Effect of Rotational Speed, Dwell Time and Plunge Depth on Properties of Microstructure of Dissimilar Aluminum Sheet Metal by FSSW

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ABSTRACT

FSSW process was developed by MAZDA Motor Corp and Kawasaki Heavy Industries to assemble the aluminum hood and rear doors of the RX-8 sport car. Since then FSSW has been used by Toyota Motor, General Motors, Ford Motor and many more etc. This technology getting interest from manufacturer of airplanes, appliances, and trains. The main goal of this study is to investigate the effect of process parameters on shear strength of FSSW joint and as well as analyze the mechanical and microstructure properties of the joint. In this present study the focus is on dissimilar alloys AA5754 and AA7075-T651 aluminum alloys. TRS, DT and PD imply an important role on heat production and material flow in FSSW, therefore it affect the development of microstructure and mechanical characteristics of the welded joint. Optical microscope, and scanning electron microscope (SEM) were conducted to characterize microstructure in welded joints. TSS and micro hardness test were used to evaluate the mechanical properties of joints. Many researchers have applied machine learning approaches like ANN to FSW but few authors have applied ANN to FSSW. In this research ANN has been applied to develop the met model of FSSW of dissimilar Al-Alloys of AA5754 and AA7075-T651. The obtained results reveal that the TSS of FSSW joint significantly affected by TRS, DT and with the tool PD. At constant TRS the PD and DT has significant effect on TSS. While on the other hand at constant DT the increment in TRS and PD has decrease the TSS.

Keywords: Friction Stir Spot Welding, Full Factorial Design, Shear Tensile Strength, Micro hardness, Neural Network

ÖZ

FSSW süreci, MAZDA Motor Corp ve Kawasaki Heavy Industries tarafından, RX-8 spor arabanın alüminyum kaputunu ve arka kapılarını monte etmek için geliştirilmiştir. O zamandan beri FSSW Toyota Motor, General Motors, Ford Motor ve daha pek çok tanınmış markalar tarafından kullanılıyor. Bu teknoloji uçak, cihaz ve tren üreticilerinin ilgisini çekmektedir. Bu çalışmanın temel amacı, süreç gerektiren parametrelerinin FSSW derzinin kayma dayanımı üzerindeki etkisini araştırmak ve buna bağlı olarak eklemin mekanik ve mikroyapı özelliklerini analiz etmektir. Bu çalışmada odak noktası AA5754 ve AA7075-T651 farklı alüminyum alaşımlarının alaşımlarıdır. TRS, DT ve PD, FSSW'de ısı üretimi ve malzeme akışı üzerinde önemli bir rol oynamaktadır, bu nedenle kaynaklı ek yerinin mikroyapı ve mekanik özelliklerinin gelişimini etkilemektedir. Kaynaklı ek yerlerinde mikro yapıyı karakterize etmek için optik mikroskop ve taramalı elektron mikroskobu (SEM) işlemi uygulanmıştır. Birçok bilim insanı FSW'ye YSA gibi makine öğrenme yaklaşım teknikleri öğrenilmiş ancak az sayıda yazar FSSW'ye YSA uygulamıştır. Bu araştırmada, AA5754 ve AA7075-T651'e benzemeyen Al-Alaşımlarının farklı AlSS alaşımlarının FSSW modelini geliştirmek için ANN uygulanmıştır. Elde edilen sonuçlar, FSSW ekleminin TSS'sinin TRS, DT ve PD aletinden önemli ölçüde etkilendiğini ortaya koymaktadır. TRS sabitinde PD ve DT, TSS üzerinde önemli bir etkiye sahiptir. Öte yandan, sabit DT'de iken, TRS ve PD'deki artış TSS'yi düşürmüştür.

Anahtar Kelimeler: Friction Stir Spot Welding, Full Factorial Design, Shear Tensile Strength, Micro hardness, Neural Network

To My Parents, Brothers, and Specially to My Sisters and Wife

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AA	Aluminum Alloy
ANN	Artificial Neural Network
BB	Box-Behnken
DT	Dwell Time
FFM	Fractional Factorial Method
FF	Full Factorial
FSW	Friction Stir Welding
FSSW	Friction Stir Spot Welding
FSP	Friction Stir Processing
PD	Plunge Depth
PR	Plunge Rate
RPM	Revolution per Minute
RS	Rotation Speed
RSM	Response Surface Methodology
RSW	Resistance Spot Welding
RFFSSW	Refill Friction Stir Spot Welding
ST	Sheet Thickness
SZ	Stir Zone
TRS	Tool Rotational Speed
TSS	Tensile Shear Strength
TMAZ	Thermo-Mechanical Affected Zone

Chapter 1

INTRODUCTION

1.1 Background

Currently the main focus is on the lightweight materials in automotive and aerospace industry to reduce the structural weight and minimize the cost and enhance the fuel efficiency. Aluminum and aluminum alloys is very attractive candidate due to their high strength and weight ratio. Aluminum and its alloys offers an extremely wide range of capabilities and applications with a unique combination of advantages that make it unique in choice of material for product and markets (Kim et al., 2017). The non-heat treatable 5XXX aluminum alloys major alloying component is magnesium which make it numerous. The 5XXX series are strain harden able and have moderately high strength, excellent corrosion resistance, and very high toughness at cryogenic temperatures to near absolute zero. The representative alloys are 5052, 5083 and 5754. The alloys 5052 and 5083 are mostly used in structural component due to high strength with increasing Mg contents. The alloy 5754 is for automotive body panel and frame applications (The Aluminum Association, 1998).

In 7XXX aluminum series major alloying element is Zn which provide a following characteristics. The 7XXX series is heat treatable, very high strength, very high toughness, typical ultimate tensile strength range is between 220 to 610 MPa. Representative alloys are 7005, 7075, 7475 and 7150. These alloys cannot be weld by commercial process. The widest application of 7XXX series is in aircraft industry, where it is used in fracture-critical design therefore high toughness alloys were developed (Kaufman, 2000). Welding of aluminum alloys is important for structural construction and aircraft fabrications. The welding of aluminum is challenging because aluminum alloys have high chemical affinity therefore to weld the aluminum alloy inert gas is required as shielding gas during welding. The industrial process used to weld aluminum alloys are MIG, TIG, PAW, RW, FSW and electron beam welding (EBW). In all these process weld able thickness is limitation. The best welding method is FSW due to minimal deterioration in mechanical properties and the process is safe and environment friendly as no fumes or spatters are generate during the welding process. Aluminum is the second most utilized metal in the industry after iron and steel. For example in cars the average use of aluminum alloy material is taking about 15% of the total body weight but in Audi A2 taking about 34% (Olabode, Kah, & Martikainen, 2013).

Figure 1.1: Mazda Rx-8 Rear Door (John Sprovieri, 2016)

In the joining methods it has been identified as hard challenge to weld dissimilar alloys. For instance aluminum to copper alloys for electrical connections and steel to aluminum alloys for weight reduction. FSW has gained much attention in the past decades. It is a solid state joining method which is revolutionary joining process invented by The Welding Institute (TWI) which is an effective way of joining material that weld poorly using fusion welding (Azizieh et al., 2016). FSW or FSSW technique does not involve bulk melting of component during the joining of joined. This numerous method inspired many researcher to exploit it for joining materials which are differ in mechanical properties, chemical composition or structure, and where the joining with fusion method can lead to detrimental reactions (DebRoy & Bhadeshia, 2010). The figure below show the importance of welding of dissimilar alloys.

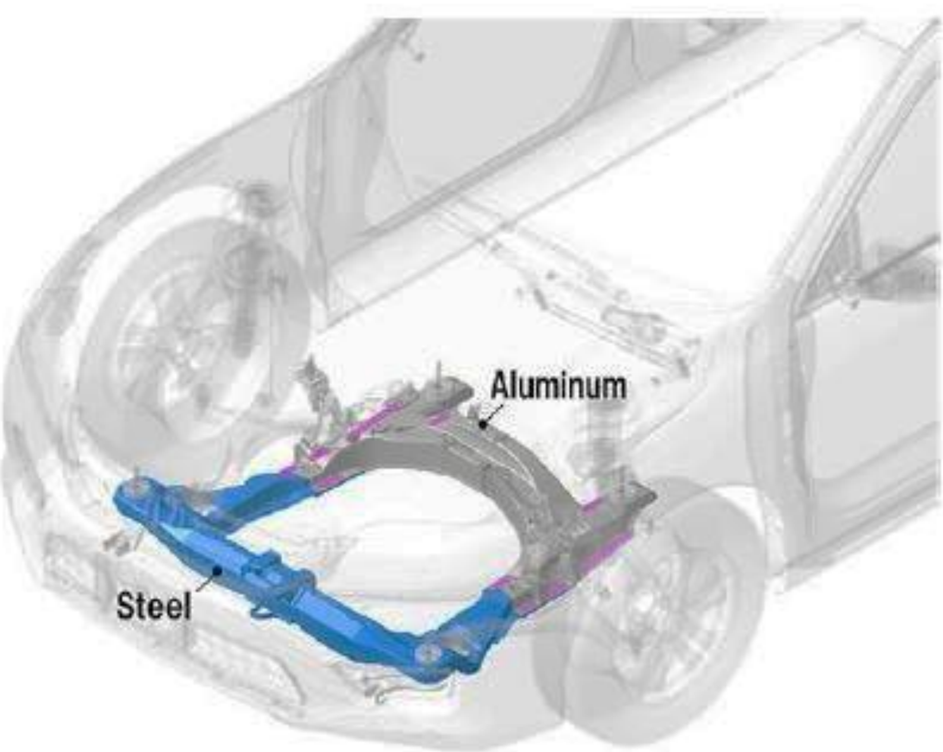


Figure 1.2: Honda Accord 2013 real Application of FSSW Technology (Honda, 2012)

The maximum temperature in dissimilar FSW of Al/steel is 631°C on the steel side, which is much lower than that as high as 1000°C in fusion welding. This reduction will limit the thermal stresses in FSW joints compared to fusion welding, and thus made it a feasible process for the Al/steel assembly in the 2013 Honda (Chen & Kovacevic, 2004). FSSW is very useful and advance version of conventional FSW. Which demonstrates a great potential to be a replacement of single point joining process like resistance spot welding and riveting. The FSSW has wider application in aerospace, aviation, and automobile industry (Yang, Fu, & Li, 2014). The FSSW has limitation and can be applied on flat face on which lapped works can placed. A hole is formed on the work surface as a result of pin insertion. Kawasaki Heavy Company has invented the FSSW technique in 2000 as an alternative of the linear FSW method(Kano et al., 2001). The basic advancement of FSSW was achieved by Mazda, Sumitomo Light Metal Industries, Ltd., Kawasaki Heavy Industries, Ltd., and Norsk Hydro Company. In 2003, Mazda start FSSW in the assembly of the rear door panel of RX-8 (Zarghani, Mousavizade, Ezatpour, & Ebrahimi, 2018).

FSSW and refill FSSW have numerous advantages compared to other joining methods. This process is not affected by surface oxides or contaminants. In comparison of same material joined with RSW had an average lap shear strength of 1002 N, while joints created with a rivet 0.125 inch in diameter produced an average shear strength of 1257 N. The joint made with refill FSSW had better fatigue strength. When compared economically FSSW is one fourth to one third the cost of other methods, like RSW, riveting or clinching (John Sprovieri, 2016).FSSW process has some advantages such as ease of joining materials, excellent mechanical properties, low distortion, and low power consumption, low cost and more economical than RSW. The strength of welds is critical when applying FSSW to load bearing components. This strength is affected mainly by process parameters and tool geometry (Jambhale, Kumar, & Kumar, 2015).

In FSSW the joining of various alloys and thickness combination needed to develop a process parameter unlike RSW. This technique can be used to join aluminum to titanium, aluminum to magnesium, aluminum to steel and steel to steel. The other problem in FSSW joining technique is the tool life. In case of aluminum joints the Mazda claim that it create a 1 million joint with one tool. Tool life is much lower when joining steel to steel (John Sprovieri, 2016).

Table 1.1: Industrial Application of FSSW in different Industry (Pan, 2007)

Company	Application	Advantages
Kawasaki heavy industry	• Building prototype railcars of next generation Shinkansen (built train) • Maglev (magnetically-levitated linear motor bullet train) by a combination of aluminum rib structures and sheet panels.	• Elimination of fasteners on fighter jet • Saving weight
Mazda Motors	• Manufacturing of all aluminum rear door and hood on Mazda RX-8 since 2003	• Reduced Energy Consumption • Reduced investment cost • Improved Work Environment • Long tool life • Little welding deformation • Short cycle time • High repeatability due to simplicity
Toyota Prius	• produce the deck lid and hood for Prius gasoline/electric hybrid vehicles	• good performance • good efficiency

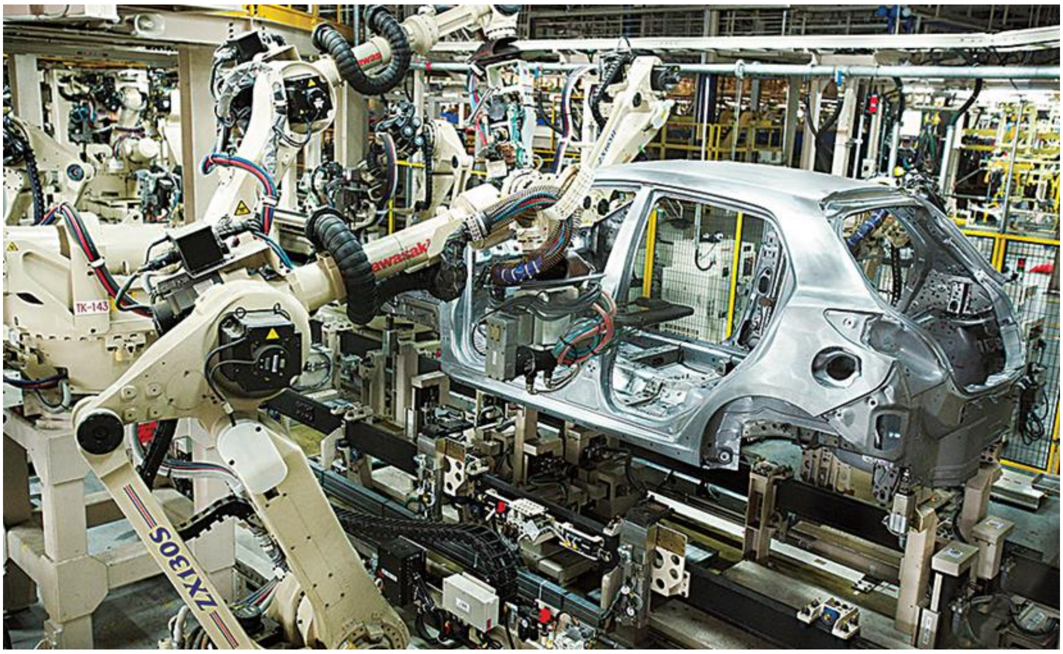


Figure 1.3: Mazda Motor Corp. and Kawasaki Heavy Industry (Mazda, 2003)

In FSSW the parameters played an important roles and have effects on the mechanical and microstructural properties of a weld. As the author (Rosendo et al., 2017) has conclude that dwell time is the most important parameter on the joint strength, and it affect the strength value almost 60%. The aim of this work is to understand the effect of welding parameters on mechanical and microstructure properties of dissimilar aluminum alloy AA5754 and AA7075-T651.

1.2 Problem Statement

In FSSW the main issue mostly faced problem is a keyhole and dissimilar alloys welding. The FSSW is a cognate technology of FSW, keyholes is inevitable if a traditional tool form is used. The welding tool which is vital for FSW has a fundamental shape of an extruding probe and shoulder. Due of this, during the retraction process of the tool, a hole, known as a keyhole, usually found at the final weld end due to the shape of the probe (Ikuta, North, & Uematsu, 2018). Moreover the keyhole which unavoidably stays at the center of the weld after withdrawal of the FSSW tool is deliberated as a detracting matter that causes stress concentration and a contraction in the active welding area of the spot weld. In addition, keyhole areas are ambitious to reach during body painting, so corrosion is expected to accumulate at these locations (Ibrahim & Yapici, 2018).

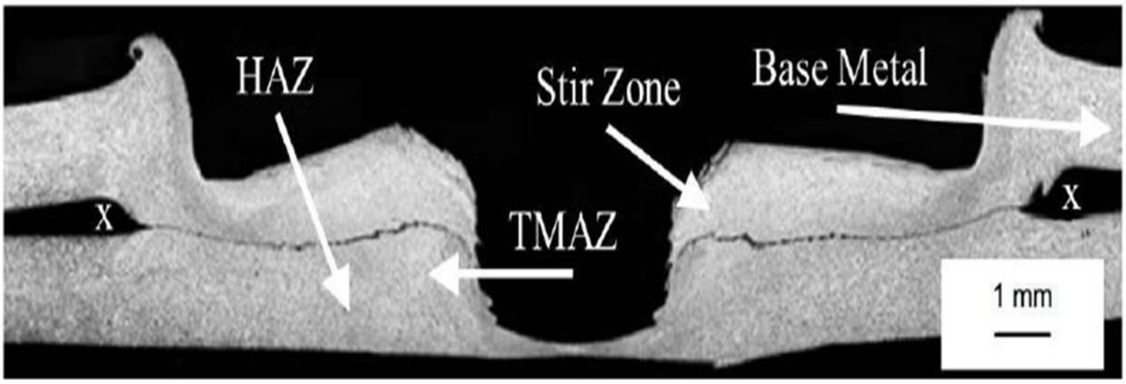


Figure 1.4: Cross Sectional view of FSSW joint (Cox, 2014)

The joining of dissimilar alloys by FSSW is possible but in this technique the main issue is need to develop a process parameter for various alloy and thickness combinations (John Sprovieri, 2016).

1.3 Objectives

This study has covers the welding parameters such as tool rotational speed, PD and DT which had a significant effect on the weld ability of dissimilar aluminum alloys AA5754 and AA7075-T651 sheet plates. The objectives of this research are as following.

i. To evaluate the effect of welding parameters on mechanical and microstructure properties of dissimilar aluminum alloys AA5754 and AA7075-T651.
ii. To investigate the microstructure distribution of dissimilar AA5754 and AA7075-T651 aluminum alloys with welding parameters.
iii. Correlate the mechanical, microstructure and weld quality of all results.

1.4 Scope of Study

The purpose of this study was to accelerate FSSW technology to promote the increased use and adoption of high strength lightweight material in automotive structures specifically heavy vehicles.

i. Two dissimilar aluminum alloys from different categories are welded by FSSW. The non-heat treatable Aluminum alloy AA5754 and heat treat able aluminum AA7075-T651 alloys.

ii. The focus will be on the shear tensile strength and the micro hardness properties of the joint created with FSSW.

iii. Microstructure analysis (qualitative) of AA5754 and AA7075-T651 alloys. Qualitative Optical Microscopy and Scanning Electron Microscopy (SEM/EDS) will focus on microstructure analysis of the joint and inner grain structure.

iv. The Neural Network Analysis (ANN) Meta Model will applied to understand the shear strength behavior of DOE created design model.

Chapter 2

LITERATURE REVIEW

In this chapter background information about materials like aluminum and aluminum alloys classification and the process parameters for FSW and its inherent advance form FSSW will be elaborated.

2.1 Aluminum and Aluminum Alloys

Aluminum and its alloys make aluminum one of the most versatile due to the combinations of provided properties like economical, and attractive metallic materials for a vast range of uses from soft, highly ductile wrapping foil to the most demanding engineering application. Aluminum resists the progress of oxidization that causes steel to rust away. The wrought alloys a four digit of 7075-T651 which is used in aircraft structural component and other high strength operation. The 7xxx series are the toughest AA with the yield strength of more than 500 MPA (J.R. Davis, 2001).

2.2 Classification of Aluminum

Aluminum and its alloys become one of the most adaptable, economical, and attractive metallic material due to unique combination of properties and for wide field of uses from soft highly ductile wrapping foil to the high strength structural engineering application. Aluminum alloys are the second alloys after steel which are used in structural metals. It is appropriate to breakdown aluminum alloys into different categories, Cast Alloy and Wrought Alloy (J.R. Davis, 2001). The principal alloying element and the families of alloys are as shown.

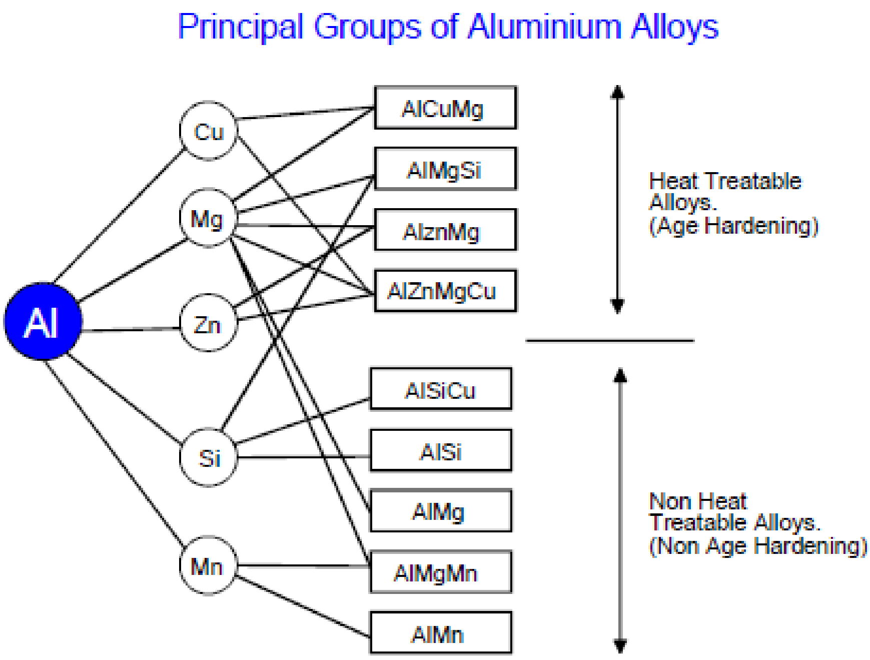


Figure 2.1: Principle Alloying Elements (Johansen, 1994)

2.2.1 Cast Alloys

Cast alloy characterized by three-digit system followed by a decimal value. The decimal .0 in all cases refers to casting alloy limit. The first digit indicates the alloying group. 1xx.x-pure composition for rotor manufacturing, 2xx.x- Copper alloying element, 3xx.x-Silicon with other element copper and magnesium, 4xx.x-Silicon, 5xx.x-Magenisum, 6xx.x-Unused, 7xx.x- Zinc, 8xx.x-Tin and 9xx.x-Unused (Joseph R. Davis, 1993).

Table 2.1: Strength range of various Cast Alloys (J.R. Davis, 2001)

Alloy system (AA designation)	Tensile strength Range	
	MPa	Ksi
Heat treated sand cast alloys (various tempers)		
Al-Cu (201-206)	353-467	51-68
Al-Cu-Ni-Mg (242)	186-221	27-32
Al-Cu-Si (295)	110-221	16-32
Al-Si-Cu (319)	186-248	27-36
Al-Si-Cu-Mg (355,5%Si, 1.25%Cu, 0.5%Mg)	159-269	23-39
Al-Si-Mg (356, 357)	159-345	23-50
Al-Si-Cu-Mg (390, 17%Si, 4.5%Cu, 0.6%Mg)	179-276	26-40
Al-Zn (712-713)	241	35
Non-heat treatable die cast alloy		
Al-Si (413, 443, F temper)	228-296	33-43
Al-Mg (513, 515, 518, F temper)	276-310	40-45
Non-heat treatable permanent mold cast alloys		
Al-Sn (850, 851, 852 T5 temper)	138-221	20-32

2.2.2 Wrought Alloys

Wrought alloys are presented in 4 digit number. 1xxx- genuine composition used in electrical and chemical industry, 2xxx-Copper alloying element, major use in aircraft, 3xxx-Manganese alloying element used in architecture application, 4xxx-Silicon alloying element used in welding rods and brazing sheets, 5xxx-Magnesium alloying element used in boat hulls gangplanks and other marine environment, 6xxx-Magnesium and silicon commonly used in architecture, 7xxx-Zinc with other element copper, magnesium, chromium and zirconium, mostly used aircraft structure and high strength features, 8xxx-Tin and Lithium and 9xxx-future use (J.R. Davis, 2001)

Table 2.2: Strength range of various Wrought Alloys (J.R. Davis, 2001)

Aluminum Association series	Types of alloy composition	Strengthening method	Tensile strength	
			MPa	Ksi
1xxx	Al	Cold work	70-175	10-25
2xxx	Al-Cu-Mg (1-2.5%Cu)	Heat treat	170-310	25-45
2xxx	Al-Cu-Mg-Si (3-6% Cu)	Heat treat	380-520	55-75
3xxx	Al-Mn-Mg	Cold work	140-280	20-40
4xxx	Al-Si	Cold work (some heat treated)	105-350	15-50
5xxx	Al-Mg (1-205%Mg)	Cold work	140-280	20-40
5xxx	Al-Mg-Mn (3-6% Mg)	Cold work	280-380	40-55
6xxx	Al-Mg-Si	Heat treated	150-380	22-55
7xxx	Al-Zn-Mg	Heat treated	380-520	55-75
7xxx	Al-Zn-Mg-Cu	Heat treated	520-620	75-90
8xxx	Al-Li-Cu-Mg	Heat Treated	280-560	40-80

2.3 Application of Aluminum and Aluminum Alloys

Aluminum alloys has wide range of application in many industries. They are being used in automotive industry, in construction of machines, aerospace industry, appliances, structures and as well as in cooking utensils and many more areas. The key chapter of the work is application of aluminum alloys in automotive industry and the type of aluminum based materials used for circuit of motor vehicles and for distinctive aggregates as well as to check the behavior in different modes of operation (Stojanovic & Bukvic, 2018).

The (Wang, Zhao, & Hao, 2018) point out that the key technical problems in the production of large capacity aluminum alloy fuel tanks by applying FSW method, containing designing of a tool, process optimization, nondestructive testing method and defect restoration method. The produced results show that the welding process enhances the high strength of aerospace aluminum alloy and enormously improved the efficiency and production accuracy. The application of aluminum alloys in automobile industry is shown in figure.

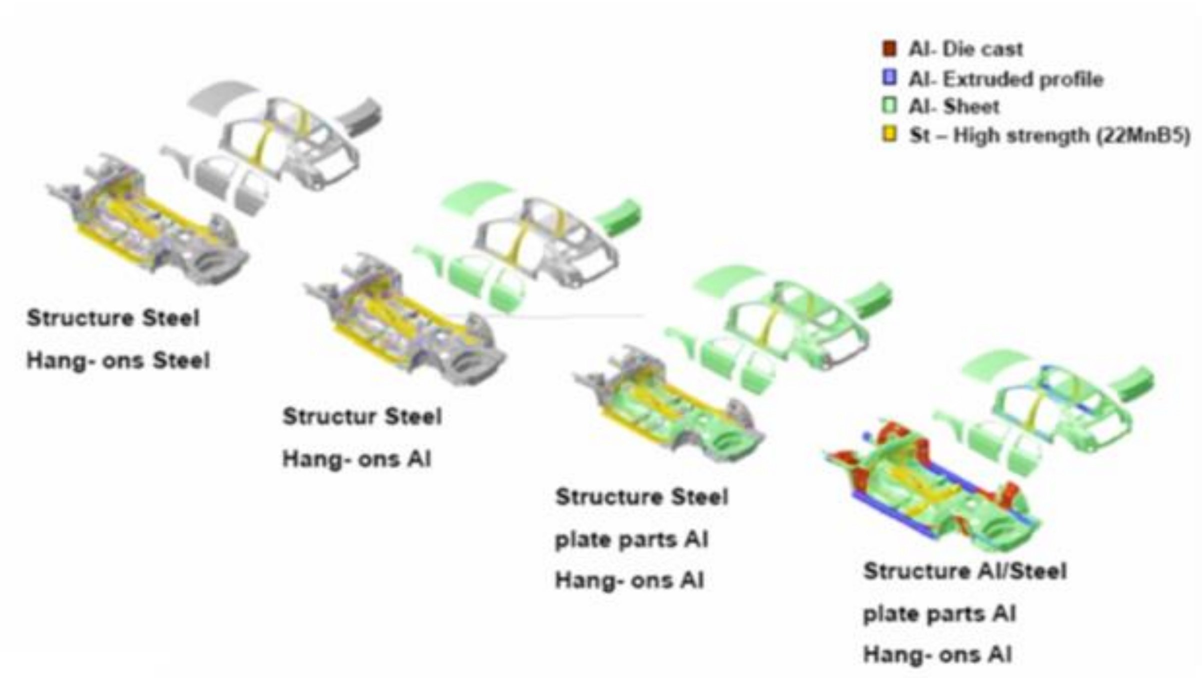


Figure 2.2: Light Weight Strategy of Audi AG (Löveborn, Larsson, & Persson, 2017)

2.4 Welding

Welding is a technique in which material with identical fundamental type or class are brought together to join through the establishment of chemical bonds under the integrate action of heat and pressure. The Author (ROBERT W. MESSLER, 2004) has explained the techniques to join the different metals by using different process now even possible to joint dissimilar metal. Welding not only applies on metal it can also possible to apply on polymers, crystalline oxide, intermetallic compounds and glasses. The combined action of heat and pressure is called welding. Sometime intermediate or filler is required or used in the welding process; the filler can be the same material type or different one even if not same composition as the base material.

2.5 Welding of Aluminum Alloys

In many ways aluminum can be joined, there are many joining techniques including removable system such as bolting including some permanent methods like welding are required in constancy of joining. There is lot of variety of methods in industry where aluminum and its alloys are commonly welded and brazed. Aluminum and its alloys for welding commonly used an electric arc with a constant tungsten electrode plus filler wire or with a continuously fed wire electrode.

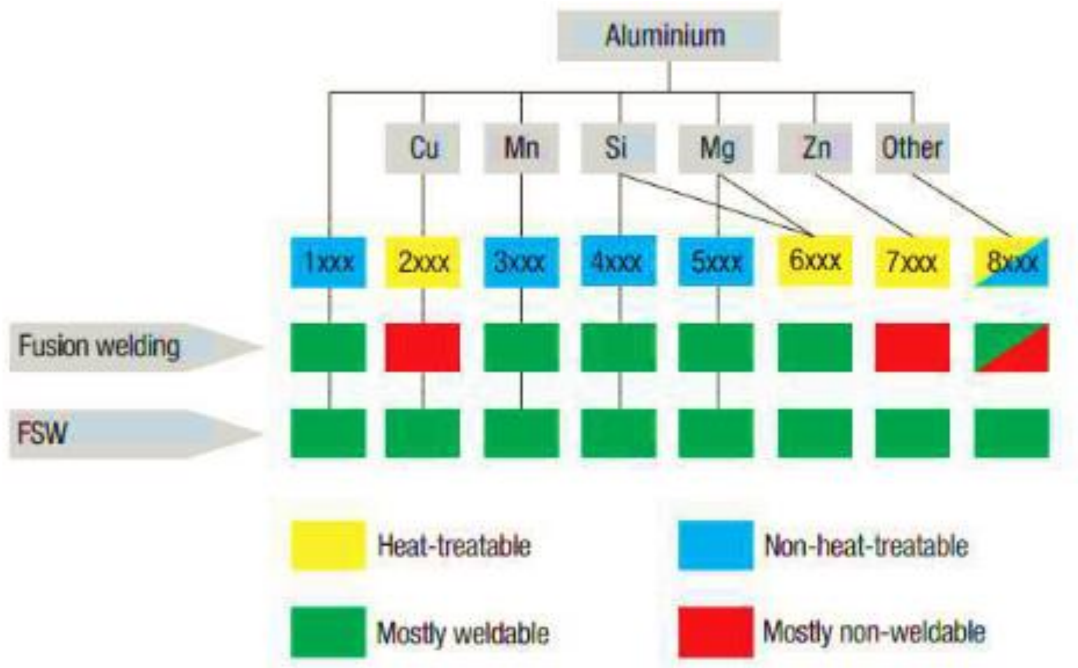


Figure 2.3: Weld ability of various Aluminum Alloys (Singh, 2014)

(Saunders, 1997) has pointed that there are two considerable elementary aspects to assure an excellent weld quality, breaking loose and eliminate the oxide film, and try to avoid the creation of new oxide during the welding process. By using fusion methods process to join aluminum and its alloys by GMAW and GTAW giving high quality weld in all position.

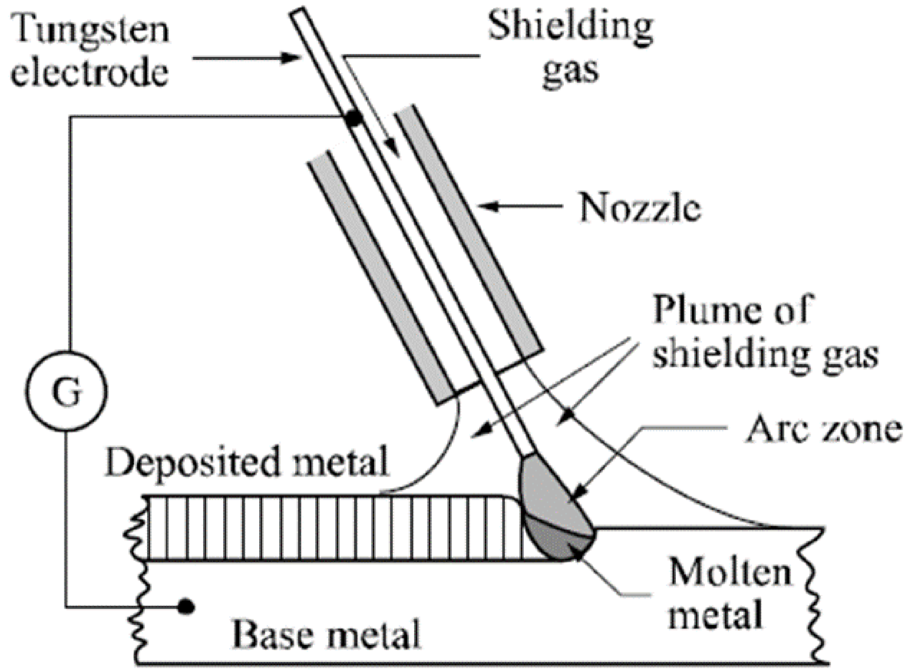


Figure 2.4: Schematic of GTAW process (Blondeau, 2008)

The author (Khojastehnezhad & Pourasl, 2018) had explored the FSW technique used to join the two AA 6061-T6 plates with implant of pure copper plate between the aluminum to investigate the consequence of copper implant on the accomplishment of the weld joint. The obtain results show that the Cu implanted weld has higher hardness than that of the other weld samples because of disruption in density and a noticeable improvement is observed in hardness due to existence of intermetallic compounds.

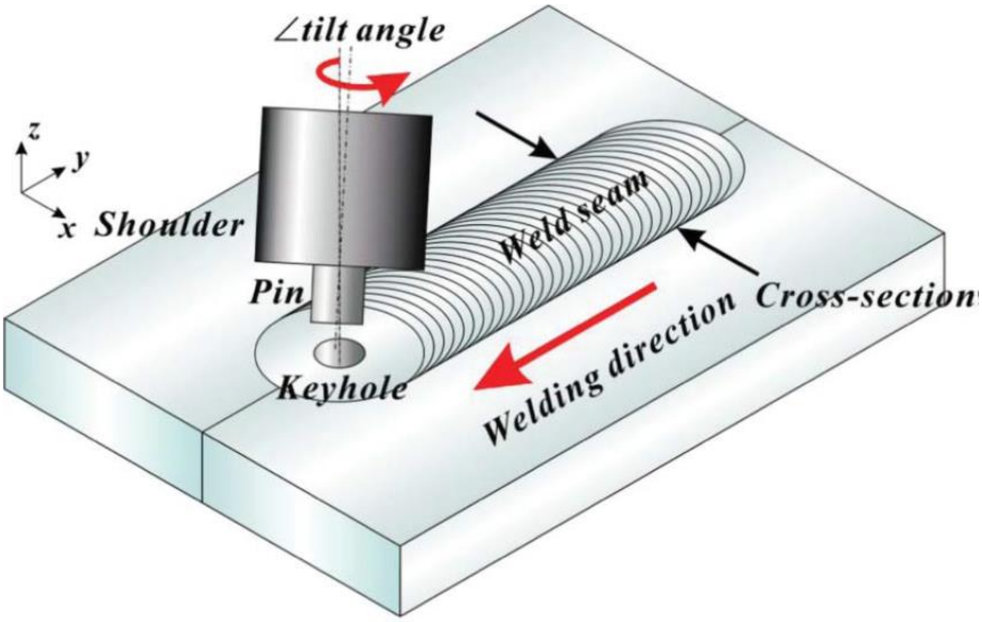


Figure 2.5: Schematic of Friction Stir Welding (FSW) (Ma, Feng, Chen, & Shen, 2018)

2.6 Friction Stir Welding (FSW)

The welding institute (TWI) at Cambridge in United Kingdom first time in 1991 invented a new process of welding called friction stir welding (FSW). The ESAB Welding and Cutting Products are the first manufacturing plant which is located in Laxa, Sweden produced and built friction stir welding machine which is commercially used. Friction stir welding is being used in production application in Europe since 1995. In FSW process heat is produced by rubbing a non-consumable tool on the interface of the surface intended for joining and due to the deformation that is created by passing a tool through the material being joined. A volumetric heating is generated by rotating tool, so as tool moved forward and continuous joint is formed.

(Singh, 2014) proposes that the FSW can be applied on a variety of joint shapes, including butt joint, dissimilar but joint, lap fillet shape and lap penetration configuration. However friction stir welding cannot use for common tee shape joint which mostly used in many fusion welding application.

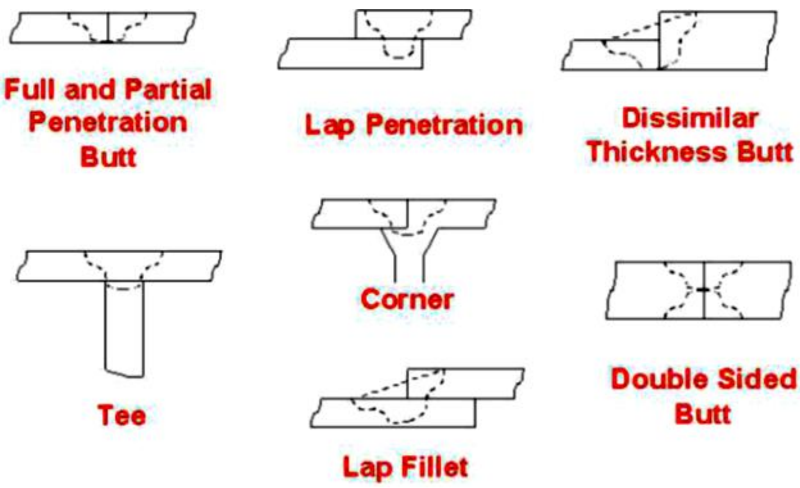


Figure 2.6: Configuration of Friction Stir Welding (Singh, 2014)

2.7 Friction Stir Spot Welding (FSSW)

FSSW is an alternative of FSW for spot welding applications. When distinguished two mechanical bonding (rivets, bolts) rather than RSW the FSSW is getting more attention due to demand of light weight material such as aluminum or magnesium in aerospace and automotive applications to reduce weight (Committee, 2015). FSSW is also a solid phase joining technology which is recently developed by the German factory GKSS.


Figure 2.7: Mazda Aluminum joining Technology by FSSW (Mazda, 2003)

2.8 Classification of Conventional Welding and FSSW

A number of welding methods are available based on the variability associated with entities joined, corresponding joining mechanism and source of energy used. The following table will explain the application of conventional and FSW.

Table 2.3: Characterization of Conventional Welding and FSSW (Ojo, Taban, & Kaluc, 2015; Yuan, 2016)

Weld Type	Working process	Advantages
	Conventional welding process	
Resistance spot welding	• Work piece are welded due to pressure applied by electrode and enormous amount of heat • Heat generated by high electric current trough contact area • Two electrode used at a moment	• Widely used in automotive industry for overlap joints. • Limited work piece deformation • High production rate • Easy automation **Disadvantages** • High heat input, Porosity, Crack, Electrode tip wear
Self-Piercing Riveting	• Cold joining process • Two or more overlapping sheets by pushing rivet trough stack without drilling. • In joining process require punch, holder, rivet, upper sheet, bottom sheet and die.	• No metallurgical process involved • Wide range of material can be joined similar or dissimilar materials. • Better performance in joining of aluminum alloys than RSW. • Environmental friendly • Low energy requirement • No fumes • Low noise emission • Superior fatigue behavior compare to RSW
	Friction Stir Spot Welding	
Refill FSSW	• Consist of three major part, clamping ring, sleeve and pin • Four operational process • First and second extrusion operation, retraction and pulling action	• Minimize material loss • Elimination of key hole defects of FSSW. • Repairing fatigue crack even perform using RFSSW
Ultrasonic Vibration Assisted FSSW	• FSSW process with addition of ultrasonic vibration effect on welding tool.	• Finer and more homogeneous grain distribution • Improve hardness and shear strength •
Double Sided FSSW	• More than one plunge tool at same time. • No linear translation of tool.	• Reduction in reactive torque • Improve mechanical strength of joint • Reduced the reaction or axial force on the spot weld.

Abrasion Circle FSSW	• Tool design with probe and plunge into the work piece • Reach at the bottom then move along circular path • Lastly tool move to the center and retracted from work piece.	• Produce high quality weld. • Creating a larger effective metallurgical bonded area. • Suitable of dissimilar weld like aluminum and steel
Swing FSSW/ Walking FSSW	• Similar to FSSW but differ in tool movement • Two step approach • Tool pin spot created and then plunge the tool. • Translation of tool for short distance	• Invented by Hitachi • It create higher strength and larger contact area.
Swept FSSW	• Rotating tool plunge to the depth to create spot weld. • Tool moved outward at a distance then swept along circular path. • Lastly return to initial position	• Increase actual weld area, eliminate hook defects and increase weld strength. • Better than traditional FSSW because of larger stir zone
Pin less FSSW	• Pin less tool with same FSSW process • Tool shoulder create frictional heat.	• High strength weld with no keyhole defect • Simple process • Better appearance with no keyhole retention • High weld strength at a short dwell time.
Embedded tool FSSW	• Drilling the surface of pin less tool. • Insertion of aluminum rod in drilled hollow cavity that embedded rod and shoulder have same end face	• Increase the rate of temperature • Friction stir welding of aluminum increase • Stir zone depth increase
Flat tool FSSW	• Pin less tool without modification of shoulder face	• Tool influence the microstructure geometry and failure modes of welded joint.
Involute or Scroll tool FSSW	• Pin less tool with scroll modification of shoulder face • Shoulder plunge depth is important variable • Scroll groove adequate stirring of material.	• Superior performance compared to conventional probe tool • Sound weld without key hole

2.9 Friction Stir Spot Welding (FSSW) Process

FSSW is similar in approach and presence to its ancestor (FSW). The author (Yang et al., 2014) highlights the FSSW process which exists on three stages that are plunging, stirring and retracting. The process began with the tool rotation at high speed. After that tool is forced into work piece with high speed until the shoulder of the tool touch the upper surface of the work piece. The plunging force of the tool causes the material to expel. After plunging the next stirring stage begin until the tool reached to the required depth. During the stirring process tool keep rotating in the work piece to generate heat in the plunging due to the frictional heat material get softened and mix in stirring stage and solid state joint established. When the required bonding achieved between the plates then tool retract from the work piece. This type of joint has a keyhole in the middle of the joint which significantly reduce the mechanical properties of the joint.

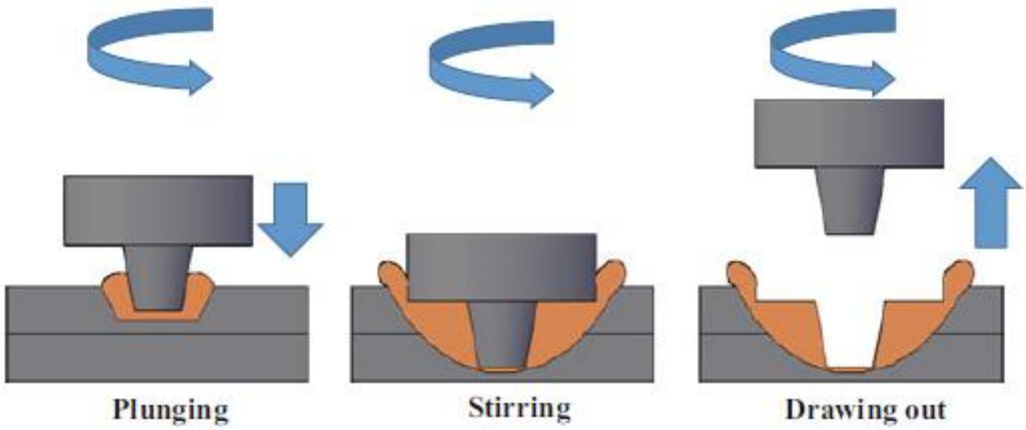


Figure 2.8: Plunging, Stirring and Retracting are FSSW process (Jose A.F.O. Correia, 2019)

The (Pan, 2007) identifies that the FSSW technique can be distributed into two different mode of utilization: load (force) control and displacement (position) control. Figure demonstrates the basic operation of load controlled and displacement-controlled by FSSW process. When the tool begins rotating, then it starts compelled into the sample at a reserved plunging rate to reach a predetermined utmost depth, then tool driven process ends and retraction process start.

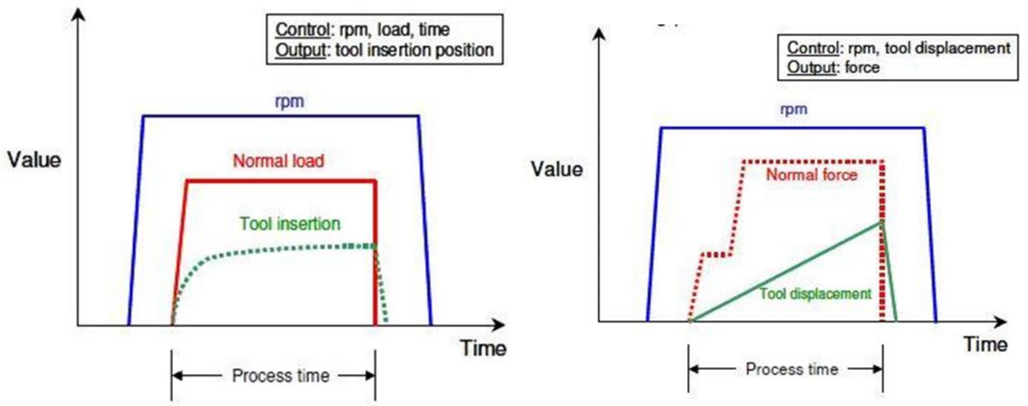


Figure 2.9: Schematic of a Load Controlled and Displacement Control (Pan, 2007)

2.10 FSSW Parameters

Several studies have been conducted to develop process parameters in achieving optimal joint strength and to provide recommendations of process guidelines. The (Bozzi et al., 2010) emphasize the importance of parameters like, TRS, PD and shoulder penetration has been studied to understand weld microstructure and the weld strength. The shear test demonstrates that FSSW fail by nugget pullout. The TSS increase when TRS increased because of large size of SZ. Three microstructural aspects play an important role on weld strength: the location and size of a SZ, and the un-welded interface tip slope. The (Pan, 2007) reported that the FSW process is dependent on the process parameters which include the TRS, DT and PD. These three parameters are most important in FSSW.

2.10.1 Tool Rotation Speed

In FSSW most dominant parameter is TRS which creates heat in the material. A lot of author has reported that an increase in weld strength is achieved when there is increase in rotational speed to a certain limit. The hardness values reduced due to high tool rotary speed. Further, this determinant has enormous impact on hardness. The (Rostamiyan, Seidanloo, Sohrabpoor, & Teimouri, 2015) states that the Increment in TRS causes escalation in heat input and acceleration in temperature Therefore, it improves the average grain size and according to the Hall–Petch law, the hardness decreases. The below table will explore the TRS which mostly used in research papers and the consequences of TRS on quality of weld.

Table 2.4: Effect of TRS Parameters on the FSSW

RPM	Material	Results	Author
1120 **1400** **1800**	1006-AISI steel/Commercial copper	• DOE analysis gives optimum welding parameters are 1,800 RPM, PD 0.85 mm & pre-heating for 15 s, • Achieved 95 percent joint efficiency.	(Abdullah & Hussein, 2018)
1300 **1500** **1700**	Aluminum 6061-T6	• The best combinations are tool rotation speed 1506 rpm, sleeve moving rate 1.01 mm/s and plunge depth of 2.46 mm.	(Zhou, Luo, et al., 2018)
380 **760** **1240** **2500**	AA7075 Aluminum	• At rotation welding speed of 2500 rpm & DT 90 s, • Maximum shear tensile strength is 194.20	(Sitthipong, Towatana, Meengam, Chainarong, & Muangjunburee, 2018)
800 **1200** **1600**	Aluminum 6061	• 1200 RPM rotary speed, PD 6 mm and DT 6 s • maximum lap shear strength and hardness achieved	(Rostamiyan et al., 2015)
900 **to** **1900**	Aluminum 8182	• The tensile shear strength increased Increment to 1300 rpm • Increase heat generation that enlarge stir zone & bonded area.	(Bozzi et al., 2010)

2.10.2 Plunge Depth (PD)

This study demonstrates that the sleeve or tool PD played a vital role in the TRS properties. The researchers (Gerlich, Su, North, & Bendzsak, 2005; Kubit, Bucior, Wydrzyński, Trzepieciński, & Pytel, 2018) describes that load capacity of the joint PD has a great impact. Increment in tool PD causes decrement in the load capacity of the joint. The tensile lap shear failure load was strongly reliant on the bonded area and the energy input to the FSSW joints for 5754 aluminum and AM60 magnesium. The energy input was higher when the TRS and the insertion depth of the tool were increased and when the plunged rate was decreased.

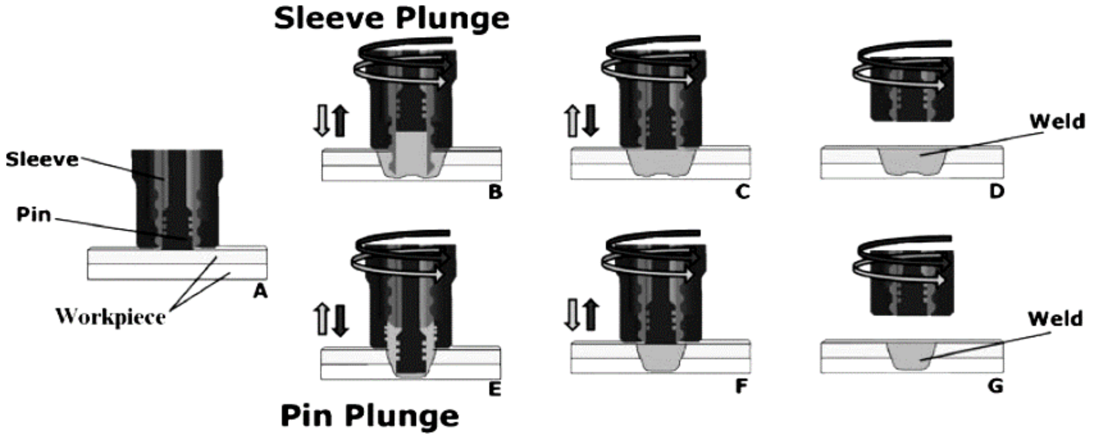


Figure 2.10: Schematic of Pin Plunge and Sleeve Plunge in A-G (Shen, Chen, Hou, Yang, & Gerlich, 2015)

2.10.3 Dwell Time (DT)

Dwell time played an important role in deformation of a metal during the FSSW process. Both authors (Kubit, Bucior, et al., 2018; Shen et al., 2015) has identifies that the increment in DT and PD can enhance the nugget thickness, in all this process DT plays a crucial role in attaining a nugget with larger size. The increment in DT and PD makes material region soften and wider which decrease hardness. The increment in DT and PD increased the overlap shear strength.

2.11 Research Gap

In last few decades' many researcher worked on FSSW joint technique. Few of them has applied DOE but they did not apply Met modeling on FSSW joint. Few of them has implemented Met modeling on FSSW shear strength but they did not applied DOE only one I found applied both techniques. Most of authors did not applied DOE and Met modeling in their research.

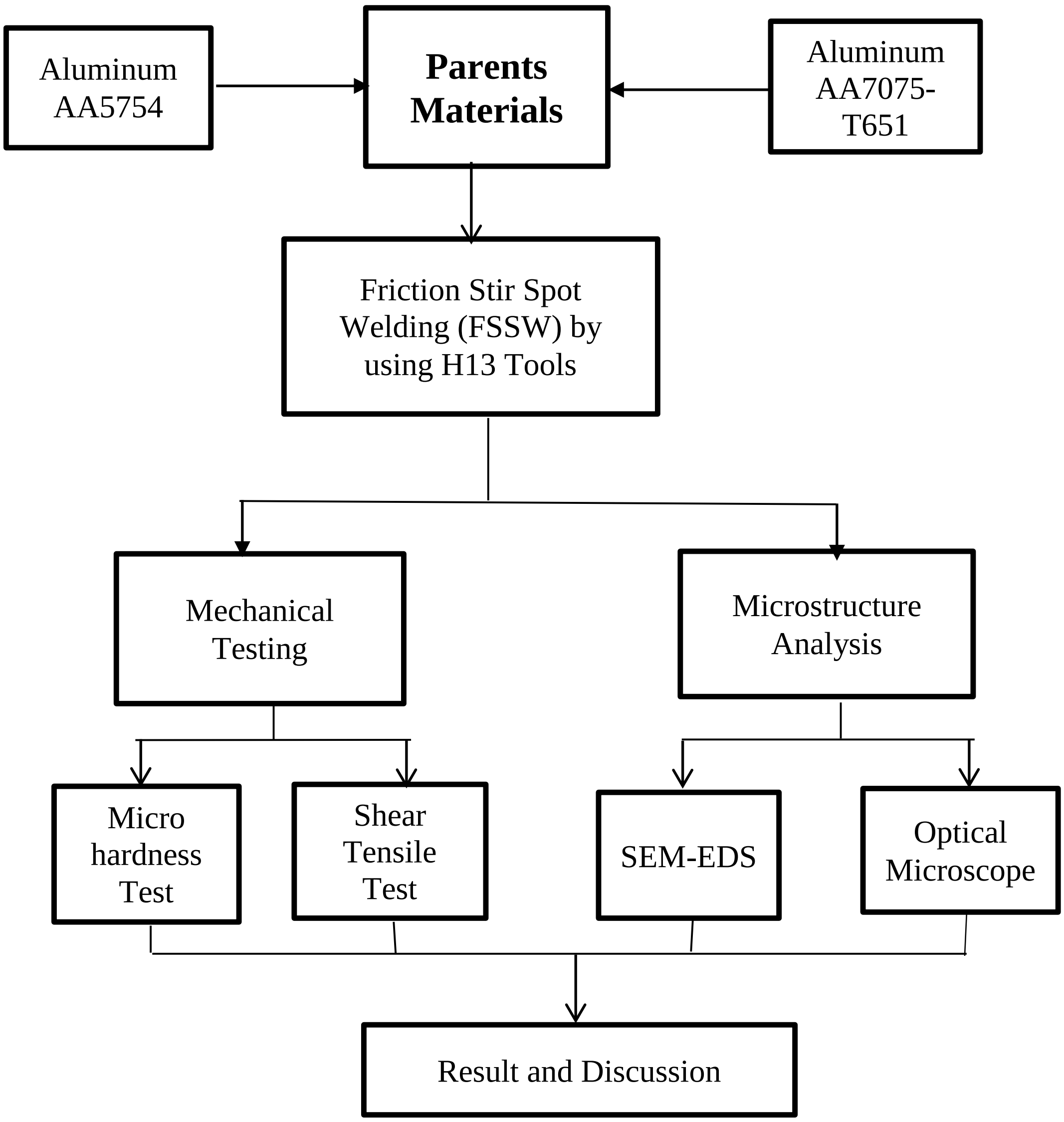
Table 2.5: FSSW Parameters Implement by many Researchers

Author	Material type	Tool type	TS dia / pin dia /length (mm)	ST (mm)	RS (rpm)	DT (s)	PR(mm/min)	PD (mm)	Force (Kg)	ANN	DOE	TSFL (N)
(Zhou et al., 2019)	Al1060 alloy and T2 copper	Cyl pin H13 steel	14/4.6/2.85	2	1500 - 3000	5	×	0.1	×	×	×	4304
(Sun, Fujii, Zhu, & Guan, 2019)	Al6061 -T6 alloy	×	12/4/1.8	1	500-700	2	×	×	500-1000	×	×	6438
(Zhou, Zhang, et al., 2018)	Al 1060/ T2 copper	Cyl pin H13.	14/4.6/2.85	2	2250	5	×	0.1	×	×	×	4304
(Kubit et al., 2018)	Al7075 -T6 sheet	Threaded tool pin	9/5.2/	1.6 upper 0.8 lower	2000 - 3000	1-1.5	3.6	1.35-1.75	×	×	×	6048
(Abdullah & Hussein, 2018)	1006-AISI steel/ copper	×	10/×/×	×	1120, 1400, 1800	15	16	0.2, 0.4	×	×	FFM	4560
(Rana, Narayanan, & Kailas, 2018)	Al5052 -H32/ HDPE/ Al5052 -H32	H13 steel flat	10/4/3	2 with 1 HDPE core	1000 - 2000	15	8	3.2	×	×	×	×
(Sun, Morisada, Fujii, & Tsuji, 2018)	Al6061 -T6 alloy	WC-Co	12/4/1	1	30-50	30	×	×	4-8 tons	×	×	5400
(Carr et al., 2018)	Al6063	H13 steel	4.8/2.41.9	1.2	2000	5	6	×	×	×	×	×
(Chu et al., 2018)	Al2198 -T8	Cyl H13 Steel	15	1.8	750, 950, 1180	3, 6, 9	10, 30, 50	×	×		BB/ ANOVA	×
(Kurtulmu & Kiraz, 2018)	HDPE	×	×	4	560, 710, 900, 1200	15, 25, 35, 45	3.3	0.1,0.2,0.3, 0.4	×	ANN	×	×
(Hamzah, 2017)	Al6061 -T6	Cyl, taper	15/5/2.5	1.6	800, 1000, 1200, 1400.	×	15	0.3	×	×	×	3200
(Kim et al., 2017)	Al5052 H32/6061-T6	Concave/convex	10.16/2.55-3.08/3-2.75	2	900, 1025, 1150, 1400	3	20 / 40	3.5	×	×	×	×
(Karthikeyan & Balasubramaian, 2017)	Al2024 -T3	×	×	2.7	×	6, 6.5, 7,7.5, 8	×	×	×	×	FF/ RSM	6590
(Shojaeefard, Behnagh, Akbari, Givi, & Farhani, 2013)	Al7075 -O/Al5073-O	Tapered	20/10-5/5.85	6	500, 565, 700, 900, 1400, 1600	×	×	20, 63,96	×	ANN	×	267 MPa

Chapter 3

METHODOLOGY

This chapter will demonstrate the methodology of whole chapter which is presented below.



3.1 Material Preparation

In this study, two 1.6 mm thick aluminum sheets of AA7075-T651 alloy and AA 5754 were used to join by FSSW. Figure below in experimental setup demonstrate a lap-shear specimen that was apply to examine the weld strength of FSSW under shear loading conditions. First thing in material preparation is surface finishing and edge to edge clearance. The surface finishing has done to clear the oxidation layer on the surface of materials by grit paper. The table below shows the properties of aluminum 7075-T651 and AA 5754.

Table 3.1: Mechanical Properties and Chemical Composition of Base Material (wt. %) (Reimann, Goebel, & Santos, 2017) and (Ding, Shen, & Gerlich, 2017)

Alloy	**Al**	**Zn**	**Mg**	**Si**	**Mn**	**Cr**	**Cu**	**Fe**	**TSσ_b (MPa)**	**YS $\sigma_{0.2}$ (MPa)**	**Elongation (%)**
7075-T651	89.39	5.82	2.63	0.084	0.05	0.19	1.57	0.18	576.1	529.3	14.76
5754	Bal.	-	2.66	0.4	0.5	0.15	-	0.4	215	140	25

3.2 Experimental Setup

The experiment has been conducted on milling machine (VERNIER-S.A. 06340-LA TRINITE) type FV250E. The aluminum alloy of 1.5 mm thick plates of AA7075-T651 and AA 5754 is used for FSSW. Material plates are clamping with a holder. Two aluminum plates of AA5754 and AA7075-T651 were placed as a lap joined. Shear tensile test was accomplished to determine the mechanical properties of base metals according to ASTM B557 M standard for size of specimen.

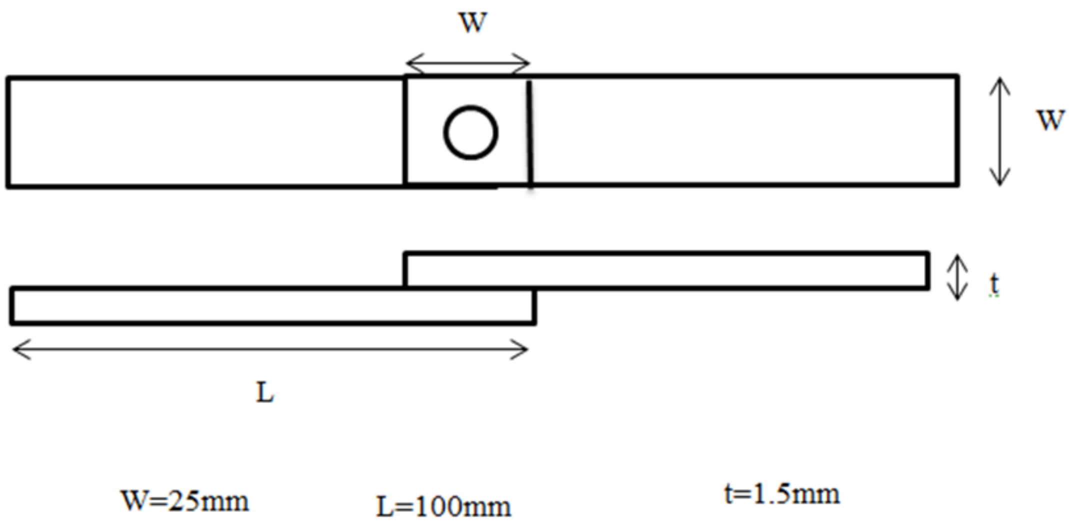


Figure 3.1: Schematic Configuration of Lap Shear Test specimen as per ASTM-B557M Standard (ASTM B 557M - 02a, 2010)

3.3 FSSW Tool

The tool used in this research is made from high strength H13 mild steel having a cylindrical shaped with shoulder diameter, pin diameter and with pin length. The pin length used to control plunge depth during FSSW process. The pin profile of the tool was cylindrical and unthreaded. Tool pin diameter is 4 mm and tool shoulder diameter is 10 mm is used in this study.

Figure 3.2: High Strength (H13) Steel Tool for FSSW

3.4 Full Factorial Design (DOE)

FSSW is a solid state welding technique and many researchers (Zhou, Luo, et al., 2018) (Chu et al., 2018) have applied Box Behnken the design of experiment (DOE), while some researcher like (Asadollahi & Khalkhali, 2018) has applied Taguchi and (Abdullah & Hussein, 2018; Bitondo et al., 2011) has applied fractional factorial design of experiment (DOE) to FSSW joints. Factorial designs are broadly used in experiments include various factors where it is essential to examine the joint effect of the factors on a response. A full factorial design will analyze all attainable mergers for a given set of factors. The 2k design is especially beneficial in the initial stages of experimental work when profuse factors are expected to be examined. The experiments associate 2k designs, it is consistently essential to investigate the magnitude and direction of the factor effects to conclude which variables are likely to be essential. To confirm this interpretation the analysis of variance generally used. The regression model can be used to generate response surface plots (Montgomery, 2006).

Table 3.2: Sample Set A Design of Experiment Parameters for FSSW

Experiment Number	RPM	PD	DT
1	1000	2.2	5
2	1000	2	2
3	1000	2.2	2
4	1000	2	5

Table 3.3: Sample Set B Design of Experiment Parameters for FSSW

Experiment Number	RPM	PD	DT
1	1400	2.2	2
2	1400	2	2
3	1000	2.2	2
4	1000	2	2

3.5 Friction Stir Spot Welding Procedure

FSSW process is a solid state welding technique where a non- consumable tool of high strength H13 was used to develop a joint. The high strength H13 steel were fabricated on a turning machine after that tool was assembled on a milling machine. The plates of aluminum 7075-T651 and aluminum 5754 with dimension of 100x25x1.5 mm were used. FSSW process was conducted on vertical universal milling machine to fabricate overlap welded joints where the AA5754 sheet placed as upper sheet and AA7075-T651 was placed at a lower sheet. Additionally, suitable backing sheets were used to acquire the desired lap spot joints. The dimensions of all specimens are according to the ASTM B557M which is 100 × 25 mm with a 25 × 25 mm2 overlap area. In order to establish the FSSW tests, a correctly designed clamping fixture were established to fix the specimen's during the welding operation. The figure illustrates the fixture position of the specimen.

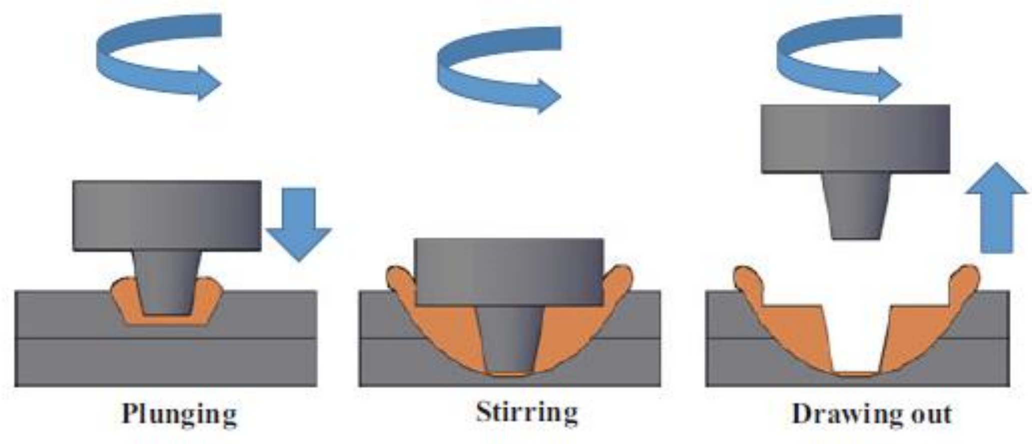


Figure 3.3: FSSW process procedure (Jose A.F.O. Correia, 2019)


Figure 3.4: Clamping fixture mechanism utilized during FSSW

According to the principles of the design of the experiments few trial experiments were conducted to observe the process of welding. A full factorial design of experiment is implemented here with two factors and two levels and third factor kept constant. The two full factorial sample set A & sample set B with 4 samples experiments were conducted on milling machine. Welding tools were created from H13 steel bar. The tool ha 10 mm shoulder diameter, and unthreaded 4 mm of pin probe diameter is used which had pin length of 2 and 2.2 mm.

The FSSW process seems similar to milling process where the tool has rotary and transverse speed. In milling process the tool cut the surface of the piece however in FSSW process the tool instead of cutting the material its go inside because the tool has no cutter edges to remove the material. The FSSW tool has bigger shoulder which will contact with surface of base material and make fractional heat which cause to raise the temperature of work piece. A rotating tool with specifically described dimensioned penetrated into the joint line of the sheets to be joined with a continuous feed rate along the joint line while rotating. The FSSW tool generates enough temperature which can easily join the materials together.

3.6 Mechanical Testing

Similar to other joining techniques, the characteristic of FSSW is steady by calculating the mechanical properties of the joint. (Mishra & Mahoney, 2007) has implies the various mechanical tests that are attended to examine both the static including endurance strength of the joints. Few of these tests are broadly used in the industry and approximately represent a test standard, while few of the tests are distinguished to a particular industry. Few of the static strength tests are lap shear, coach peel, and cross tension, wherein the implementation of load on the joint alter, therefore stress concentration areas as a result varies around the weld.

Figure 3.5: Sample Set A specimens for Mechanical Testing process

Mechanical testing is performed after completing the experiment to check the strength of the joint and to know the flaws during welding process occurred. (Feng et al., 2005) demonstrates that the tensile-shear and cross-tension mechanical testing were accomplished for preferred welding conditions to assess the mechanical strength of the joints. According to ASTM B557M standard the tensile shear specimen prepared 25-mm wide and 100-mm long. The weld was creating at the center of the overlapping 25 mm region. After get successful sound weld results next step to evaluation of mechanical properties. The most adopted mechanical test methods for friction stir spot welding is shear tensile test, micro hardness test, and the microstructural examination will be conducted.

3.7 Tensile Shear Strength Test

The purpose of tensile shear test is to examine the strength of two dissimilar joints of aluminum alloys. The specimen which has length of 100 mm long and 25 mm width is clamped in a shear testing machine whose one end is clamped on upper jaws of machine and other one is in lower jaw of shear tensile machine. The clamping of specimen in shear tensile machine is shown in figure.

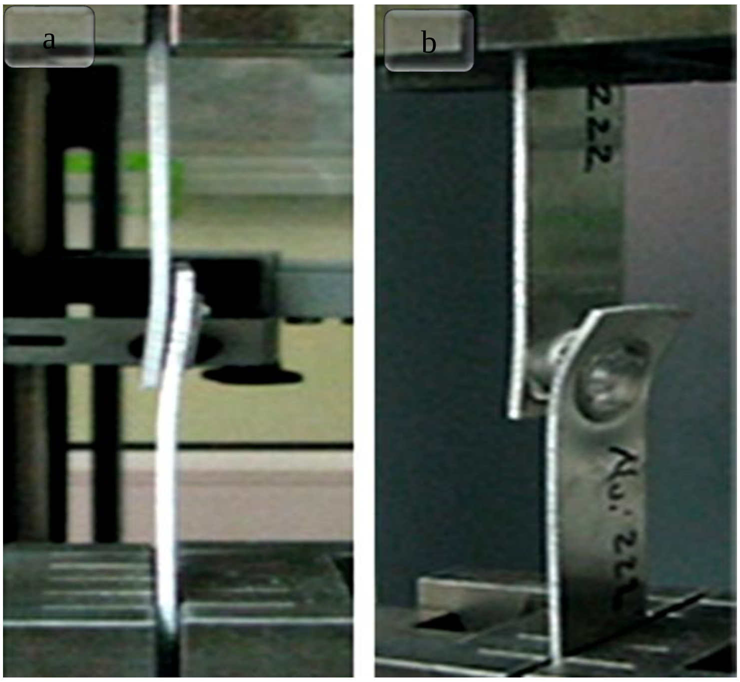


Figure 3.6: Dissimilar FSSW joint Lap-Shear Tensile Test for Sample Set A & B: (a) before the Test (b) after the Test

3.8 Hardness Test

Hardness test is utilizes to tackle the mechanical properties of a material which are being used in engineering design, structure and in other development projects. The main intention of hardness test is to conclude the appropriateness of the material for selected application. The (Chandler, 1999) has observes that the application of hardness test is easier than any other test which makes it dominant to other testing methods. The importance of hardness testing has to do with the connection between hardness and other mechanical properties of material. The hardness test and tensile test measure the resistance of a metal to flow and the results of both tests almost parallel to each other. Micro hardness test is conducted according to standard ASTM E384-11e[1] (ASTM E384-11, 2012).

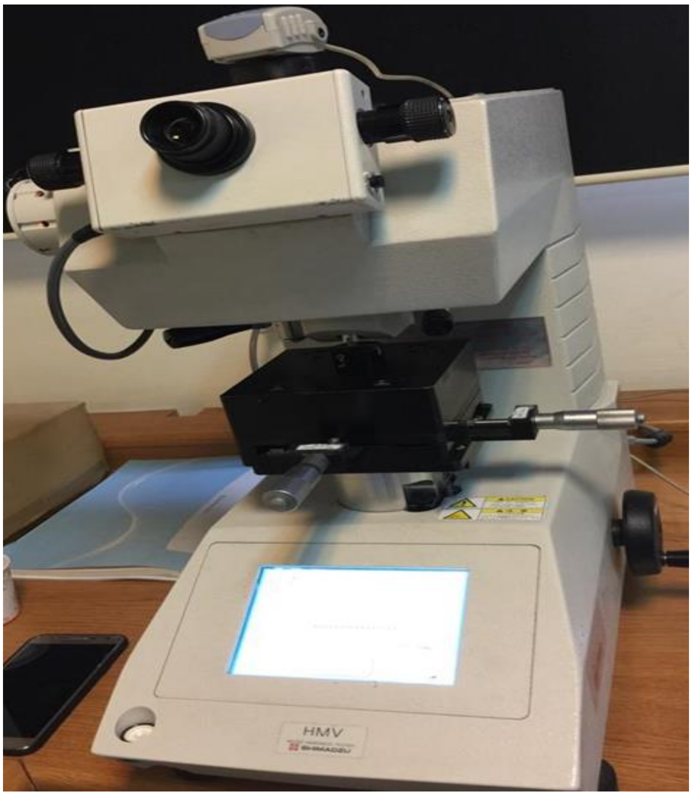


Figure 3.7: Micro Hardness Machine used for Testing

3.9 Microstructure Examination

The microstructural observations provide valuable information regarding the metallurgy of the joint. Nugget/SZ size, actual weld depth, and hook formation (thinning of top sheet) are some of the geometrical information that are possible to visualize through the cross sectional images. The scanning electron microscope machine is shown in figure. This machine is utilized to evaluate the microstructure properties of dissimilar alloys. Also optical microscope machine is illustrated with one specimen result on screen.

Figure 3.8: JEOL JSM-6400 Equipped with a NORAN System 6 X-Ray Microanalysis System

Figure 3.9: Optical Microscope Machine used for Characterization of Material

Chapter 4

RESULTS AND DISCUSSION

The following chapter will describe the mechanical and microstructure testing results in detail with figs and result oriented tables. The result will be discussed according to obtained figures and data from the described methods.

4.1 Scanning Electron Microscopy (SEM)

SEM analysis is used to evaluate the internal microstructure of the joint. As Fig 4.1 shows the key hole of the 2nd experiment of sample set A which clearly illustrates the penetration difference between upper and lower sheet of experiment which conducted on different plunge depth. Geometry of the weld demonstrates the mixing phenomena. In this Figure aluminum AA5754 is penetrating into the aluminum 7075-T651. Fig 4.1 indentation profiles reflect the general shape of the pin probe profile, the tool has flat probe and unthreaded bottom of profile is flat. The similar phenomena observed the following author(Tran, Pan, & Pan, 2009) in his research investigation. The obtained results demonstrates that the heated and softened upper sheet material pushed down near the probe pin of the tool into the lower sheet. Also can see from the figure the heated and softened material of the upper sheet rose upward and outward due to the probe pin indentation.

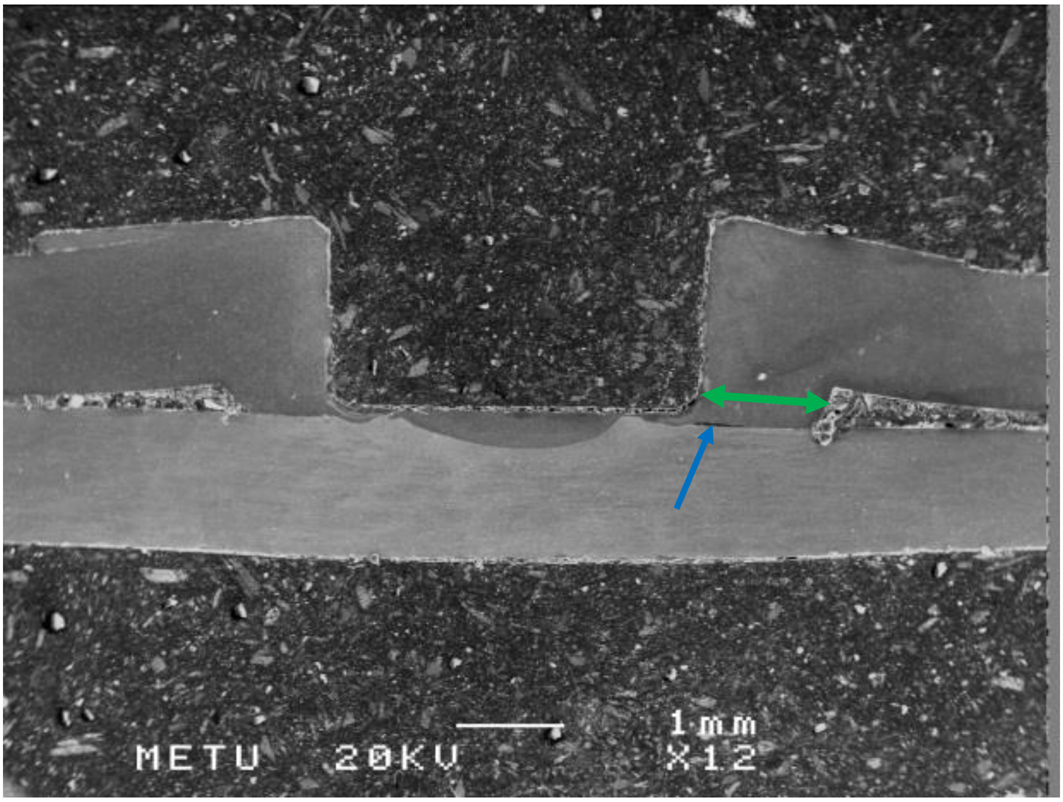


Figure 4.1: Scanning Electron Microscopy of 5754/7075-T651 key hole of FSSW for Sample Set A

Fig 4.1 shows the PD of the tool in lower sheet material stirred and did not mixed very well with upper sheet material. As shown in fig 4.1 shows the area of the tool on upper sheet and applied force and high rotation of the tool penetrate inside the upper sheet and deform the material, the indentation of the tool shoulder resulted in radial expansion of the upper sheet along the outer circumference of the tool shoulder indentation. Because of tool indentation inside the upper sheet with rotational speed of 1400 rpm material become soft and begins to bend around the circumference of the tool.

4.2 Optical Microscope

The optical microscope demonstrates the stir zone and its cross section shown in figure. The optical microscope demonstrates the heat penetration into the lower sheet under the pin hole of the tool. Figure 4.2 shows the material flow and mixing in the SZ of the weld joint. The fig demonstrates the TMAZ under the tool shoulder and near the boundary of the tool pin length.

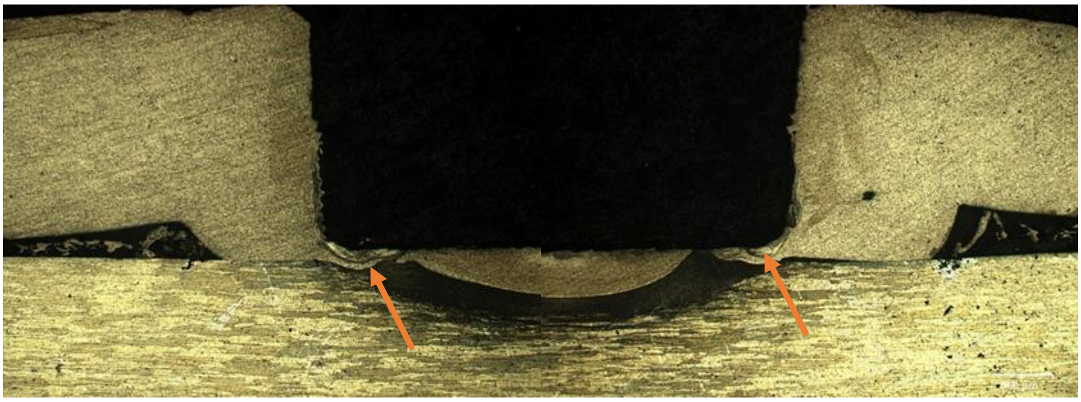


Figure 4.2: Cross Sectional view 2nd Experiment of Sample Set B

Figure 4.2 pointer clearly shows the hook formation during the mixing of lower aluminum 7075-T651 sheet material with upper AA5754 aluminum sheet. In this section also can observe the micro crack propagation between the upper and lower sheet. The author (Tran et al., 2009) also explore the crack propagation in his investigation in these specified material.

4.3 Micro-hardness Analysis

The Vickers hardness distributions of the welds made at two different welding conditions were measured and compared to observe the influence of different parameters of joints. In these samples the TRS and time is constant only the varying the PD of the specimen. The Vickers hardness test was conducted on these specifications of machine at 0.5HV and load of 4.903 N at DT of 10 second. During metallographic examination the specimen of AA5754 and AA7075-T651 were etched by using Keller's reagent (H_2O 95ml, HCL 1.5ml, HNO_3 2.5ml, HF 1m)

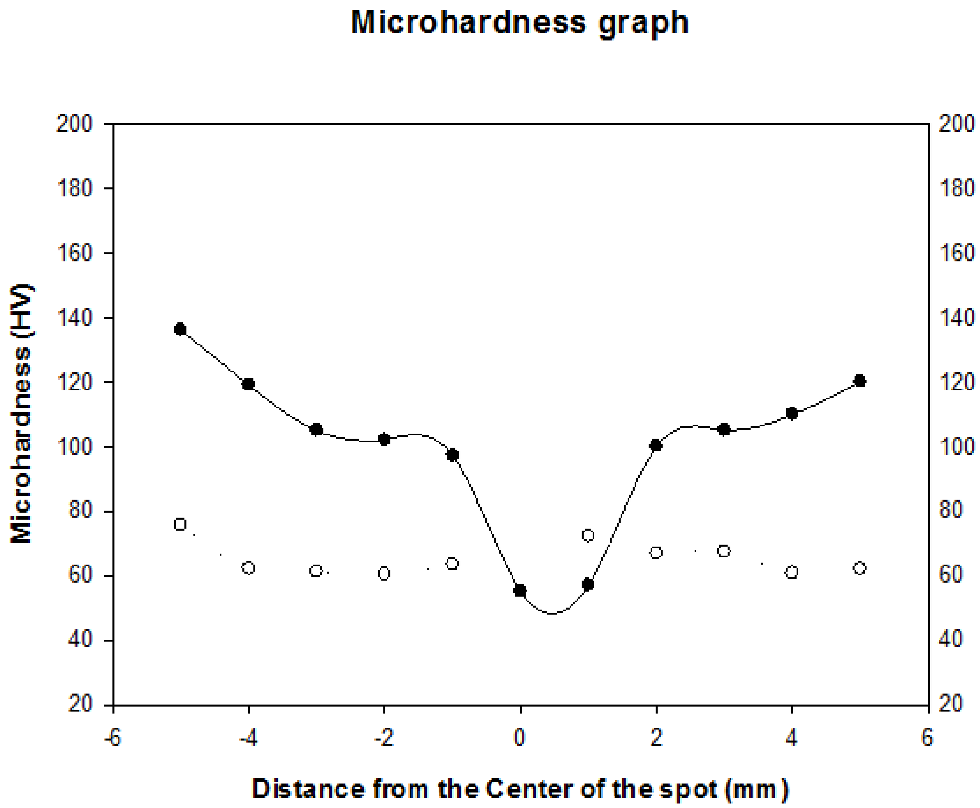


Figure 4.3: Micro Hardness graph for 2nd Experiment of Sample Set B

In the HAZ the hardness of base material and upper sheet increased under the shoulder indentation of the tool. The researcher (Fujimoto, Inuzuka, Koga, & Seta, 2005) demonstrate that the hardness obviously increase in the area with in the shoulder diameter and the maximum hardness achieved in the stir zone. The increase in hardness is because of large plastic deformation in area under the tool shoulder.

4.4 Lap Shear Tensile Tests

Lap shear tensile test has been conducted according to the described sample set A which has constant rotational speed and PD and DT is changing. The main purpose was to observe the effect of parameters on the shear strength of the joint. The effect of TRS, PD and DT on strength were investigated by many researchers (Mahmoud & Khalifa, 2014; Merzoug, Mazari, Berrahal, & Imad, 2010; Piccini & Svoboda, 2015; Shiraly, Shamanian, Toroghinejad, & Ahmadi Jazani, 2014).

Table 4.1: Shear Tensile Strength Results for Sample Set A

Experiment No	RPM	PD	DT	Failure load (N)
1	1000	2.2	5	862.54347
2	1000	2	2	806.58826
3	1000	2.2	2	639.56813
4	1000	2	5	634.50066

As can observed from the lower figure when the PD was 2.2 mm and DT 5 second then maximum shear strength obtained comparatively to DT of 2 second. A completely opposite trend has been noticed when PD is 2 mm and DT is 2 second getting higher shear tensile strength compare to the DT of 5 second. It means when PD is 2 mm at less DT getting higher strength which totally opposite the phenomena observed in PD of 2.2 mm. The author (Kubit, Kluz, et al., 2018; Merzoug et al., 2010) has also specified the result that the PD has great impact on load capacity and the structure of the joint. From sample set A it is clearly observed that by increasing PD and DT improved the strength joint of the weld and same trend following author (Shen et al., 2015) has described in his research.

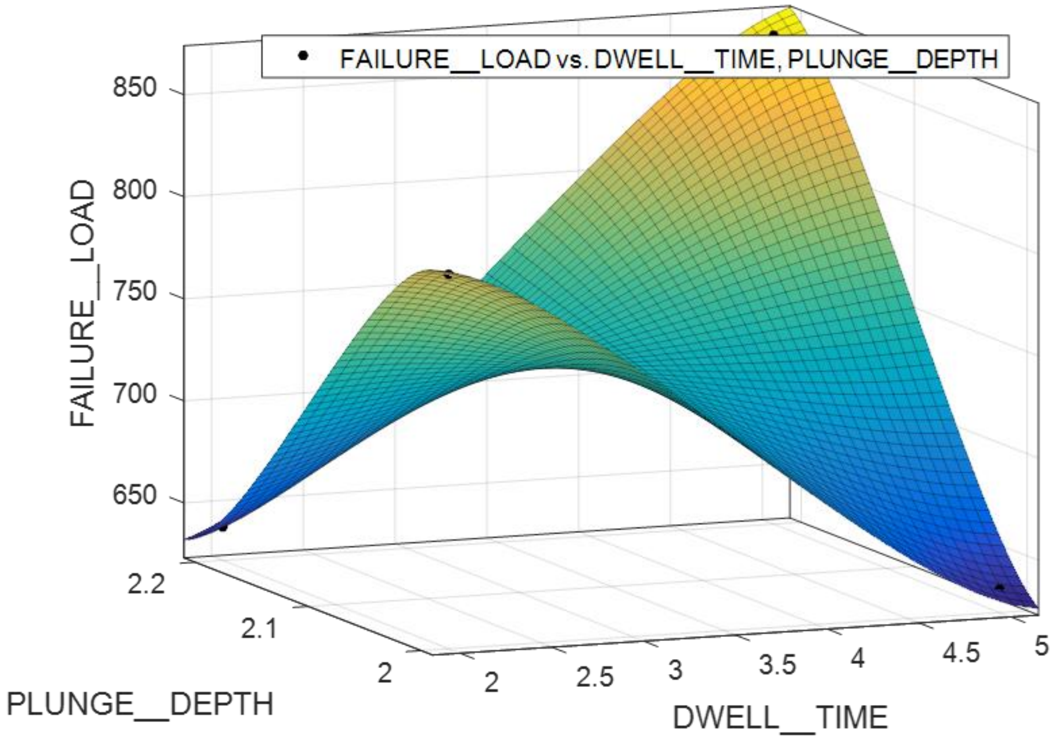


Figure 4.4: Graphical Representation of Failure Load for Sample Set A

Table 4.2: Shear Tensile Strength Results for Sample Set B

Experiment No	RPM	PD	DT	Failure load (N)
1	1400	2.2	2	769.64726
2	1400	2	2	704.69999
3	1000	2.2	2	639.56813
4	1000	2	2	806.58826

As has been observed from the figure 4.5 maximum shear tensile strength observed at PD of 2 mm in sample set B at constant DT of 2 second. In sample set B at constant DT the effect of PD is not effecting the shear tensile strength. Figure 4.5 shows that the maximum shear tensile strength in obtained at lower TRS at constant dwell time 2 second. As TRS increase keeping DT constant then shear strength of the joint decreases, so from this analysis it is obvious that when TRS increase and DT remain constant then the shear strength of the joint decreases. The author(Mahmoud &

Khalifa, 2014) has described that at constant DT of 2 s, increasing the TRS from 400-1000 rpm increases the tensile shear strength. The following authors (Bozzi et al., 2010; Indumathi, Rajyalakshmi, & Rajasekhar, 2018; Zarghani et al., 2018) also investigate the same trend. Further increment after TRS to 1200 rpm it begin to reduce the tensile shear strength. Which means that at a specific level of TRS the tensile strength of the joint increases after the 1200 rpm the tensile shear strength of the joint decreases. It also came under observation at TRS of 1400 rpm and PD of 2.2 mm obtained higher shear tensile strength compared to same TRS speed at PD of 2 mm. it means that PD has a significant effect on shear tensile strength and high rpm.

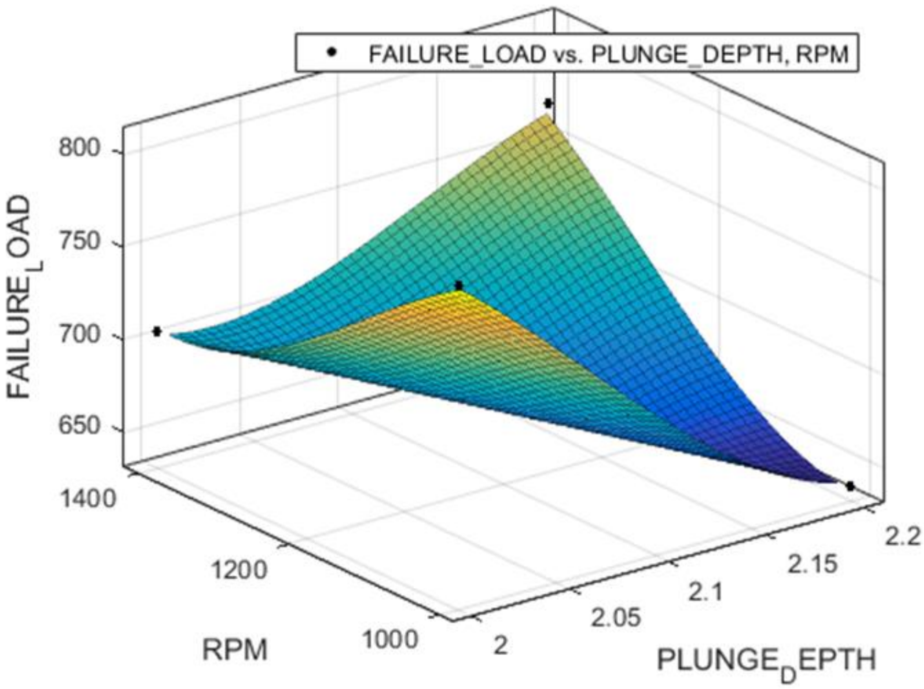


Figure 4.5: Graphical Representation of Failure Load for Sample Set B

Chapter 5

METAMODELING

Friction Stir Welding is solid state welding technique to weld dissimilar metal or alloys various researchers (Heidarzadeh, 2019; Ranjith, Giridharan, & Senthil, 2017; Shojaeefard, Akbari, & Asadi, 2014; Tansel, Demetgul, Okuyucu, & Yapici, 2010) have applied meta modeling approaches like ANN and (Heidarzadeh, 2019b; Kadaganchi, Gankidi, & Gokhale, 2015; Ravi Sankar & Umamaheswarrao, 2017; Shanavas & Edwin Raja Dhas, 2017) has applied the Response Surface Model technique to FSW but very few authors (Kurtulmu & Kiraz, 2018) has applied meta model technique like ANN to "FSSW" on polymers materials. In this research ANN have being applied to develop the Meta model of FSSW of dissimilar Al-Alloys.

5.1 Artificial Neural Network (ANN)

The ANNs become very prominent in many engineering fields because of their interesting features such as learning induction, speedy computation and less difficulty in implementation. ANNs are commonly consisting of number of simple and highly associated processing elements arrange in layers. (Ghetiya & Patel, 2014) has applied the applications of ANNs in various fields like signal processing, manufacturing, bio-electric signal categorization pattern recognition and many more fields. (Muthu et al., 2018) acknowledge that ANN is a collection of biological network of neurons utilized to resolve complex functions in different optimization techniques. ANN are stimulate from biological network order that consist of various simultaneous processing components called neurons. Mathematical models of ANNs were established to predict the consequence of the distinctive input parameters and their interaction effect on the responses of tensile strength and hardness.

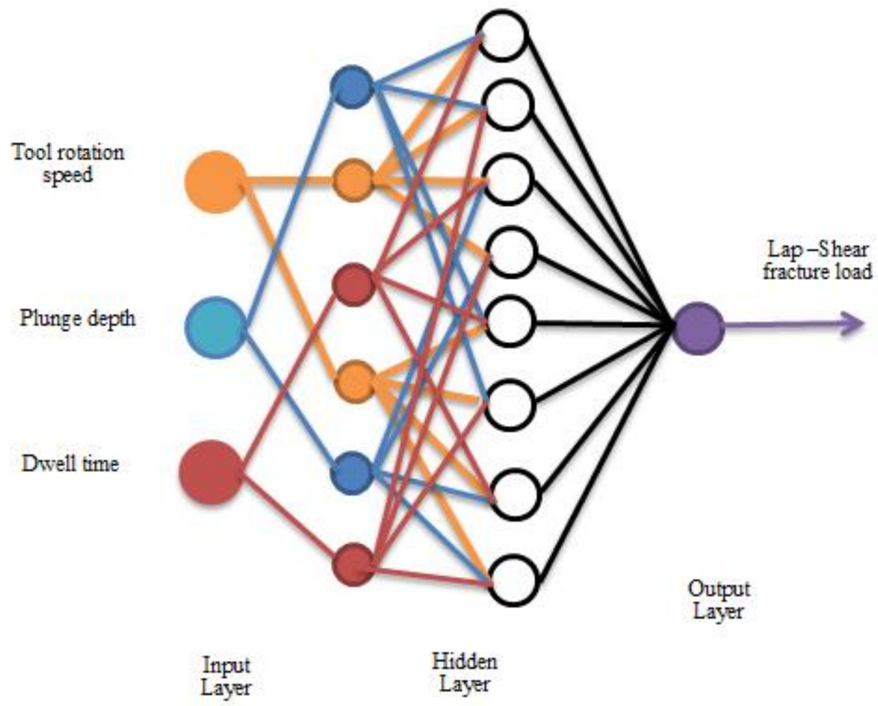


Figure 5.1: The ANNs Model Structure

5.2 Discussion on ANNs Results

The above figure 5.1 is the ANN model which where develop to generate the results. The Table 5.1 and 5.2 shows the variation between the experiment and ANN predicted results of tensile shear strength of dissimilar aluminum alloys welded by FSSW. The variation in experimental and predicted result is obvious. The plots of experimental result and the predicted out for training data, validation data, test data and overall data are given in fig 5.2. The correlation coefficient of training data for sample set A is 0.99626. The closeness of correlation training data and validation data indicates that the prediction efficiency of the model is acceptable. The overall value of the model was found to be 0.99625 which indicate the good prediction efficiency of the ANN model. As we can predict from the figure 5.3 the correlation efficiency of training data is 0.97287. The validation data is 1 and training data value is close to it which indicates good results. The overall R value is 0.97703 which is almost close to the training data value. The error percentage results is presented in table 5.1 and in table 5.2.

Table 5.1: Full Factorial Design of Sample Set A

Experiment No	RPM	PD	DT	Failure load (N)	Predicted (ANN)	Error %
1	1000	2.2	5	862.54347	865.6	0.35436243
2	1000	2	2	806.58826	814.5	0.980889556
3	1000	2.2	2	639.56813	644	0.692947286
4	1000	2	5	634.50066	636.1	0.25206278

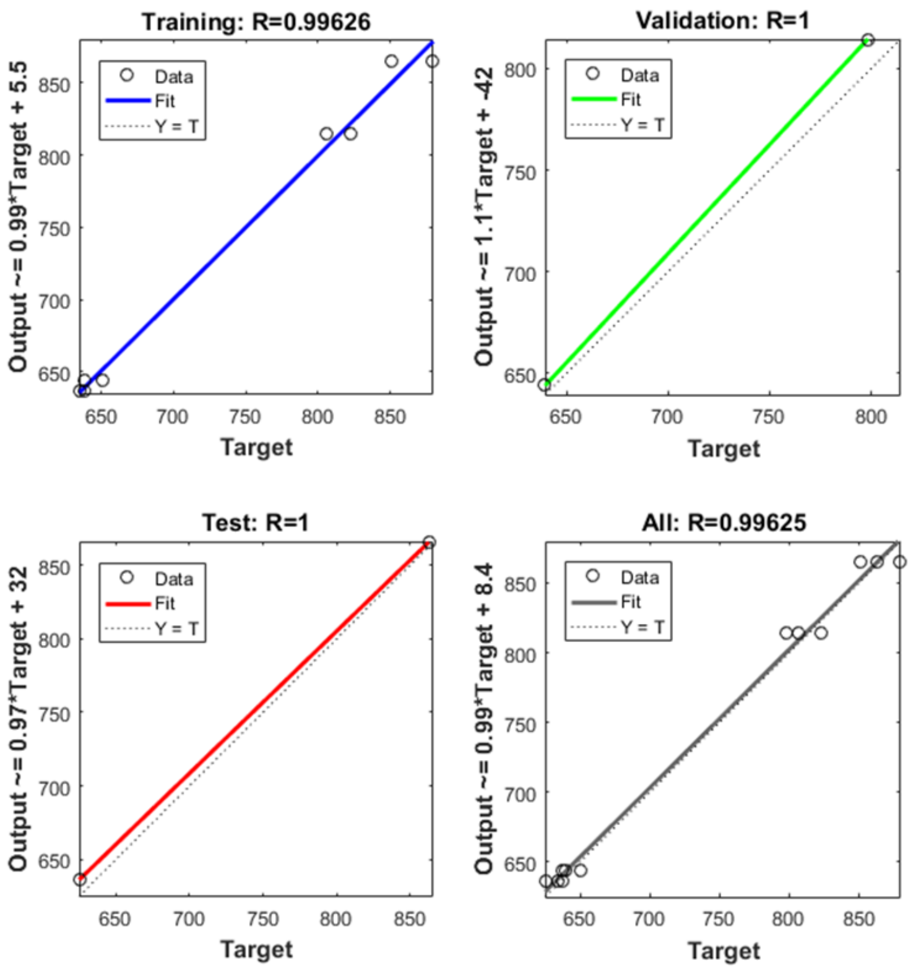


Figure 5.2: ANNs Result for Sample Set A

Table 5.2: Full Factorial Design of Sample Set B

Experiment No	RPM	PD	DT	Failure load (N)	Predicted	Error %
1	1400	2.2	2	769.64726	769.9	0.03283842
2	1400	2	2	704.69999	712	1.035903236
3	1000	2.2	2	639.56813	636.5	-0.479719025
4	1000	2	2	806.58826	815.8	1.142062246

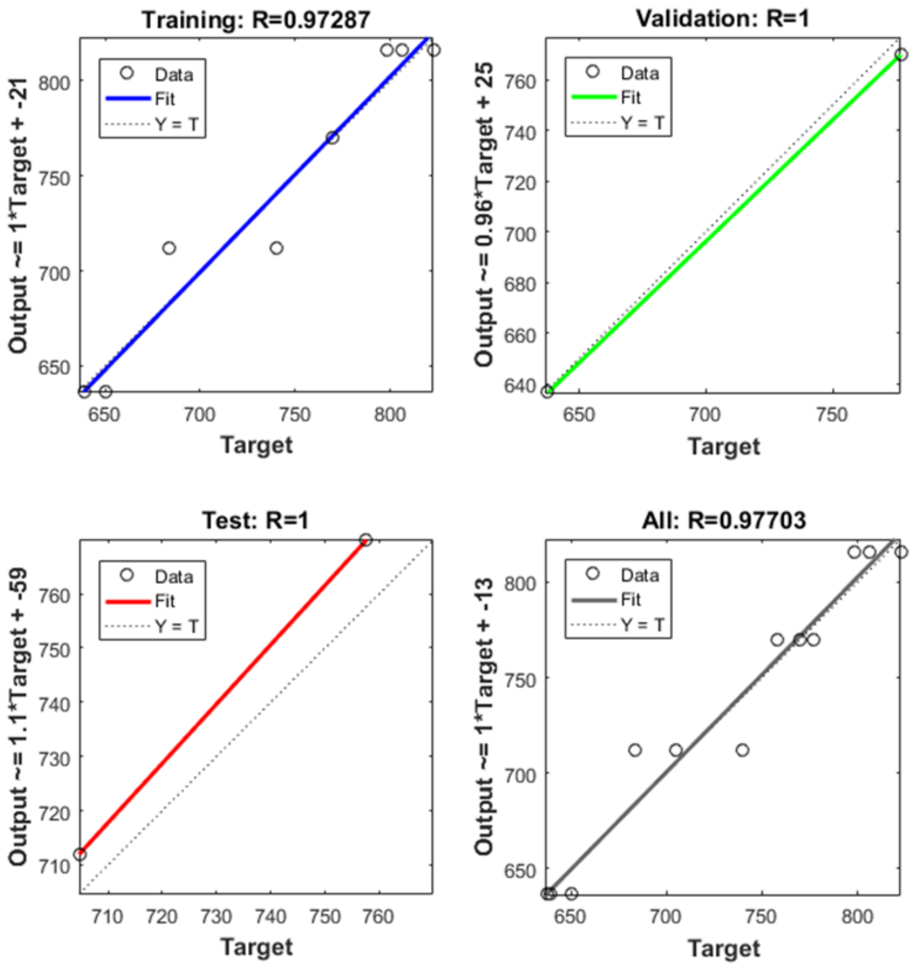


Figure 5.3: ANNs Result for Sample Set B

Chapter 6

CONCLUSION

The effect of rotational speed, dwell time and plunge depth on mechanical and microstructure properties of dissimilar aluminum AA5754 and AA7075-T651 sheet are investigated by experiments. Dissimilar aluminum alloys 5754/7075-T651 friction stir spot welds conducted according to the design of experiment procedure. Many researchers have applied machine learning approaches like ANN to FSW but very few authors have applied ANN to "FSSW". In this research ANN have being applied to develop the met model of FSSW of dissimilar Al-Alloys. The main results are compiled in this research are following:

- The tensile shear strength of FSSW significantly affected by tool rotation speed, dwell time and the tool plunge depth.
- The increase in tool rotation speed to 1400 rpm and plunge depth 2 mm at constant dwell time decreases the tensile shear strength in a sample set B, whoever at rotational speed of 1000 rpm and plunge depth of 2 mm at constant dwell time of 2 second obtained a maximum shear tensile strength.
- The increase in rotational speed in sample set B at PD of 2 mm decrease the tensile shear strength.
- It also observed that at TRS of 1400 rpm increment in PD improves the joint strength in sample set B which has significant effect on shear tensile strength.
- The increase in the tool pin plunge depth and dwell time in sample set A increases the tensile shear strength.

- Effect of tool plunge depth parameter on the tensile shear strength is greater than dwell time and tool rotation.

6.1 Future Recommendations

My future recommendation in this study is following:

- The effect of tool geometry and profile can be further explored. Threaded tool pin can be used to develop the FSSW joint.
- The effect of using internal adhesive oblique bonding can explore.
- Multiple FSSW weld can be compared to see their effect on shear strength and response surface methodology can be implemented to predict the error percentage with ANN.
- Other DOE can be applied like Taguchi for uncertainty and worst case analysis.
- Multiple Spot weld can be made instead of single spot joint on a sheet to predict the behavior of joint and their properties.

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