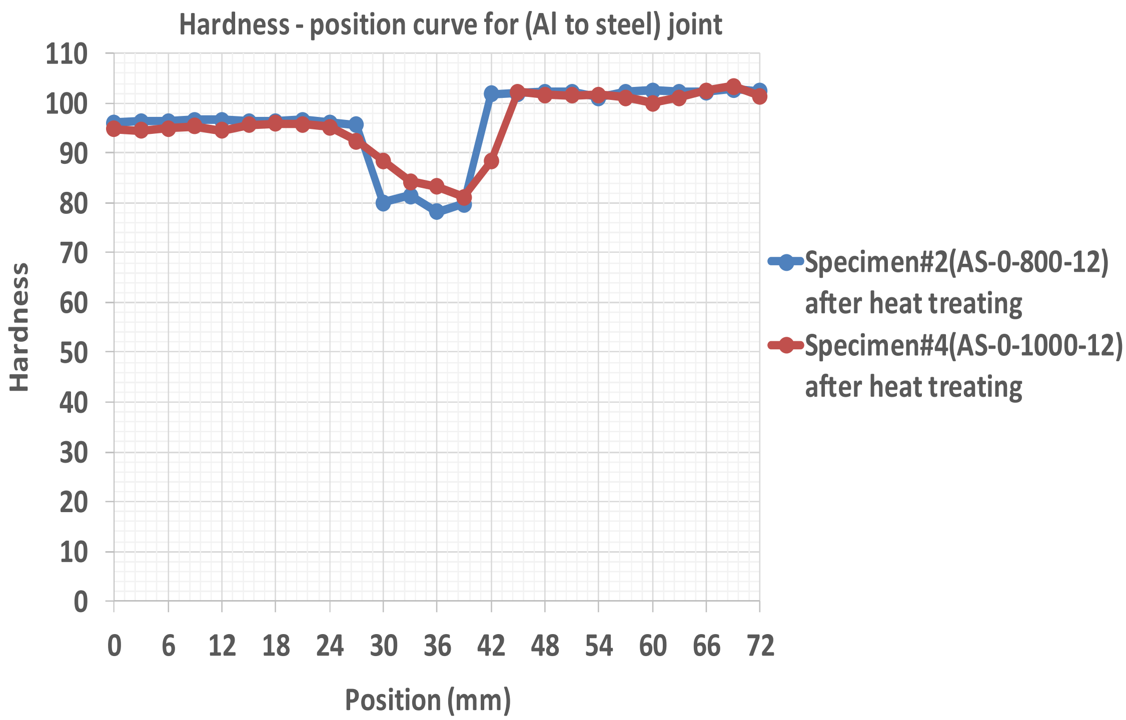


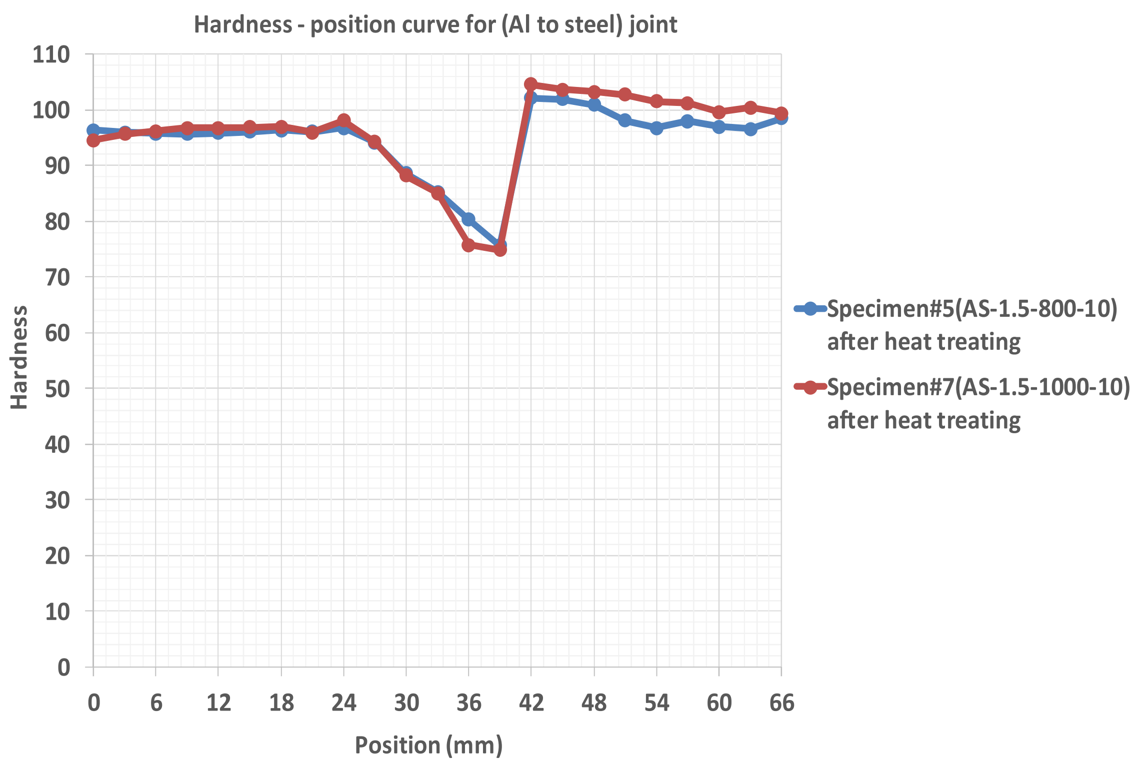
Effect of Varying Travel Speed after Heat Treatment



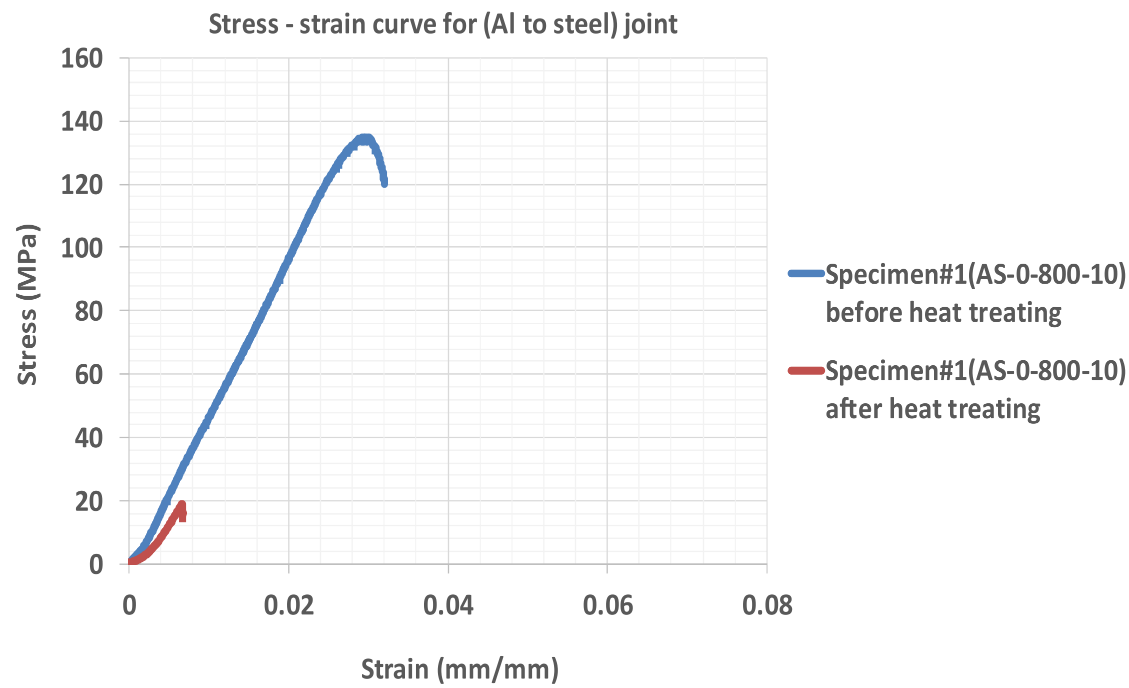


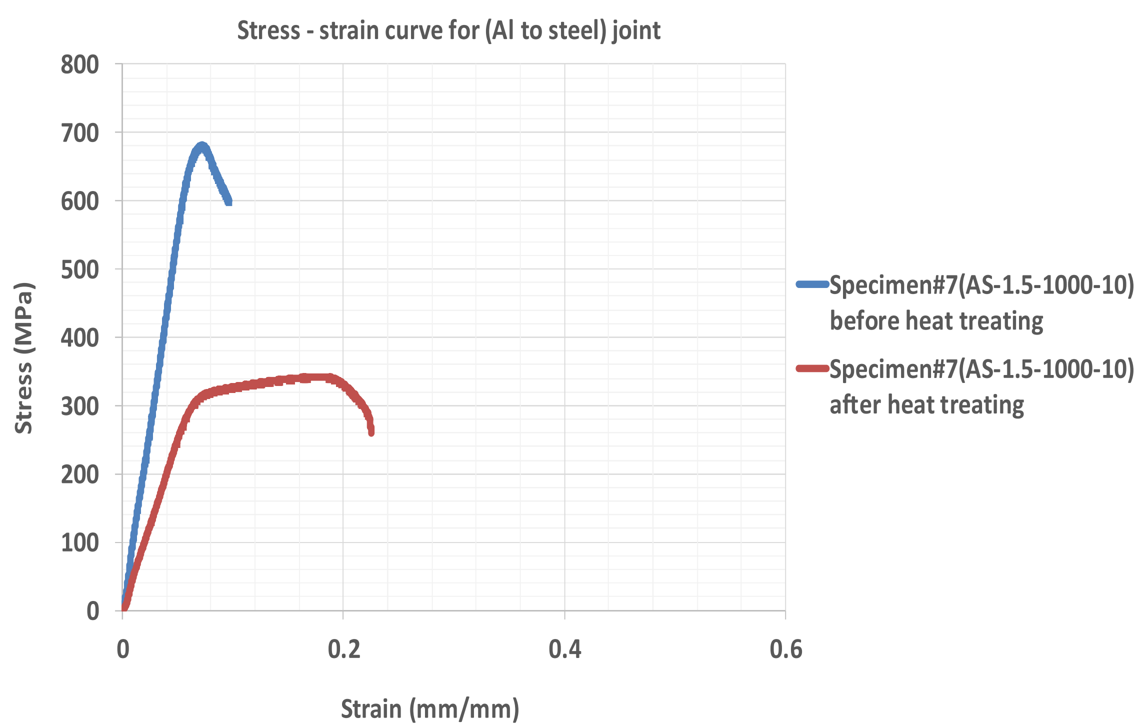
Effect of Varying Rotation Speed after Heat Treatment



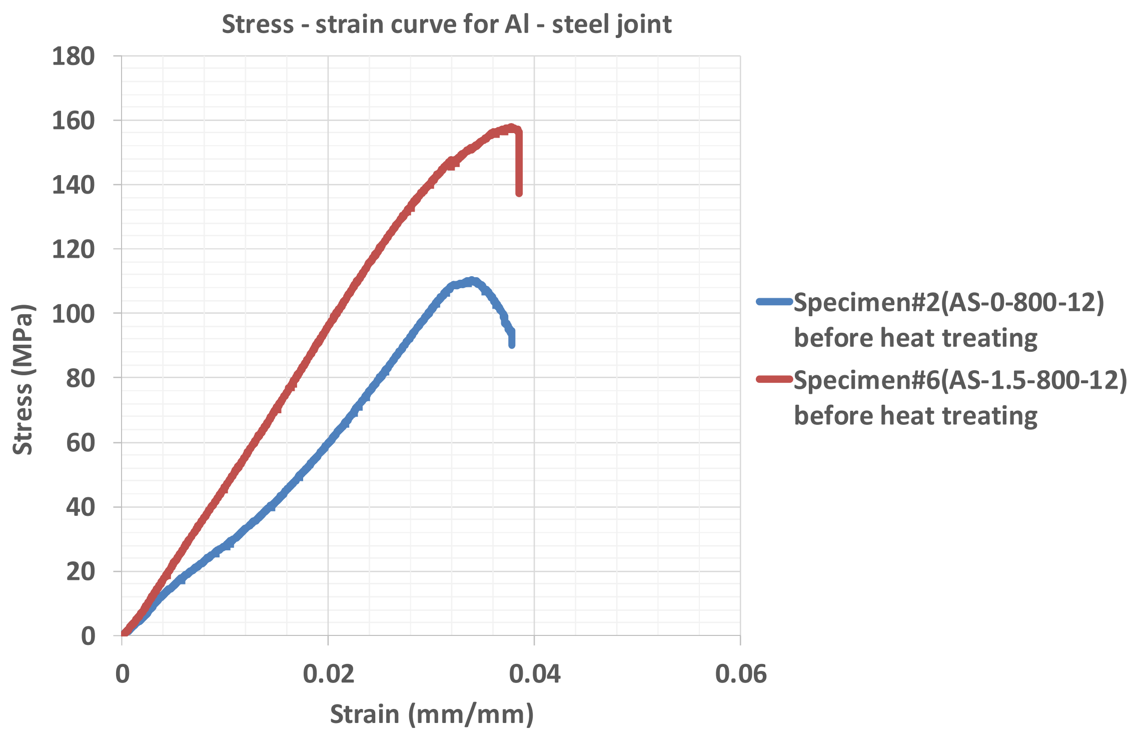


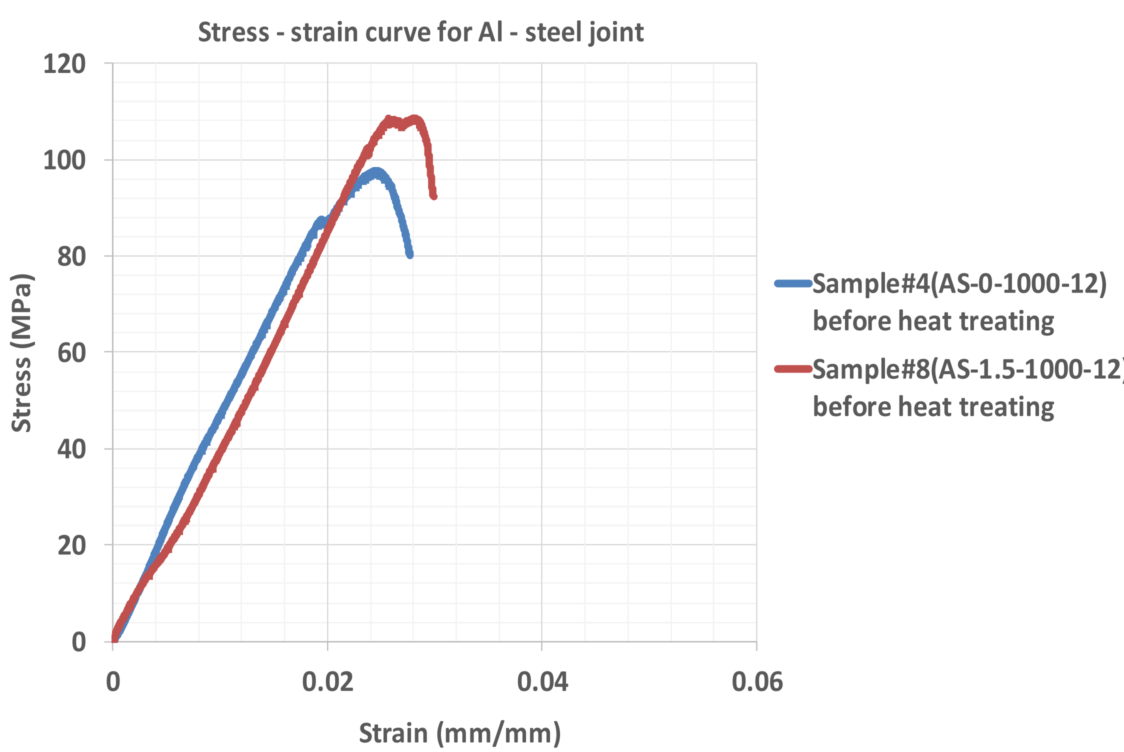
Tension Test Comparison before and after Heat Treatment



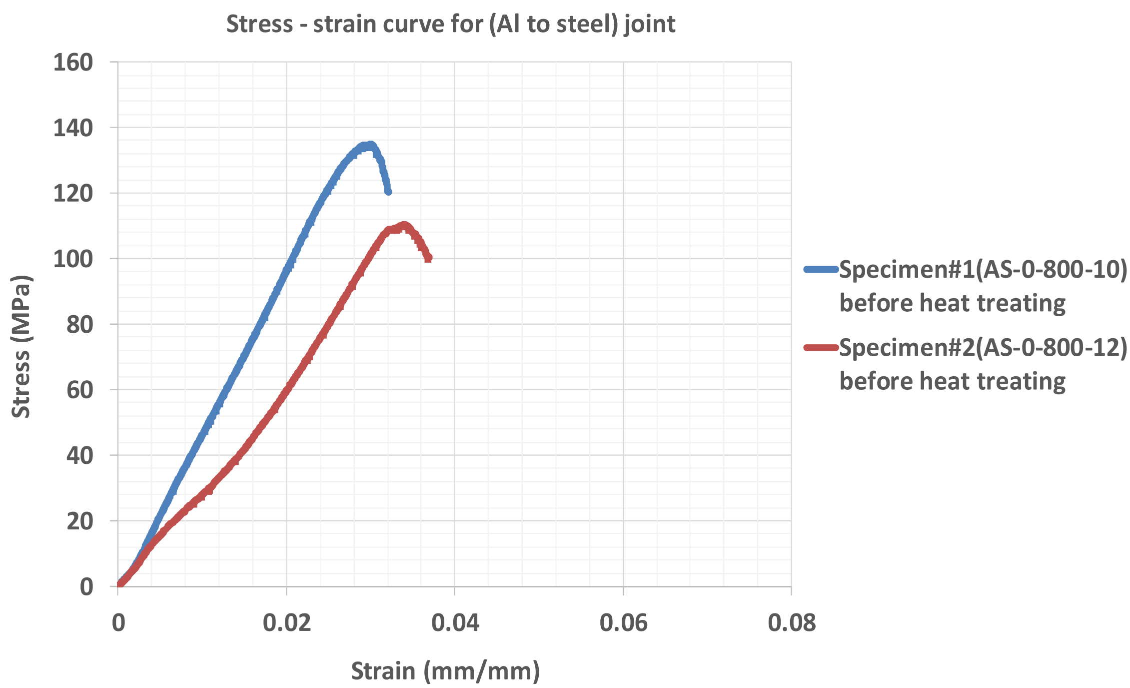


Effect of Varying Tilt Angle before Heat Treatment

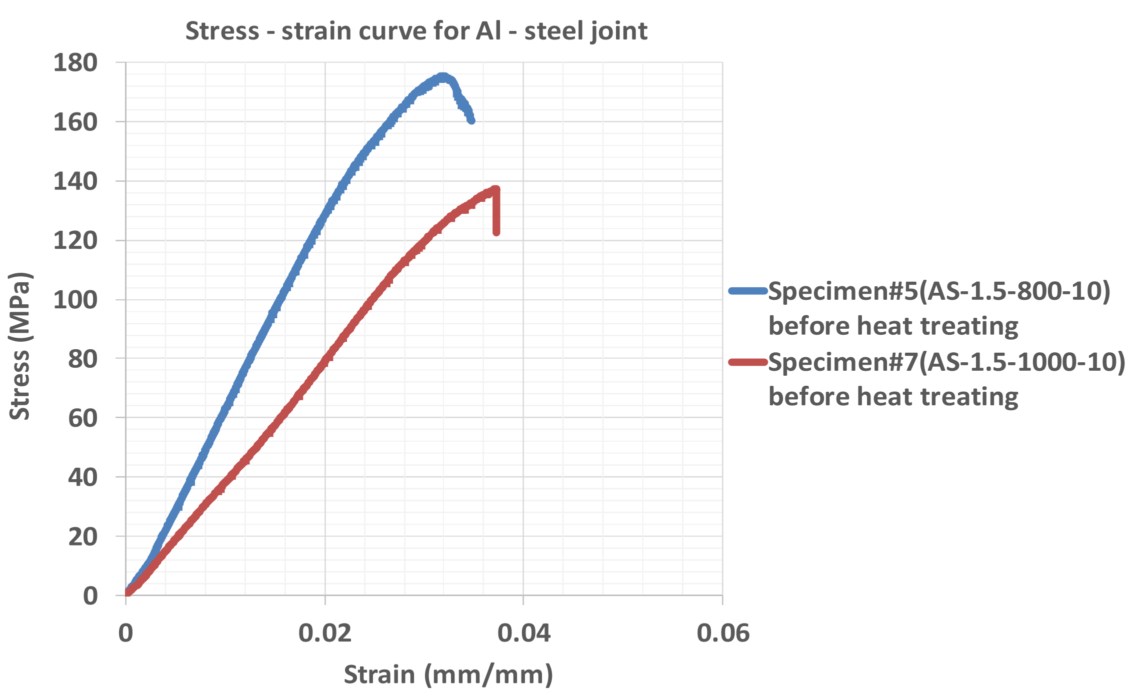




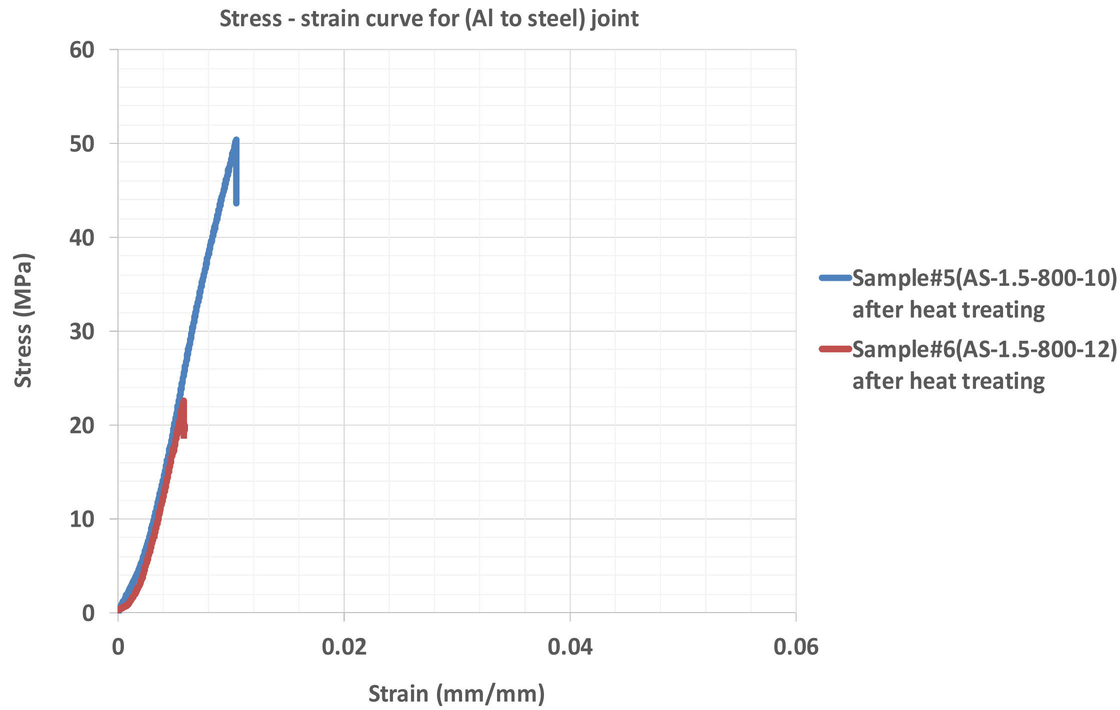
Effect of Varying Travel Speed before Heat Treatment



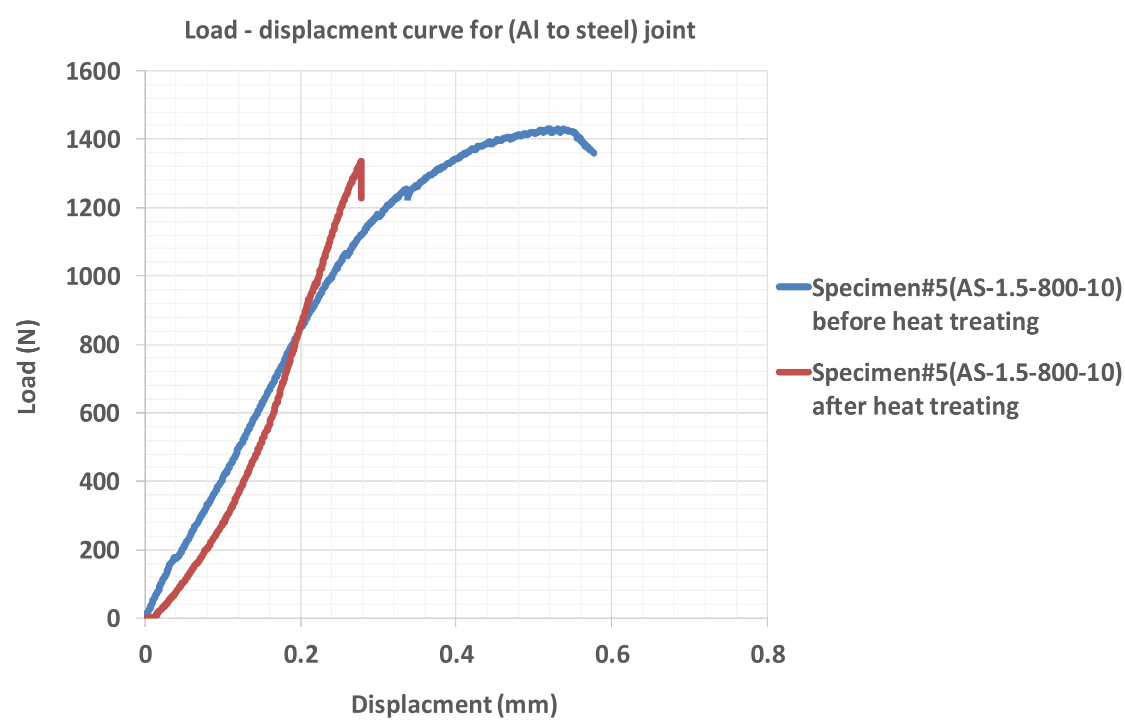
Effect of Varying Rotation Speed before Heat Treatment



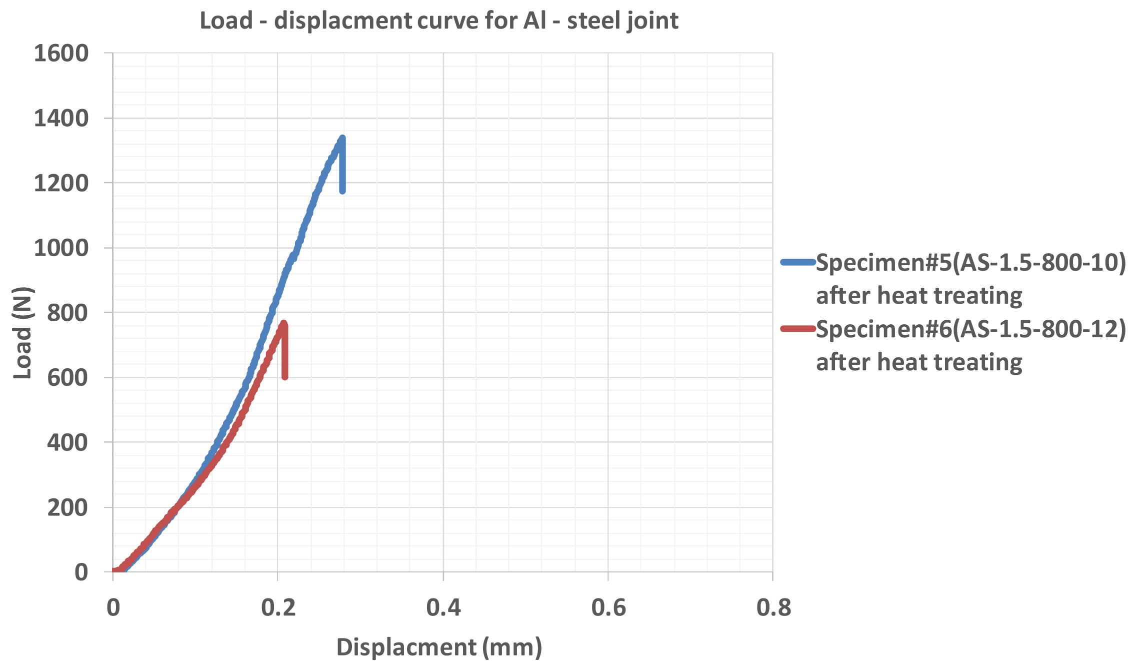
Effect of Varying Travel Speed after Heat Treatment



Bending Comparison before and after Heat Treatment



Effect of Varying Travel Speed after Heat Treatment



Effect of Varying Rotation Speed after Heat Treatment