Investigations on Joining of Dissimilar Materials by Resistance Spot Welding

M.Tech. Thesis

By

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Discipline of Mechanical Engineering

Indian Institute of Technology Indore

July 2018

Investigations on Joining of Dissimilar Materials by Resistance Spot Welding

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By

ABHISHEK AHIRWAR

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Candidate's Declaration

I hereby certify that the work which is being presented in the thesis entitled **"Investigations on Joining of Dissimilar Materials by Resistance Spot Welding** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING , Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2017 to July 2018 under the supervision of **Dr. Jayaprakash Murugesan, Assistant Professor,** Discipline of Metallurgy Engineering and Material Science.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Mr. ABHISHEK AHIRWAR

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

Dr. JAYAPRAKASH MURUGESAN

Mr. ABHISHEK AHIRWAR has successfully given his M.Tech. Oral Examination, held on**……………………….**

Signature of M.Tech Thesis Supervisor
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Signature of Convener, DPGC
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Signature of PSPC Member 1
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Signature of PSPC Member 2
Date:

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Last, but not least, I would like to dedicate this thesis to **my parents**, **sister** and **my friends**, for their love, patience, and understanding, because without their support, I would have never reached where I am today.

ABHISHEK AHIRWAR

DEDICATED

TO

MY FAMILY

AND

MY GUIDE

ABSTRACT

Emerging trends in manufacturing such as light weighting, increased performance and functionality increases the use of multi-material, hybrid structures and thus the need for joining of dissimilar materials. The properties of the different materials are jointly utilized to achieve product performance. The joining processes can, on the other hand be challenging due to different properties. This thesis focused on state of the art research in joining dissimilar materials by resistance welding. Resistance spot welding is a widely used technique for fabricating sheet metal assemblies because of its high speed, efficiency, reduced cost and suitability for automation. The objective of this thesis was to study the effect of process parameters particularly on the structure and properties of resistance spot welded dissimilar sheet metal joint. Two different materials, mild steel HR1 and aluminium alloy 6061 or stainless steel (SS 316L grade) and aluminium alloy 6061 were used to be welded. Welding current in the range of 4 kA to 6 kA and welding cycle time of 15 to 21 milliseconds was used as process variables. The welded coupons were examined by different characterization techniques such as macroscopic, optical microscopic and scanning electron microscopy, EDX analysis, tensile testing and micro hardness measurements. In this study, asymmetrical shape weld nugget was formed to join two different materials. Weld nugget size increased with an increase in welding current and welding cycle time and this affected the mechanical properties. Optical microscopy and SEM analysis clearly showed different zones like base metal, heat affected zone and fusion zone. Micro hardness of the weld nugget was maximum because of the formation of brittle intermetallic layer. An increase in both welding current and cycle, increases tensile strength of the weld coupon up to certain limit but after that it decrease in case of joining Al alloy with mild steel but in case of Al alloy and stainless steel it increase with increase of welding current and time.

Table of Contents

Item **Page No.**

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

RSW	Resistance spot welding
GTAW	Gas Tungsten Arc Welding
GMAW	Gas metal arc welding
HAZ	Heat Affected Zone
SPS	Spark Plasma Sintering
IMC	Intermetallic Compound
NDT	Non-Destructive Test
FZ	Fusion zone
BM	Base metal
SEM	Scanning Electron Microscopic
EDX	Energy Dispersive X-ray
UTS	Universal testing machine
Fe	Ferum
Al	Aluminium
Cr	Chromium
Mg	Magnesium
SS	Stainless steel
MS	Mild steel
AC	Alternate Current
kA	Kilo ampere
K	Kelvin
Ao	Area
P	Load
mm	Millimeter
µm	Micrometer
kN	kilo Newton
sec	Second
δ	Specimens Gage Length
Lo	Original Gage Length
HV	Hardness Value
MPa	Mega Pascal

Chapter 1 INTRODUCTION

Joining process is used to assemble individual parts into a larger, more complex component or assembly. The process used to bring separate parts of components together to produce a unified whole assembly or structural entity This bond can be forms, by one or a combination of several of the following processes:

Mechanical—a joint formed through a mechanical mechanism,

Chemical—a bond formed through chemical reaction,

Thermal—a bond formed through applying thermal energy.

1.1 Joining of dissimilar materials

The drive for more optimal, lightweight and high performance structures, and the trend of integrating an increased number of functions in each part can be met by combining various materials into a multi-material hybrid structure. The different properties of the different materials are jointly utilized to achieve the product performance needed. This trend is reported for several industries such as: Automotive, Aeronautics, Tooling, Implants, Power generation, and Marine application. The mix of new materials will require a systematic approach to material selection: these materials will interact with each other in new ways, and new manufacturing systems might be needed. This requires the ability to simultaneously optimize material choice and geometry. Recent developments include proposals for multi-material design procedures, and optimal material selection with respect to light weight and recyclability. In modern car body structures high strength steels can be used in the longitudinal beams for strength, aluminium alloys in bumper beams for lightweight and crashworthiness and composite sheets in panels for lightweight and high stiffness. The EU FP6–project super light Car (Figure 1) showed how mass can be reduced by combining aluminium, steel, magnesium and glass fibre reinforced thermo-plastics. Figure 1 shows some examples of dissimilar weld joints.

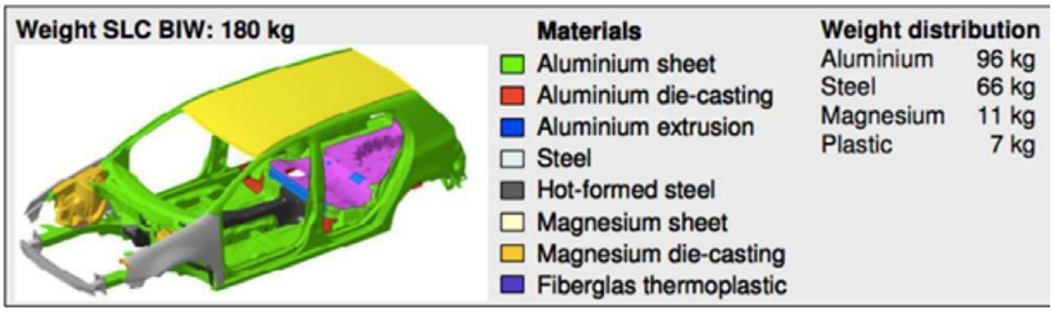

Figure 1: Frame of a car with dissimilar material weld [1]

Dissimilar materials joining [2] can be described as: ‘‘materials or material combinations that are difficult to join, either because of their individual chemical compositions or because of large differences in physical properties between the two materials being joined’’. Different joining processes have unique strengths and limitations for the joining of dissimilar materials. There are, however, significant challenges when materials of different chemical, mechanical, thermal, or electrical properties are to be joined together. The incompatibility on chemical, thermal and physical levels (thermal expansion, ductility, fatigue/fracture mechanics, elastic modulus etc.) can create problems both for the joining process itself, but also for the structural integrity of the joints during the use phase of the product. The field of joining is very large and there are a large number of different joining methods.

1.2 Background of dissimilar metal joining

Joining dissimilar materials is often more difficult than joining the same material or alloys with minor differences in composition; however, many dissimilar materials can be joined successfully with the appropriate joining process and specialized procedures. Since 1970, over 20,000 articles have been published on dissimilar material joining (DMJ). Most of the DMJ research during this period of time has been associated with metallic systems most commonly used in industry including carbon and low-alloy steels, stainless steel, nickel, copper, and aluminum alloys. There has also been increasing research of DMJ involving titanium alloys, ceramics, polymers, and composites materials starting from the 1980s and 1990s. Increased use of these materials for engineering applications is growing because of special performance requirements for corrosion resistance, high strength-to-weight ratio, erosion resistance, or high-temperature strength.

1.3 Background of the Resistance Spot Welding

Resistance spot welding (Figure 2) is one of the oldest of the electric welding processes in use by industry today. The weld is made by a combination of heat, pressure, and time. As the name resistance welding implies, it is the resistance of the material to be welded to current flow that causes a localized heating in the part. The pressure exerted by the tongs and electrode tips, through which the current flows, holds the parts to be welded in intimate contact before, during, and after the welding current time cycle. The required amount of time current flows in the joint is determined by material thickness and type, the amount of current flowing, and the cross-sectional area of the welding tip contact surface.

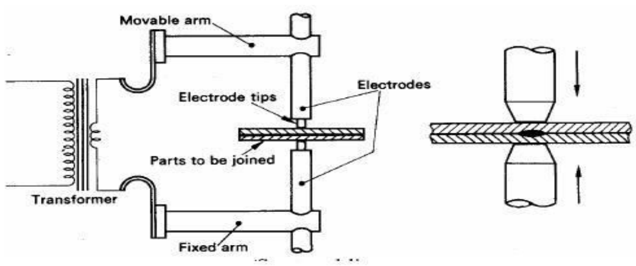

Figure 2: Spot welding [3]

1.4 Problem Statement

There are significant challenges when materials of different chemical, mechanical, thermal, or electrical properties are to be joined together. The incompatibility on chemical, thermal and physical levels (thermal expansion, ductility, fatigue/fracture mechanics, elastic modulus etc.) can create problems both for the joining process itself, but also for the structural integrity of the joints during the use phase of the product. Even though Al alloy to steel welding have a advantages, it also have a drawback due to its attribution to the large difference between their melting points, the nearly zero solid solubility of iron in aluminum, and the formation of brittle intermetallic compound (IMC) such as Fe2Al5 and FeAl3 which can cause a detrimental effect on the mechanical property of the workpiece. Due to this reason, there is a demand to fabricate it. Therefore, the details investigation will be done on the dissimilar welding especially aluminium and steel sheet. Both of the materials will be joined by the spot welding process and researching of the microstructure and mechanical properties of the dissimilar welding will be done. In this study, the effect of welding current and welding time on the tensile shear strength of welding joints in electrical resistance spot welding of mild steel and aluminium alloy metal sheet and Stainless steel to Al alloy metal sheet are investigate. It has to developed experiment to carry out the time and current effect in welding mild steel sheet to aluminium alloy sheet by resistance spot welding machine. While doing the experiment, it has to select welding current periods and adjust the welding time and vice versa .during the welding process. The electrode pressure is fixed. After doing the experiment is one of the important success strategies to analyze the data of the mild steel and Al alloy metals and stainless steel and Al alloy metal sheet, which were produce suitable current and time effect of the spot welding.

1.5 Objective

The primary aim of this work is to optimize the parameters for resistance spot welding of dissimilar metals with particular reference of mild steel and aluminium alloy or stainless steel and Al alloy. The physical and mechanical properties of welded joints will be determined. The properties will be correlated with the microstructure of the welded joint.

The importance of this research works are given below.

1) To develop a joint between Mild steel to aluminium alloy and stainless steel to Al alloy by resistance spot welding.
2) To study the effect of different parameter (Current and Time) on joining strength of MS to aluminium alloy and SS to Al alloy by spot welding.
3) To study microstructural and mechanical properties of joint.
4) To identify the ranges of process parameters for resistance spot welding of mild steel to aluminium alloy and SS to Al alloy for the high strength of joint

5) To estimate the amount of load that could be apply to each different nugget diameter size before the welded joints is fails or rupture.

1.6 Scope of study

The scope of project covered study and analysis about the effect of welding current and welding time on welding mild steel to Al alloy sheet and SS to Al alloy metal sheet by using resistance spot welding machine. This will be done by using experiment and the result would be analyzed by using tensile test. Mild steel and Al alloy and SS and Al alloy sheet metals will be selected and being welded by electrical resistance spot welding machine. The electrode forms, material type, cooling water flow rate and electrode force were fixed. The only variable is the welding current and time. The welded sample will expose to tensile shear test in order to determine the joint strength. The tensile speed was remained constant during the test.

1.7 Methodology of Present Research Work

Figure 3 gives the methodology to be followed for the present work.

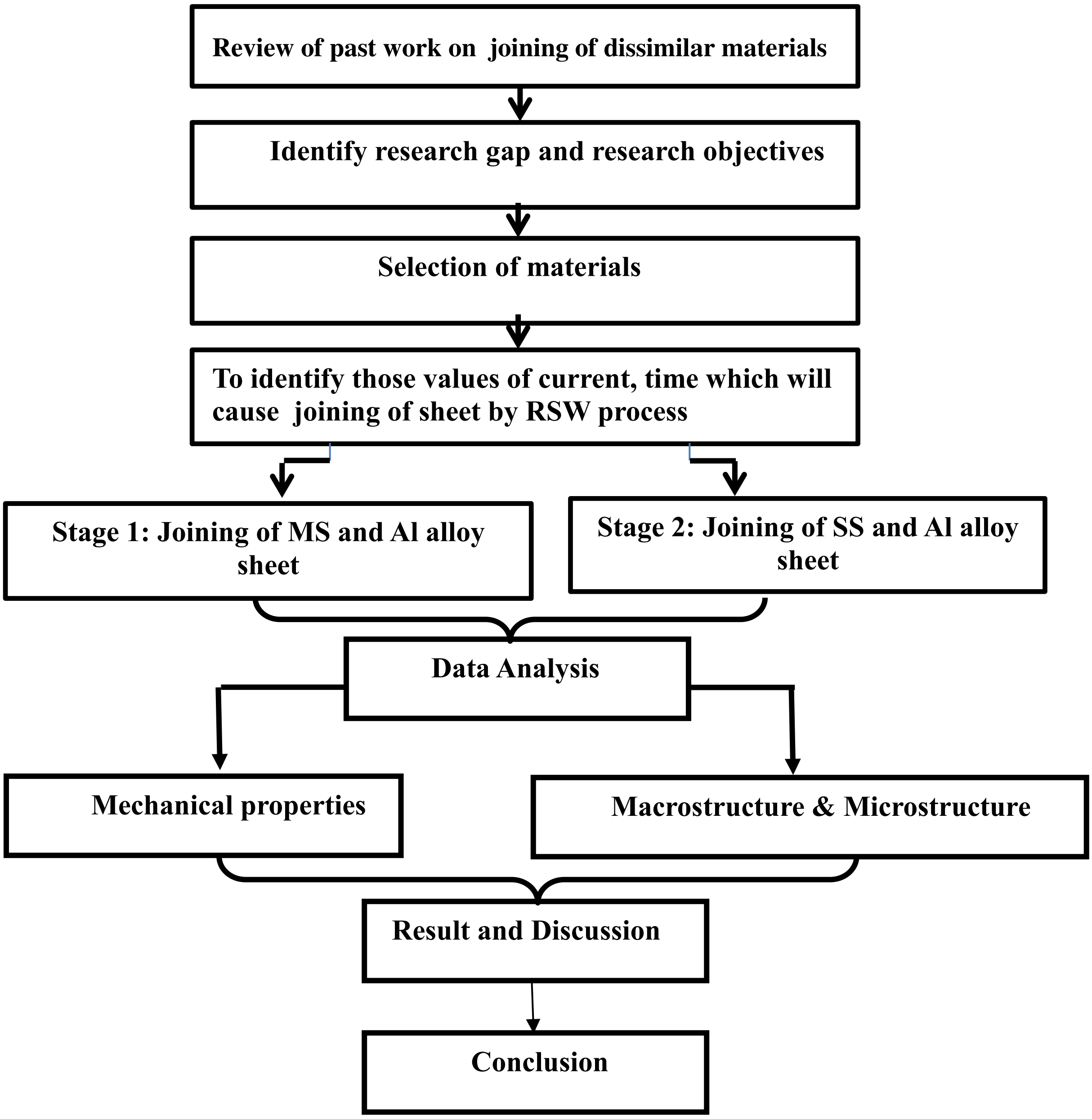

Figure 3: Research methodology used in the present work

Chapter 2 LITERATURE REVIEW

2.1 Background of dissimilar metal joining

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2.2 Background of the Resistance Spot Welding

Resistance spot welding (Figure 4) is one of the oldest of the electric welding processes in use by industry today. The weld is made by a combination of heat, pressure, and time. As the name resistance welding implies, it is the resistance of the material to be welded to current flow that causes a localized heating in the part. The pressure exerted by the tongs and electrode tips, through which the current flows, holds the parts to be welded in intimate contact before, during, and after the welding current time cycle. The required amount of time current flows in the joint is determined by material thickness and type, the amount of current flowing, and the cross-sectional area of the welding tip contact surface.

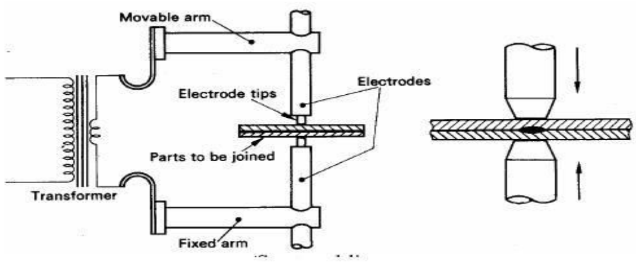


Figure 4: Spot welding [3]

2.3 The Principles of the Electrical Resistance Spot Welding

In the spot welding process, two or three overlapped or stacked stamped components are welded together as a result of the heat created by electrical resistance. This is provided by the work pieces as they are weld together under pressure between two electrodes. Spot welding may be performed manually, robotically or by a dedicated spot welding machine. The similar spot welds having same property can be obtained in high production speeds by controlling welding current, electrode force and weld time automatically. Figure 5 shows resistance occurred in RSW at different part of machine.

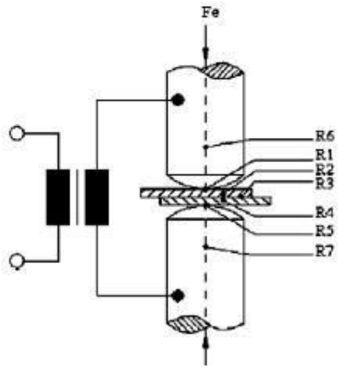


Figure 5: The resistances occurred in resistance spot welding [3]

Fe = Electrode Force

R1 = Upper Specimen Resistance

R2 = Upper Specimen – Upper Electrode contact Resistance

R3 = Upper Specimen – Bottom Specimen contact Resistance

R4 = Bottom Specimen Resistance

R5 = Bottom Specimen – Bottom Electrode contact Resistance

R6 = Upper Electrode Resistance

R7 = Bottom Electrode Resistance

The required low voltage (5–20 V) and high current intensity (2000–15,000 A) for welding process is obtained from transformators and the pressure is obtained from hydraulic, mechanic and pneumatic devices. Figure 6 shows the schematic illustration of resistance spot welding machine.

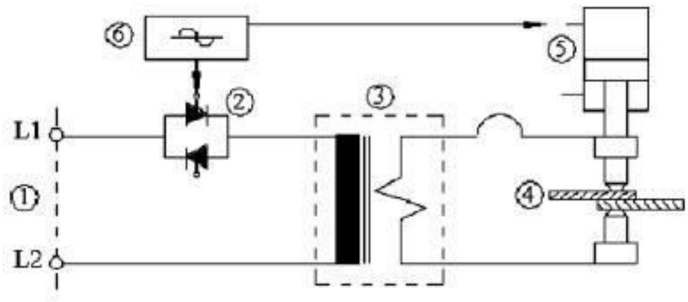


Figure 6: The schematic illustration of electrical resistance spot welding machine [3]

1 – Circuit Connection

2 – Current Amplificator

3 – Transformator

4 – Secondary Circuit

5 – Force Transformation System

6 – Process Control Devices

The welding current must pass from the electrodes through the work. Its continuity is assured by forces applied to the electrodes. The sequence of operation must first develop sufficient heat to raise a confined volume of metal to the molten state. This metal is then allowed to cool while under pressure until it has adequate strength to hold the parts together. The current density and pressure must be such that a nugget is formed, but not so high that molten metal is expelled from the weld zone. The duration of weld current must be sufficiently short to prevent excessive heating of the electrode faces.

The heat required for these resistance welding processes is produced by the resistance of the workpieces to an electric current passing through the material. Because of the short electric current path in the work and limited weld time, relatively high welding currents are required to develop the necessary welding heat. The amount of heat generated depends upon three factors:

(1) The amperage

(2) The resistance of the conductor and

(3) The duration of current.

These three factors affect the heat generated as expressed in the formula

$$\mathbf{Q = I^2 Rt} \qquad \mathbf{2.1}$$

Where Q = heat generated, joules; I = current, amperes; R = resistance of the work, ohms; t = duration of current, seconds.

The resistance is influenced by welding pressure through its effect on contact resistance at the interface between the workpieces. Pieces to be spot welded must be clamped tightly together at the weld location to enable the passage of the current. Everything else being equal, as the electrode force or welding pressure is increased, the amperage will also increase up to some limiting value.

Spot welds are discrete weld locations that look like small circles on the assembled components. They are not continuous, linear welds. Low volume components are usually done manually, whereas high volumes can be achieved best by using robots or dedicated weld equipment. Electrodes play a vital role in these devices. They must have adequate strength and hardness, because weld quality will deteriorate as tip deformation proceeds. In addition, a momentary reduction in electrode force permits the internal metal pressure to rupture unfused metal in weld zone. Internal voids or excessive electrode indentation may result. The welding process is generally performed in less than one second. This time is called as period.

2.4 Welding Parameters

Key welding parameters for RSW are welding current, weld force, welding time. Other factors that can also influence welds include conduction angles and electrode shape and size. Welding parameters for sheet steel RSW has been studied in great detail and has resulted in the standardization for particular material thicknesses. These standards were derived for conventional high strength steels and are constituted by the “Recommended Practices for Evaluating the Resistance Spot Welding Behavior of Automotive Sheet Steel

Materials" [4] and the "Resistance Welding Manual" .The three main parameters which require detailed experimental testing include weld current, weld time, and weld force and these are detailed in the following sections.

2.4.1 Weld current

Welding current is essential for heat generation. Both AC and DC welding processes can be used to provide high current densities which subsequently generate the heat required for fusion. Hofman [5] showed that both types of current provide similar weld qualities; however, the DC system can reduce electrical demands when welding Advanced High- Strength Steels (AHSS), Making DC RSW more efficient. Current profiles for RSW can be altered with the addition of up slopes, down slopes and pulsing. Tawade [6] showed that the addition of up sloping can aid in increasing the window in the welding lobe for AHSS. Khan [7] showed use of pulsing for in-situ tempering of the weldments. It was shown that the mechanical performance of weldments could be altered with the addition of weld pulses, which resulted in hardening or softening of the final weld microstructure. If the current passed during the weld time is too high for the combination of electrode caps in use, their condition and contact area, the weld time, the weld force, and the materials being welded, it will generate more heat and results in excessive indentation, cracks and holes, expulsion/burn through, sticking electrodes, rapid electrode cap wear and "brassy" appearance to weld surface on galvanized steels.

2.4.2 Weld Time

Welding time is directly proportional to the amount of heat being generated. Increased welding time results in increased heat generation. For AC welding supplies the unit time measurements is in cycles (1 Second= 50 cycles). Weld time for DC power supplies is measured in milliseconds. Weld time is normally set depending on the material thickness and coating conditions. The interaction of zinc coating at the interface can require increased welding time. Dickenson [8] showed a 50%-100% increase in time was required to weld zinc coated steel. Increased time allows for the molten zinc to be displaced from the weld area; furthermore, it facilitates nugget growth which enhances the mechanical performance of weldments. However, excessive welding time results in expulsion due to nugget overgrowth. This can introduce weld defects into the weldment, such as voids and excessive indentation, which adversely affect weld performance.

2.4.3 Weld Force

Most RSW processes utilize two distinct welding forces, an initial squeeze followed by an increase to the full welding force. The initial squeeze is required to avoid impacting of the electrodes and aid in material alignment. This is followed by the application of a full force which can be experimentally determined or selected from recommended handbook values.

The welding force can influence the contact resistance of a material. Higher welding forces typically results in better interfacial contact and reduced resistance. This can result in lower heat generation during welding, which needs to be compensated with increase weld time or higher current inputs. In addition, excessive welding force can cause excessive indentation in the work piece

2.5 Range of material for spot welding

Spot welding facilitates if:

- There is sufficient contact resistance sheet-to-sheet for heat to be generated by the heavy current flow.
- The heat is not conducted away too rapidly from the point at which welding is desired.

Therefore, that good conductor of heat and electricity such as copper, aluminium or silver present greater difficulties than do iron and steel, which are moderate conductors in comparison.

2.5.1 Spot weld of ferrous metals

2.5.1.1 Mild steel and iron

If the material whether sheet or rolled sections, is clean, little difficulty should be experienced. Low-carbon steel can be satisfactorily resistance welded using a wide range of time, current, and electrode force parameters. Carbon content has the greatest effect on weldability of steels; weld hardness increases rapidly with a small rise in carbon content. To obtain acceptable weld performance, carbon content should be kept below 0.10% + 0.3t, where ‘t’ is the sheet thickness in inches. For materials above this range, post weld tempering may be necessary.

2.5.1.2 Hardenable steels(Excluding high-speed steels)

Only in thin material, the cooling rate from the welding temperature is exceedingly rapid, since the water-cooled electrodes conduct away much heat during the after-weld pressure period. The result of such a high cooling rate is an intense hardening effect on the weld nugget and its immediate surroundings, and such an effect might cause the welds to be brittle and unserviceable. To overcome this trouble with small parts, they are charged into an annealing furnace after welding, so that they are ‘’let down’’ gradually.

2.5.1.3 High speed steels

The welding of small pieces of high-speed steels to tool shanks for use in lathes, planers, etc., has received some attention, but it should be pointed out that in this respect spot welding is in nature of a makeshift, since modern electrically butt-welded tools are available with the advantages of cheapness and efficiency.

2.5.1.4 Stainless steels

These steels are divided into four groups:

1. Ferritic (stainless irons, etc.)
2. Martensitic (cuttery and similar quantities)
3. Austenitic (non-stabilized)
4. Austenitic (stabilized)

These groups behave differently with respect to spot welding, but it is doubtful whether very much spot welding is carried out in Groups 1 and 2.

- Group 1 behaves as mild steel: pressure should be kept on a little longer after welding, however.
- Group 2 has pronounced air hardening qualities and should therefore be treated as hardenable steels.
- Group 3 includes the well known 18/8 variety of stainless steel. Since this particular quality is subject to the phenomenon known as weld

decay, a machine of high capacity is to be preferred so that the heating and eventual cooling can take place in the shortest possible time.

- Group 4 has additional elements such as titanium and niobium, the presence of which tends to inhibit weld decay. Such steels, therefore, may be spot welded in the polished condition, and require no further treatment other than a little buffing to remove handling marks.

The short welding period is necessary in stainless steels to prevent carbide precipitation when the carbon content is high enough to permit it.

2.5.1.5 Zinc-coated steels

The present trend in the automotive industry toward the use of larger amounts of zinc-coated steels in assemblies demands that certain strict guidelines regarding the selection of equipment and the choice of welding schedules are rigidly followed. The available welding ranges for zinc-iron and zinc-nickel coated steels are similar to those for uncoated mild steel although displaced toward slightly higher currents. When these steels are coated, it is necessary that the film thickness not exceed 1 to 1.5 μm in order to facilitate breakthrough of the film to enable current flow between the welding electrodes at the low secondary voltages.

2.5.2 Non-ferrous materials

2.5.2.1 Aluminium, Al-Magnesium and Al-Manganese alloys

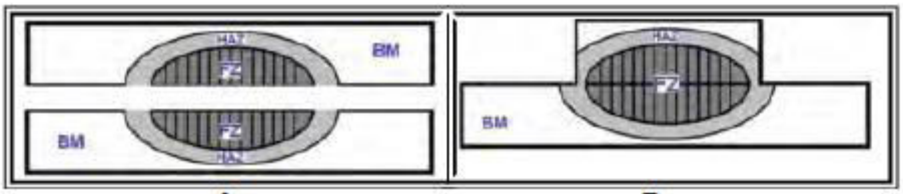
All of these may be spot welded satisfactorily if the insulating skin of oxide is removed and the machine has a sufficiently high capacity since aluminium is a good conductor of heat and electricity and therefore a ''difficult'' metal. In addition, the narrow plastic range between softening and melting means that welding pressures, time and current need to be closely controlled. Moreover, careful control of the electrode force is necessary to minimize the probability of cracking or porosity in the weld.

2.5.3 Dissimilar materials

The dissimilar materials are harder to weld because of their different melting temperatures, thermal and electrical properties, plastic ranges and the alloys formed in the weld region. However, the majority of the combinations of ductile metals and alloys can be spot welded. Some, like copper to aluminium, and aluminum to magnesium, form alloys having little strength. Others, such as zinc and some of the high-chromium alloys, experience grain growth even during a short welding period. The combination like low carbon steel to stainless steel is also studied by some researchers.

2.6 Spot weld failure modes

Failure of spot welds may affect the vehicle's stiffness and noise, vibration, and harshness (NVH) performance on a global level [9]. Therefore, the failure characteristics of spot welds are very important parameters for the automotive industry. Failure mode of resistance spot welds (RSWs) is a qualitative measure of mechanical properties. Figure 7 shows the schematic representation of the main fracture mode during mechanical testing of the spot welds. Basically, spot welds can fail in two distinct modes described as follows [10, 11]: Interfacial failure (IF) mode in which the fracture propagates through the fusion zone FZ (Figure 7 A). It is believed that this failure mode has a detrimental effect on the crashworthiness of the vehicles. Pullout failure (PF) mode in which the failure occurs via withdrawal of the weld nugget from one sheet. In this mode, fracture may initiate in the base metal (BM), heat-affected zone (HAZ), or HAZ/FZ (Figure 7 B) depending on the metallurgical and geometrical characteristics of the weld zone and the loading conditions. Generally, the PF mode exhibits the most satisfactory mechanical properties. Failure mode under which RSWs fail is an indicator of their load-bearing capacity and energy absorption capability. Spot welds that fail in the nugget pullout mode provide higher peak loads and energy absorption levels than spot welds that fail in the interfacial fracture one. To ensure reliability of spot welds during vehicle lifetime, process parameters should be adjusted so that the pullout failure mode is guaranteed. The transition from IF mode to PF mode is generally related to the increase in the size of the FZ above a minimum value. The minimum FZ size is a function of sheet thickness, BM/HAZ/FZ material properties, and loading conditions. Due to its significant impact on joint reliability, the failure mode has been an interesting issue for some recent studies.



A B

Figure 7: Schematic representation of typical failure modes during mechanical testing: A- Interfacial; B - pull-out [11]

Vanden Bossche [12] had attempted to analyze the state of stress around the spot weld nugget to establish weldability criteria. A lap shear sample joint was used for the investigation. Two different failure modes for the spot welded joint were considered for this study, namely the interfacial mode and the nugget pull out mode. The interfacial mode was designated to be the failure in the spot weld nugget. The nugget pull out mode was assumed for the failure occurrences near the heat affected zone on the sheet metal coupon. For the nugget pull out mode the analysis procedure involved the equilibrium study of the assumed state of stresses caused by the normal and shear loads acting around the nugget on the sheet metal coupon. For the interfacial failure the analysis was done from the point of view of the formation of a plastic hinge at the weld nugget. For both stress states, the equivalent stress was calculated using the distortion energy theory. To determine the transition among the failure modes, the critical nugget diameter to thickness ratio was determined utilizing the inequality condition.

Later Nakano[13] extended this study to investigate the strain rate effect on the failure of the spot welded joint. In this study the finite element simulation was undertaken along with the analytical approach. It was reported that the failure mode of the spot weld joint was not affected for the account of the strain rate effect. Failures of the welds were detected through the force displacement curves obtained from these experimental results together with the optical and Scanning Electron Microscopic (SEM) images of the weld nugget. Most of the specimens for the tensile shear coupon and the coach peel coupon failed in the nugget pull out mode of failure (which can be referred to as the material failure). But the causes of the initiations of failure in these two cases were different. The reason of failure for the tensile shear specimens was due to localized necking near the boundary of the base metal and heat affected zone. However the nugget pull out failure in the coach peel specimen was initiated by micro void coalescence.

2.7 Typical defect due to spot welding

A defect inversely affects the quality of a spot weld. Hence their reasons and their appearances should be understood carefully to adjust the spot welding process

Table 1: Spot weld issues and their possible causes [14] S: Strong relationship W: Weak relationship

	Weld issues							
No.	**Possible Causes**	**Missing weld**	**Weld undersize**	**Stuck weld**	**Indentation**	**Burn Throgh**	**Holes & cracks**	**Weld non**
1	Weld current low	S	S	S				S
2	Weld current high				S	S	S	
3	Weld current short	S		W				S
4	Weld current long				S	W		

parameters in order to avoid them. The weld issues and their possible causes are given briefly in Table 1

2.8 Summary

Many researchers investigated resistance spot welding of similar metal. There are many established data set up for similar metal like low carbon steel, stainless steel or non-ferrous steel. But it is very important and interesting to study resistance spot welding of dissimilar metals. Above all discussion is shown different properties and characteristics of similar metal. Here we try to find different parametric effect on dissimilar spot welded Mild steel to Al alloy and stainless steel to Al alloy. Mechanical properties of sheet metal promises improved crash performance and reductions in weight for automotive applications. The RSW process provides a quick and effective method for spot welding sheet steel and has been largely adapted in the automotive industry. The various parameters involved in RSW can influence the weldability and mechanical performance of weldments. Some key parameters include:

1) Welding Force
2) Welding Time
3) Welding Current

Much of the literature can explain the effects of zinc coatings, electrode degradation and the weldability of traditional AHSS and other material. In depth examination and comparison of RSW Mild steel to Al alloy and stainless steel to Al alloy as dissimilar metal is yet to be conducted. The majority of studies conducted on dissimilar metals are limited to process optimization. In turn, minimal work has been done to understand the metallurgical aspect of RSW dissimilar metals resistance welding. Compared to similar welds, weld nugget of dissimilar Mild steel (MS) / Al alloy RSWs has two distinct features: Asymmetrical shape (FZ size of Al alloy side is greater than that of for mild steel side due to its higher resistivity) and shifting of final solidification line from sheet/sheet interface into the Al alloy side. As a direct result, the mechanical performance of dissimilar MS/Al alloy is determined by FZ size of MS side. In joint dissimilar RSWs of Mild steel to Al alloy, microstructure and hardness of the fusion zone which are controlled by dilution and fusion zone size of MS steel side mainly govern the failure mode. By increase in welding current, increasing fusion zone size coupled with the formation of IMC layer which will lead to transition from interfacial to pullout failure mode. The hardness of the fusion zone which is governed by the dilution between two base metals. This thesis examines the metallurgical and mechanical properties of RSW dissimilar metals. From above discussion, it was clear that the spot weld nugget diameter is the most critical parameter to determine the mode of failure for the spot welded joint. Detailed analysis of microstructure and mechanical performance of welded dissimilar metals is conducted to attain an in depth understanding of phase transformation caused by weld thermal cycles. Finally, this is a comparative study was done on spot Mild steel to Al alloy and stainless steel to Al alloy RSW process.

Chapter 3 EXPERIMENTAL PROCEDURE

3.1 Material Selection:

Materials were collected from the local market of indore. The surface finish should be smooth, with only fine tool marks, and should be the same as the reference sample.

3.1.1 Aluminium 6061 (Al-Mg-Si Alloys)

There are many types of aluminium. The aluminium chosen for this research are aluminium 6061. Aluminium 6061 is in the 6xxx series and has good weldability. The 6xxx alloys have moderately higher strength coupled with excellent corrosion resistance. It also have a higher strength and broad use in

welded structural, such as truck and marine frames and railroad cars and pipelines. The aluminium melting point is 660 °C.

The characteristic of 6xxx series materials are:

- Heat treatable
- High corrosion resistance, excellent extrudability, moderate strength
- Typical ultimate tensile strength range is 124-400 MPa.
- Building and construction, highway, automotive, marine application

3.1.2 Mild steel (HR1)

MS (HR1) is used in steel frame buildings, ship building, automobile bodies, sheet metal applications, heavy machinery industry because it is so versatile, cost effective and easy to manufacture.

The characteristic of MS (HR1) materials are:

- Corrosive in nature
- Strength & hardenability is less
- Prone to pitting corrosion
- Cheap

3.1.3. Stainless Steel (316L)

SS316L is overwhelmingly used in marine exterior trim, food and pharmaceutical processing equipment, industrial equipment that handles the corrosive process chemicals used to produce inks, photographic chemicals, paper, textiles, bleaches and rubber.

The characteristic of SS316L materials are:

- Highly corrosion & heat resistant due to Ni
- Improved hardenability & strength due to Cr
- Increased resistance to pitting corrosion due to Mo
- Costly

The mechanical properties of the selected materials are shown in Table 2.

The chemical composition of the selected materials is shown in Table 3.

Table 2: Mechanical properties of the selected Sheet metals [15]

Mechanical Properties	Al alloy 6061	MS	SS316L
Ultimate Tensile Strength (MPa)	310	440	480
Young's Modulus (MPa)	69×10^3	205×10^3	193×10^3
Density (kg/m3)	2700	7850	8000
Coefficient of thermal expansion (m/m°C)	23.6×10^{-6}		16.0×10^{-6}
Thermal Conductiviy (W/mk)	167		16.0
Specific Heat (kJ/kgk)		0.5108	0.5000
Melting Point (°C)	582-652	1350-1530	1370-1400

Table 3: Chemical composition of the selected Sheet metals [15]

Component (wt %)	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Al alloy 6061	95.8-98.6	0.04-0.35	0.15-0.4	Max 0.7	0.8-1.2	0.15	0.4-0.8	Max 0.15	Max 0.25

Component (wt %)	C	Cr	Mn	P	S	Si	Mo	Ni	Fe
SS316L	0.021	17.02	1.51	0.026	0.01	0.415	2.16	10.21	67.87
MS (HR1)	0.15		0.60	0.05	0.035				Balance

3.2 Specimen dimension:

Material thickness is around 2 mm. the test coupon were cut as per guideline specified for this range of thickness in 'recommended practice for test methods for evaluating the resistance spot welding behavior of automotive sheet steel materials (ANSI/AWS/SAE) all of the steel sheets were of the same batch for their respective thickness. Figure 8 shows standard dimension of tensile test specimen.

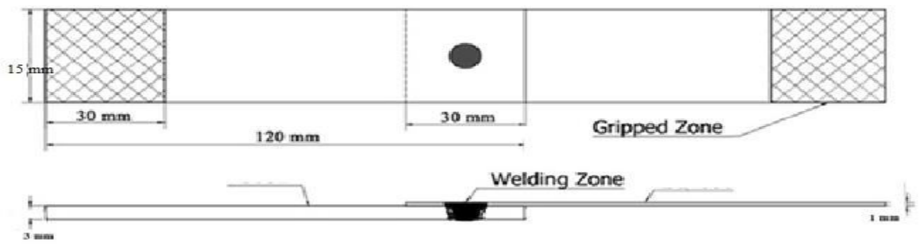


Figure 8: Standard dimension of tensile test specimen as per ANSI/AWS/SAE.

3.3 Welding equipment: Resistance spot welding set up:

The resistance spot welding samples are produced by using manual operated single phase resistance spot welding machine.

Figure 9: Resistance Spot Welding Machine

Figure 9 Show the resistance spot welding machine. Welding was conducted using rod type electrode with 7 mm face diameter. Cooling water flows during the welding process.

3.4 Determination of nugget diameter of spot welds:

The coupons were checked after spot welding to determine the weld nugget diameter. The checking process was conducted by digital Vernier caliper. For parameter optimization, the most crucial dimension to be determined is studying the nugget diameter of spot welded coupons and it plays the vital role in determining the mode of failure of the joint. Several standards are set to determine the nugget dimension for a particular sheet metal thickness. Several researchers have also proposed mathematical equation for the calculation of these standards and calculation were based upon the lap shear coupon configuration. American welding society (AWS), American national standards institute (ANSI) and Society of Automotive Engineers (SAE) jointly recommended the size of the spot weld nugget diameter for the steel according to the following equation

$$\mathbf{d = 4\sqrt{t}} \qquad \mathbf{3.1}$$

Where d and t is the nugget diameter and sheet thickness in mm respectively.

3.5 Mechanical Testing

Several mechanical testing such as tensile test, micro hardness tests were performed to find out the properties of the resistance spot welded dissimilar metal.

3.6.1 Tensile Share test:

Joint mechanical properties at different process parameters were evaluated by measuring the maximum load to failure during overlap tensile shear testing. Care was taken to maintain coplanar alignment during mechanical testing. This test consists of pulling in tension to destruction on tinius universal testing machine (Figure 10).

Figure 10: Universal testing machine.

Dimension of the tensile specimen is follow AWS standard.

3.6.2 Hardness Test:

To conduct the micro hardness test, a Vickers hardness testing machine (figure 11) is used. The basic equation to measure the hardness of any material is as follows

$$\mathbf{HV=1.854(F/d^2)} \qquad \mathbf{3.2}$$

Where HV is the hardness value, F is the force and d is the average diagonal distance of the indentation in mm. The test set up is shown in the Figure 11. Test load used in experiment is 100 grams.

Figure 11: Hardness testing machine

3.7 Metallographic Examination:

Sample preparation is an essential part of microscopy and there are many techniques that can be used. The approaches very commonly used to prepare specimens for analysis are as follows: The sample needs to be cut to size using one of the slicing methods. The cut sample is either set in a mold or mounted externally on a polishing mount. This step is followed by a series of coarser to finer grinding on SiC grit paper. For optical microscopy and SEM, subsequent fine polish is done using alumina suspension. Polished samples are then cleaned thoroughly and etched chemically or thermally to reveal surface contrast. During Sample preparation all welding dissimilar metals are cut through longitudinal direction of the weld nugget. Then all cross section are etched by appropriate etching reagent to distinguished the different phase in the fusion zone, heat affected zone and thermo mechanically affected zone of resistance spot welded dissimilar metal. Here we are using Keller's etching reagent.

3.7.1 Microscopy:

Optical microscope was used to observed metallographic samples. Here we use Dewinter microscope (Figure 12) for metallographic observation and imaging of the structure.

Figure 12: Optical microscope

3.7.2. Scanning Electron Image Analysis

The SEM can automatically perform image analysis and with the advanced of chemical characterization using Energy Dispersive X-ray (EDX) detector. . Here we use Supra Field Emission Scanning Electron Microscope (Figure 13). Dilution of chemical component like chromium, nickel etc. in the fusion zone of dissimilar welded metal also analysis by EDX technique.

Operating condition:

1. Specimen was placed on the stage of the scanning electron microscope so that the specimen surface is perpendicular to the optical axis.
2. Images were examined by using different magnifications.
3. Images were chemically micro-analyzed by use of energy dispersive x-ray detector.

Figure 13: Field Emission Scanning Electron Microscope

Chapter 4 RESULTS AND DISCUSSION PART 1

4.1 Macro structural observation

Macroscopic view of the asymmetrical weld nuggets from dissimilar metal spot welding is shown in Figure 14 a. It is clear that weld nugget of the dissimilar metal welded coupon is of a symmetrical shape and also found that final solidification line shift from sheet/sheet interface in to the aluminium side (Figure 14 b).

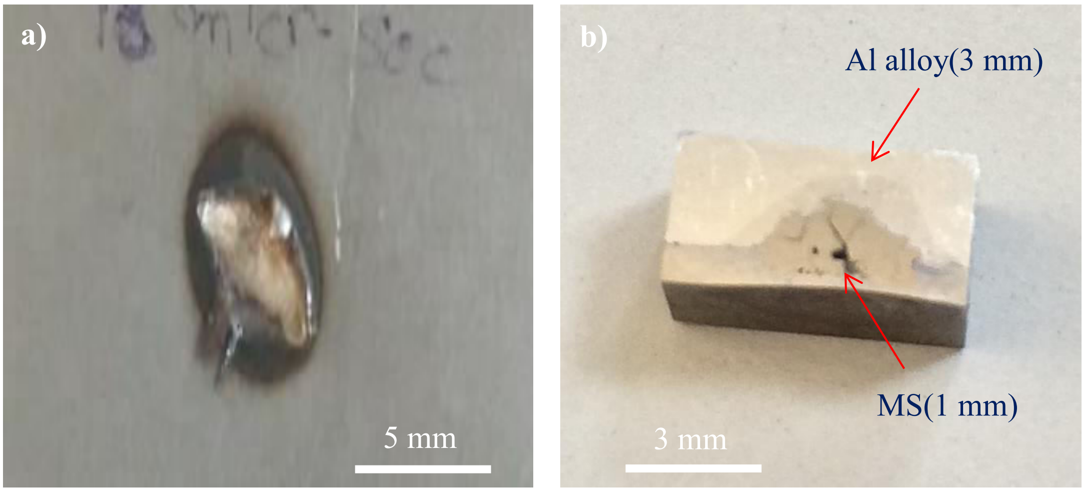


Figure 14 : Asymmetrical weld nuggets from dissimilar metal spot welding a) Front view of welded joint b) Cross section view of welded joint

The fusion zone size and penetration depth of the aluminium is higher than mild steel side. It can be seen that welding parameters have an important role on fusion zone size. An increase in welding current increases weld nugget size significantly at constant weld time but with respect to weld time no significant change occurs in fusion zone size, both of these discuses in section 4.2. Different electrical resistance and thermal conductivity is found at different metal sheets and this is the main cause of asymmetrical weld nugget. Thermal expansion coefficient is another property of the material which affect on welding property. So the different property of electrical resistivity, thermal conductivity and thermal expansion coefficient is the main cause of asymmetrical weld nugget. The Thermal conductivity coefficients are higher in aluminium alloy (154 $Wm^{-1}K^{-1}$) as compare to mild steel (52 $Wm^{-1}K^{-1}$). Thermal expansion coefficient of Aluminium alloy is 23.4×10^{-6} m/m°C where as Mild steel have lower thermal expansion coefficient 9.9×10^{-6} m/m°C. Technically this phenomenon is called heat imbalance. This heat imbalance makes asymmetrical weld nugget. This result was found by different researchers. Monsouri, Majid P found that compared to similar welds, weld nugget of dissimilar Al alloy/Mild steel RSWs has two distinct feature: Asymmetrical shape (fusion zone of aluminium alloy side is greater than that of for mild steel side due to its higher resistivity) and shifting of the final solidification line from sheet/sheet interface to the aluminium side.

4.2 Weld nugget dimension:

Resistance spot welding was done by using resistance heating and application of force without using filler metal. Dissimilar metals, Aluminium alloy and mild steel are welded, so the weld nugget was asymmetrical in shape. The coupons were checked after spot welding to determine the weld nugget diameter (Figure 15). The checking process was conducted by digital Vernier caliper.

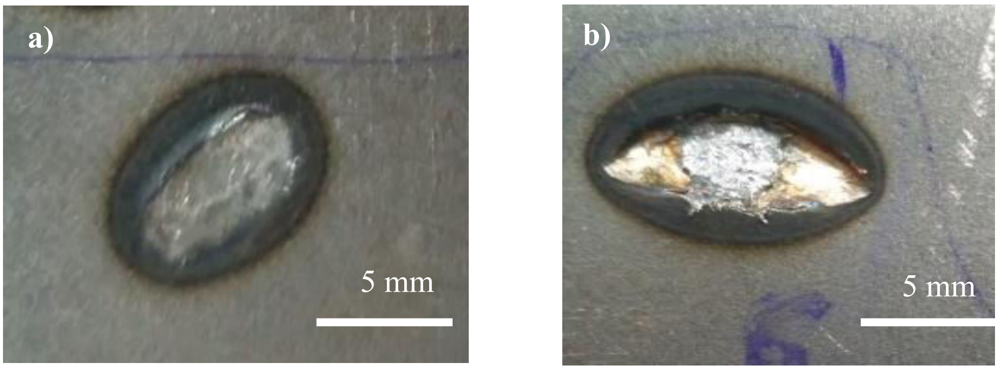
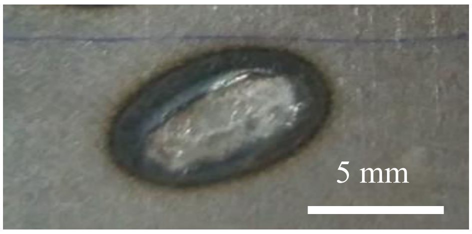


Figure 15: Measuring of weld nugget (a) Sample welded at 4 kA and 18 millisecond (b) Sample Sample welded at 6 kA and 18 millisecond

Here we found different size of the weld nugget at different welding parameter. These results are shown in the table 4 and 5.Figure 16 and figure 17 show macroscopic view of nugget at different parameters.

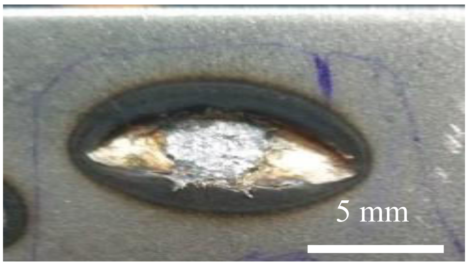
Table 4: Weld nugget dimension at 18 milliseconds Cycle time, but different weld current

Constant weld Time: 18 milliseconds		
Sample No	**Current kA**	**Nugget Size mm**
Sample 1	**4**	**4.93**
Sample 2	**5**	**6.36**
Sample 3	**6**	**7.78**



Sample 1

Sample 2

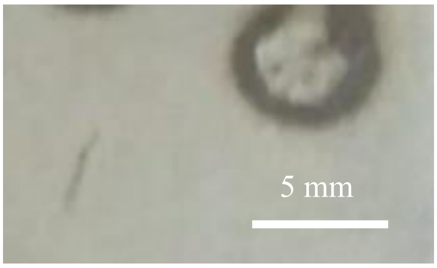


Sample 3

Figure 16: Effect of welding current at constant weld time in macroscopic view

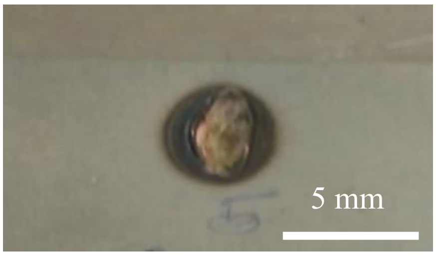
Table 5: Weld nugget dimension at constant welding current , but different weld cycle time

Constant welding Current : 5 kA		
Sample No	**Weld cycle time milliseconds**	**Nugget Size mm**
Sample 4	**15**	**5.89**
Sample 5	**18**	**6.36**
Sample 6	**21**	**7.25**



Sample 4

Sample 5



Sample 6

Figure 17: Effect of welding cycle time at constant weld current in macroscopic view

From all of these figures we can draw a final discussion. From sample 1 to 3 in figure 16, we found that at constant weld cycle time an increase in weld current increases the weld nugget size. From sample 4 to 6 in figure 17, we found that at constant welding current weld cycle time have same effect. Weld nugget growth as a function of welding current and welding time occurs at four stages, as follow:

I. Incubation stage: no melting occurs and weld nugget is not formed,
II. Nugget formation and rapid nugget growth stage
III. Slow nugget growth rate stage, and
IV. Expulsion

Indeed, weld nugget growth rate is affected by two phenomena: increase in electric resistance due to increasing the metals temperature and decrease in electric resistance due weld nugget formation and growth. At early stages of weld growth, which weld nugget is small, resistance increase due to heating material (because of welding current or welding cycle) overcomes resistance decrease weld nugget growth. However, increasing weld nugget diameter increases the effect of resistance decrease caused by weld nugget growth. Therefore, weld nugget growth rate decreases by further increase in welding current or welding cycle time.

4.3 Micro structural observation:

Figure 18 shows the three different zones of the welded joint. These are

1. Base metal (BM) which remained unaffected during the welding process.
2. Heat affected zone (HAZ) which experienced solid state microstructural alteration during thermal cycle of welding.
3. Fusion zone (FZ) or weld nugget which experienced melting and solidification during thermal cycle of welding.

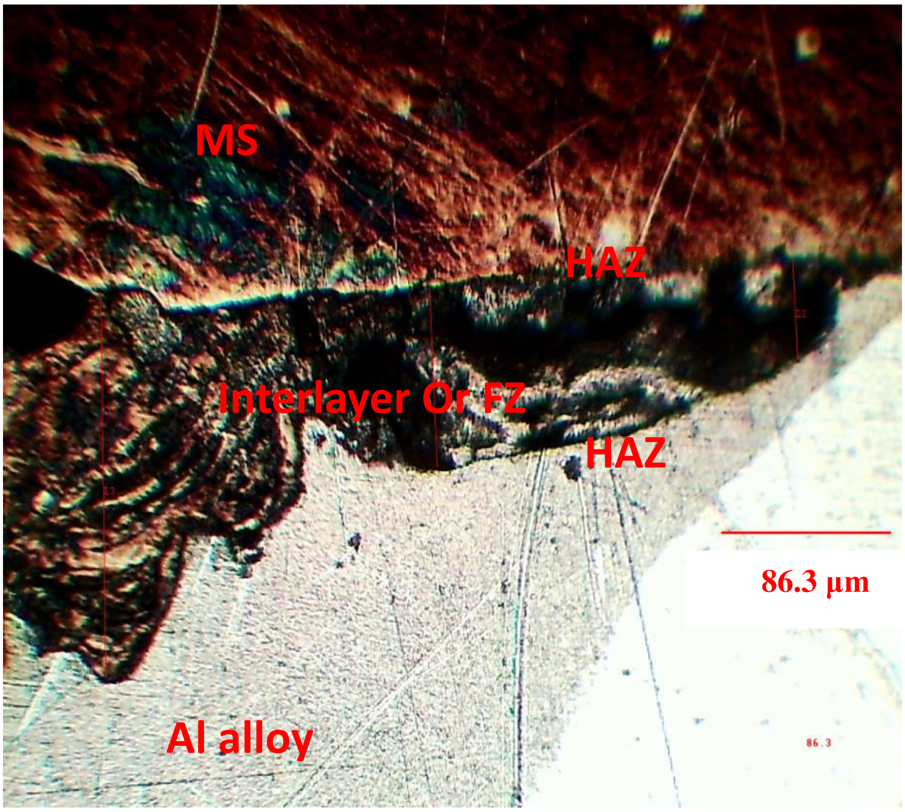


Figure 18: Weld at 6 kA and 18 milliseconds weld time

After observing different microstructure images (figure 19 to 23) of welded sample at different parameter we can conclude that on increases the welding parameter like welding current and welding time reaction layer thickness increases. The formation of brittle reaction layer occur at the welding interface due to large difference in physical and thermal properties between aluminum alloy and mild steel. According to Fe-Al binary phase diagram and intermetallic compound species analysis of aluminum and mild steel, the reaction layer product on the side of aluminum is FeAl3 and the reaction layer product on the side of steel is Fe2Al5.

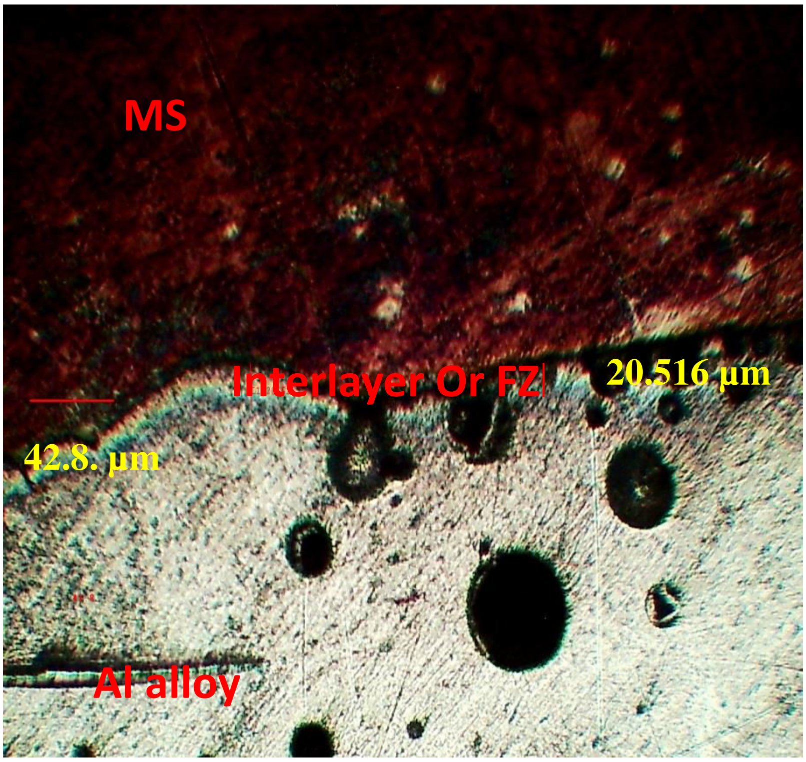


Figure 19: Weld at 4 kA and 18 milliseconds weld time reaction layer thickness approx. 20.516 micron

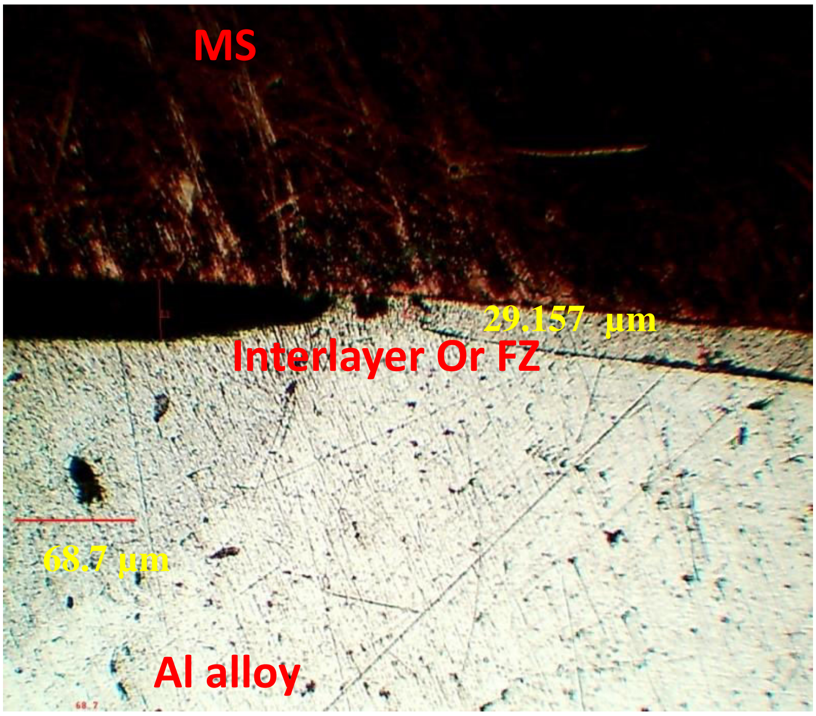


Figure 20: Weld at 5 kA and 18 milliseconds weld time reaction layer thickness approx. 29.157 micron

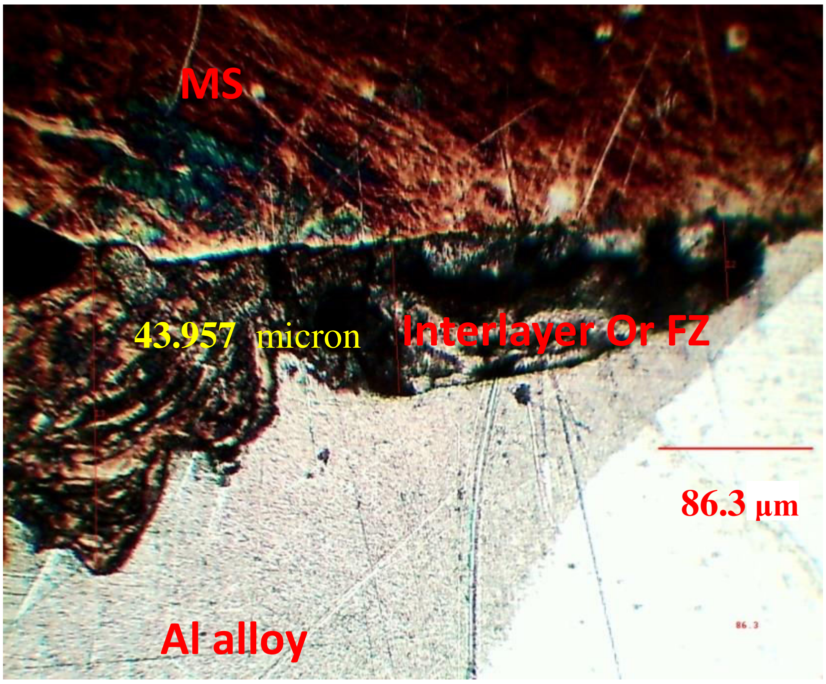


Figure 21: Weld at 6 kA and 18 milliseconds weld time reaction layer thickness approx. 43.957 micron

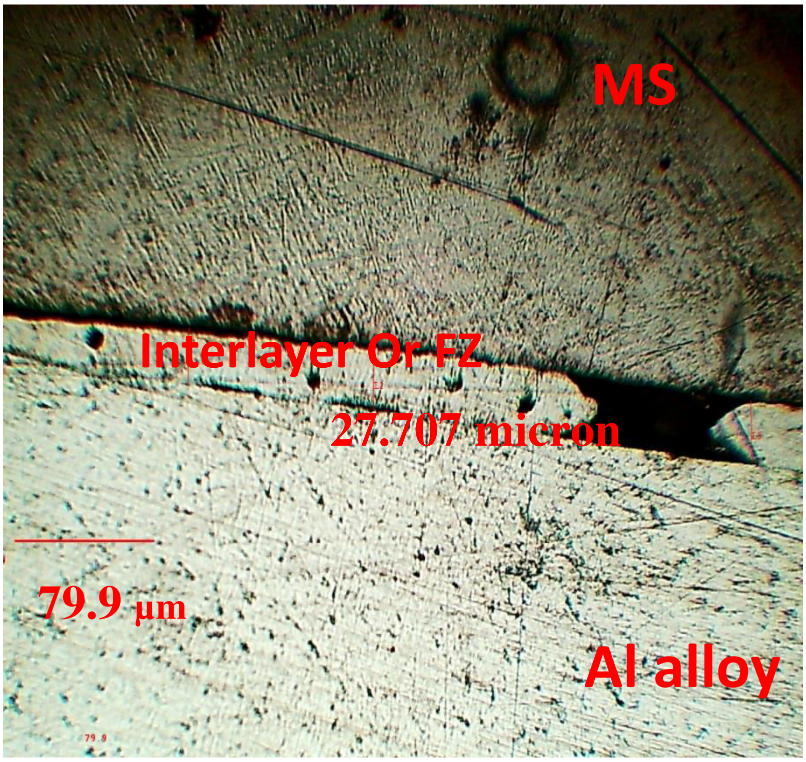


Figure 22: Weld at 5 kA and 15 milliseconds weld time reaction layer thickness approx. 27.707 micron

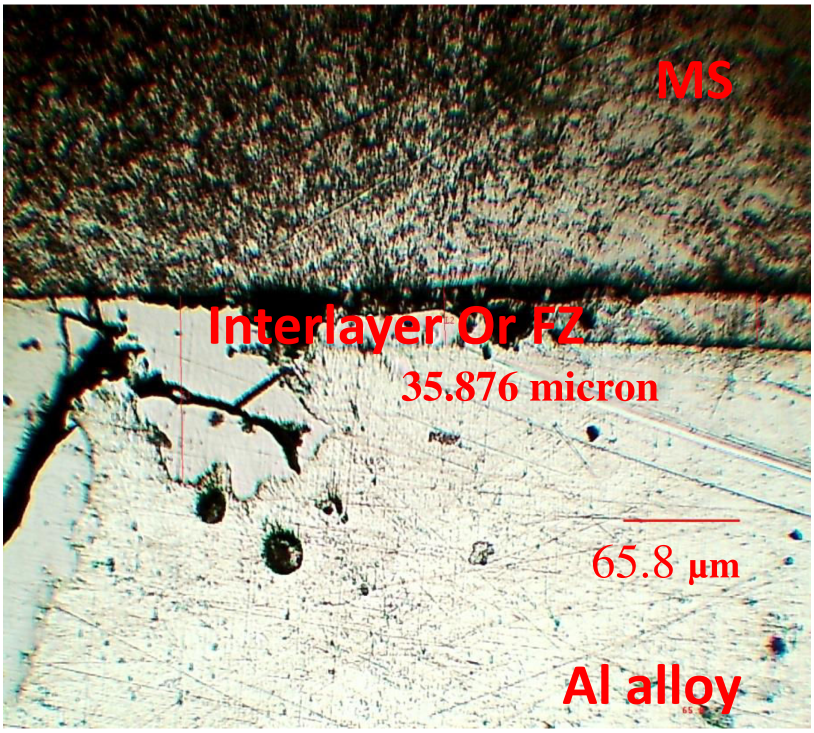


Figure 23: Weld at 5 kA and 21 milliseconds weld time reaction layer thickness approx. 35.876 micron

4.4 Tensile Properties:

A shear test was conducted and the schematic of tensile specimens are shown in Figure 24. Results show (Figure 25 to 36) that at constant welding cycle time an increase in welding current increases the maximum tensile load. At lower current this value is very low which is not suitable for working condition .Figure 28 show at 5 kA welding current and 18 milliseconds welding time nugget has the maximum tensile strength .Increasing welding time and welding current to some extent, increase Tensile strength further after it decreased. The maximum tensile shear load reached 465 N at 5 kA welding current and 18 milliseconds weld time. This is because the tensile shear load of the joint is influenced by nugget size and thickness of the intermetallic compound formed at the welding interface. In the low current range, the impact of nugget size on the tensile shear load is greater than the latter, whereas the thickness of intermetallic compound plays a major role in the high current range.

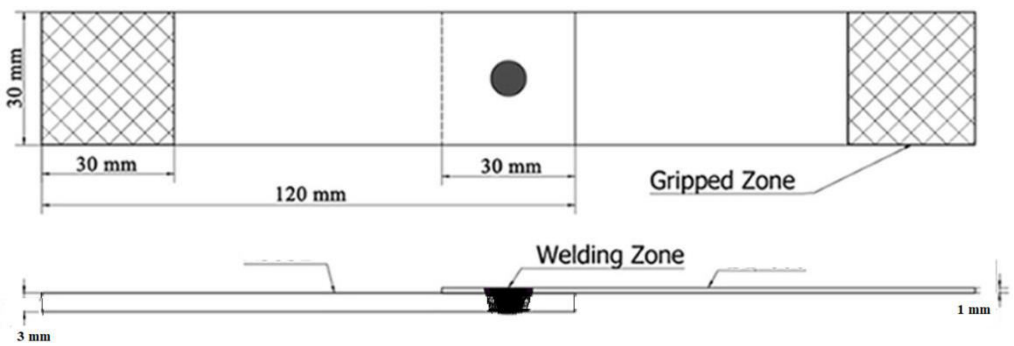


Figure 24: Schematic diagram of a tensile shear testing sample.

4.4.1 Tensile load for Fracture of Al-MS Weld joint at different parameter

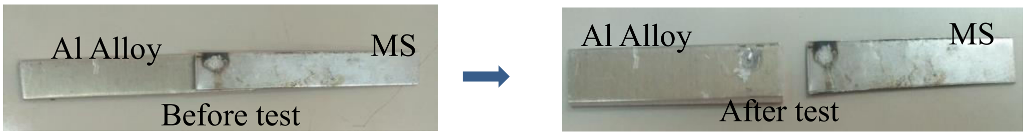
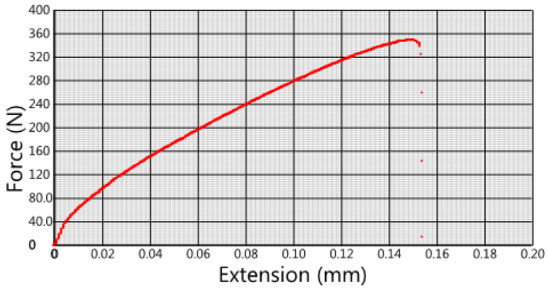


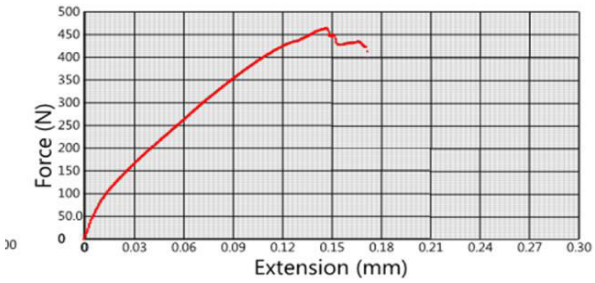
Figure 25: Tensile test specimen of mild steel and aluminium alloy sample spot welded at 4 kA for 18 milliseconds



BREAK FORCE = 350 N

Figure 26: Force extension diagram of mild steel and aluminium alloy sample spot welded at 4 kA for 18 milliseconds

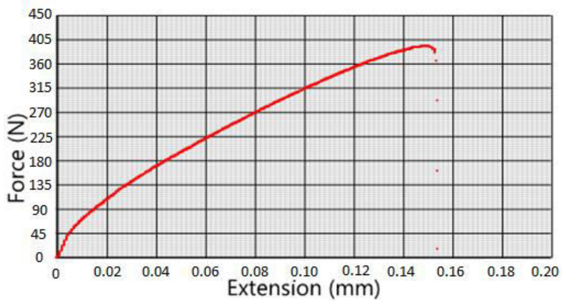
Figure 27: Tensile test specimen of mild steel and aluminium alloy sample spot welded at 5 kA for 18 milliseconds



BREAK FORCE = 465 N

Figure 28: Force extension diagram of mild steel and aluminium alloy sample spot welded at 5 kA for 18 milliseconds

Figure 29: Tensile test specimen of mild steel and aluminium alloy sample spot welded at 6 kA for milliseconds



BREAK FORCE = 403 N

Figure 30: Force extension diagram of mild steel and aluminium alloy sample spot welded at 6 kA for 18 milliseconds

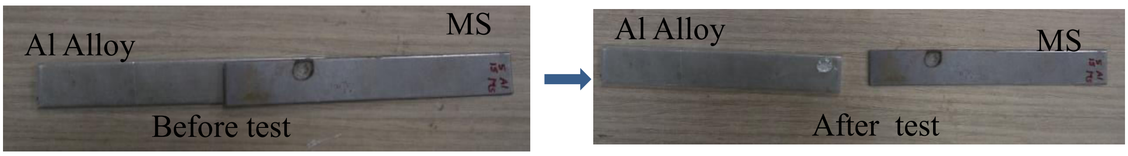
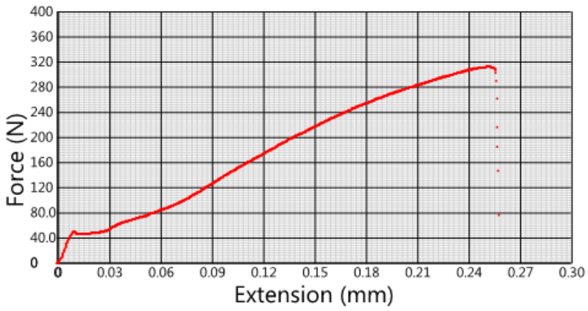


Figure 31: Tensile test specimen of mild steel and aluminium alloy sample spot welded at 5 kA for 15 milliseconds



BREAK FORCE = 313 N

Figure 32: Force extension diagram of mild steel and aluminium alloy sample spot welded at 5 kA for 15 milliseconds

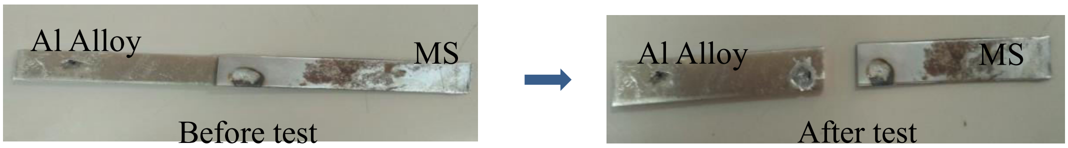
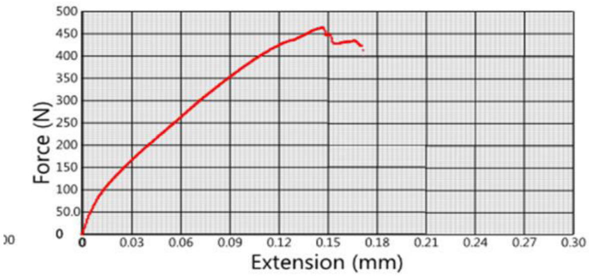


Figure 33: Tensile test specimen of mild steel and aluminium alloy sample spot welded at 5 kA for 18 milliseconds



BREAK FORCE = 465 N

Figure 34: Force extension diagram of mild steel and aluminium alloy sample spot welded at 5 kA for 18 milliseconds

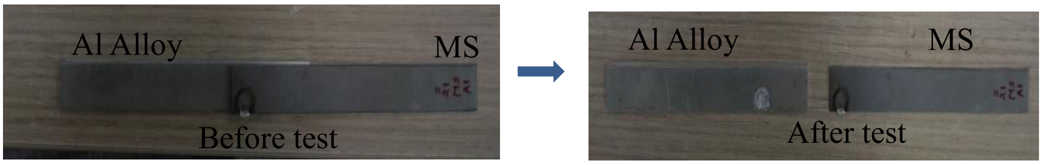
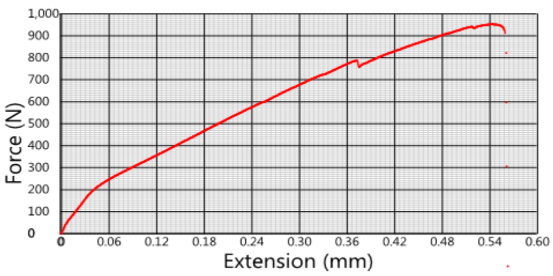


Figure 35: Tensile test specimen of mild steel and aluminium alloy sample spot welded at 5 kA for 21 milliseconds



BREAK FORCE =953 N

Figure 36: Force extension diagram of mild steel and aluminium alloy sample spot welded at 5 kA for 21 milliseconds

4.5 Hardness measurement

The hardness test was performed in a micro hardness testing machine. The detail test setup is given in previous chapter. Hardness value is measured in different section (base metal and at interlayer) around the weld nugget. From result we can say that hardness value is a function of welding current and welding time. From result it can be seen that hardness of the interlayer increases (Table 7) as the Welding current increase, it is because of the formation of thick brittle intermetallic layer at high temperature. Figure 37 shows micro hardness test indentation. Table 6 and 7 show value of hardness at different zone.

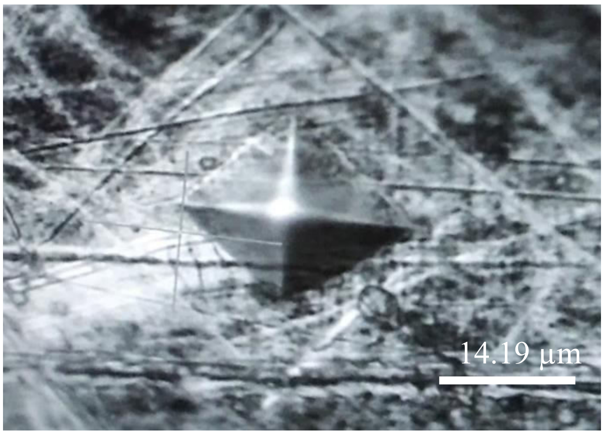


Figure 37: Micro hardness test indentation

Table 6: Hardness value of a sample weld at 5 kA and 18 milliseconds weld time at different zone

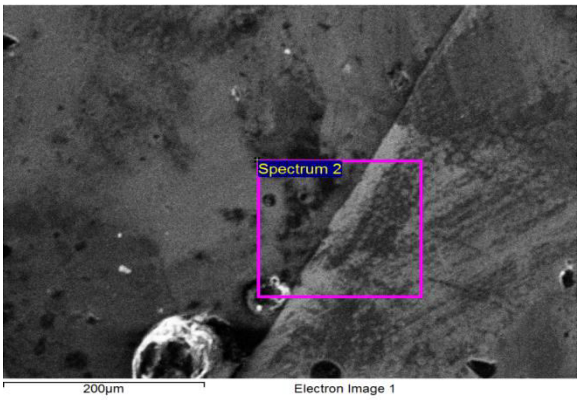
Zone	Hardness value
MS	265±10 HV
Interlayer	218±10 HV
Al alloy	86±10 HV

Table 7: Hardness value of a sample weld at 6 kA and 18 milliseconds weld time at different zone

Zone	Hardness value
MS	288±10 HV
Interlayer	399±10 HV
Al alloy	78±10 HV

4.6 EDX test results:

The energy dispersive X-ray (EDX) test results are presented below. Figure 38 shows different element present at welded zone.



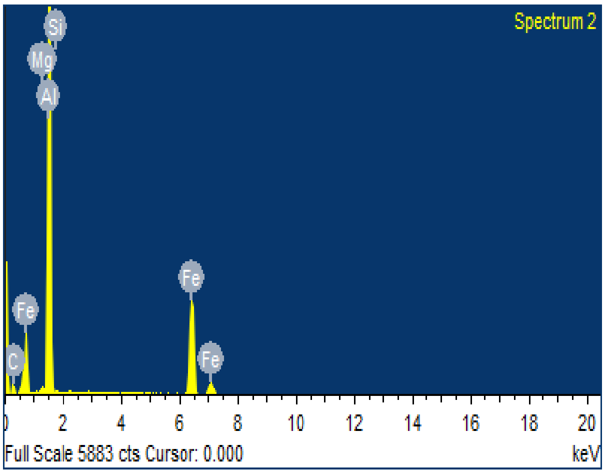


Figure 38: EDX composition analysis of sample weld at 5 kA and 18 milliseconds weld time

Chapter 5 RESULT & DISCUSSION PART 2

5.1 Macro structural observation

Macroscopic view of weld nugget of resistance welded Al alloy and SS metal is shown in Figure 39 a. It is clear that weld nugget of the dissimilar metal welded coupon is of asymmetrical shape and also found that final solidification line shift from sheet/sheet interface in to the aluminium side. The fusion zone size and penetration depth of the aluminiun is higher than stainless steel side (Figure 39 b). It can be seen that welding parameters have an important role on fusion zone size. An increase in welding current increases weld nugget size significantly at constant weld time but with respect to weld time no significant change occurs in fusion zone size.

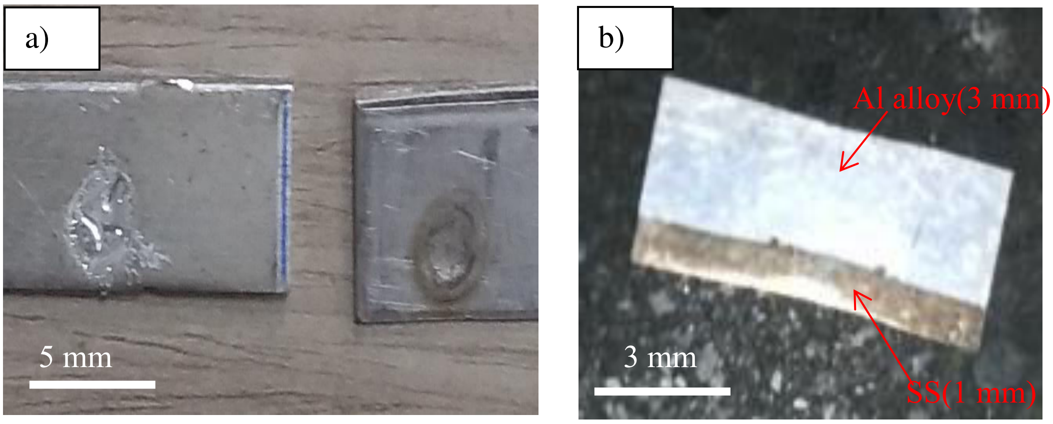


Figure 39: Weld nuggets of Al alloy and SS spot welded sample a) Front view of welded joint b) Cross section view of welded joint

Figure 39 b show cross section area of welded joint in which 3 mm Al alloy and 1 mm thickness sheet are joint by spot welding process.

5.2 Weld nugget dimension:

Increases in welding current increases weld nugget size at constant weld time and vice versa. The checking process was conducted by digital Vernier caliper. Here we found different size of the weld nugget at different welding parameter. These results are shown in the table 8 and 9.Figure 40 and figure 41 show macroscopic view of nugget at different parameters.

Table 8: Weld nugget dimension at 18 milliseconds cycle time, but different weld current

Constant weld Time: 18 milliseconds		
Sample No	**Current kA**	**Nugget Size mm**
Sample 1	**4**	**4.86**
Sample 2	**5**	**5.69**
Sample 3	**6**	**6.63**

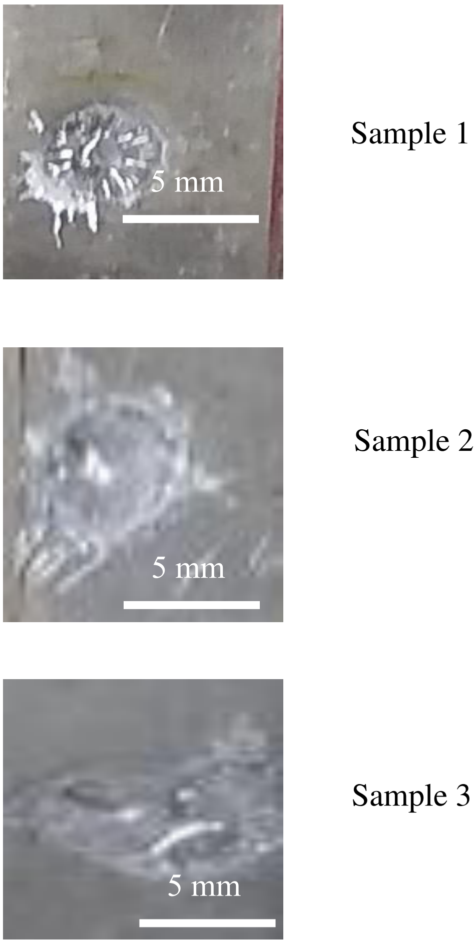
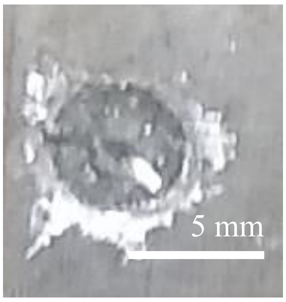


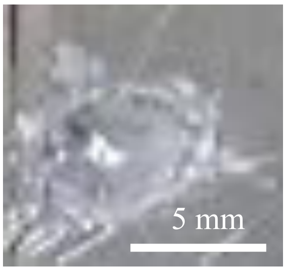
Figure 40: Effect of welding current at constant weld time in macroscopic view

Table 9: Weld nugget dimension at constant welding current, but different weld cycle time

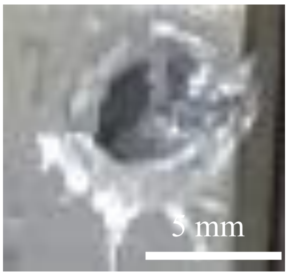
Constant welding Current : 5 kA		
Sample No	**Weld cycle time Milliseconds**	**Nugget Size mm**
S-4	**15**	**5.12**
S-5	**18**	**5.69**
S-6	**21**	**7.44**



Sample 4



Sample 5



Sample 6

Figure 41: Effect of welding cycle time at constant weld current in macroscopic view

5.3 Microstructure observation

Result shows (Figure 42 to 47) as increasing welding current and welding time interlayer thickness increases so increase weld strength.

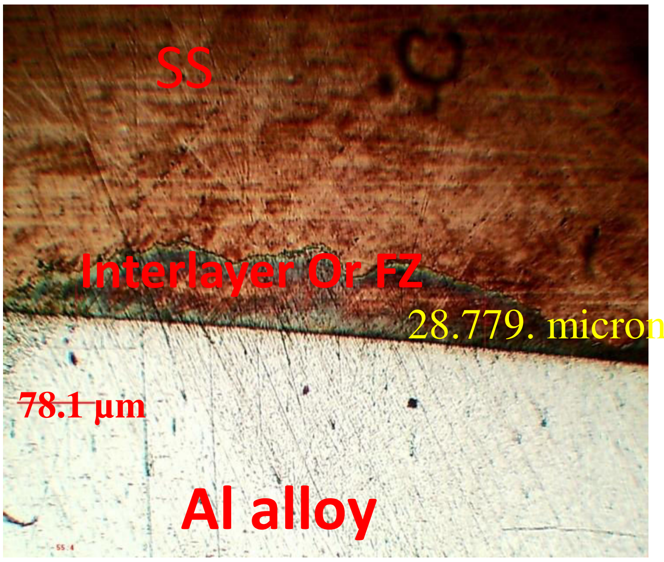


Figure 42: Weld at 4 kA and 18 milliseconds weld time reaction layer thickness approx. 28.779 micron

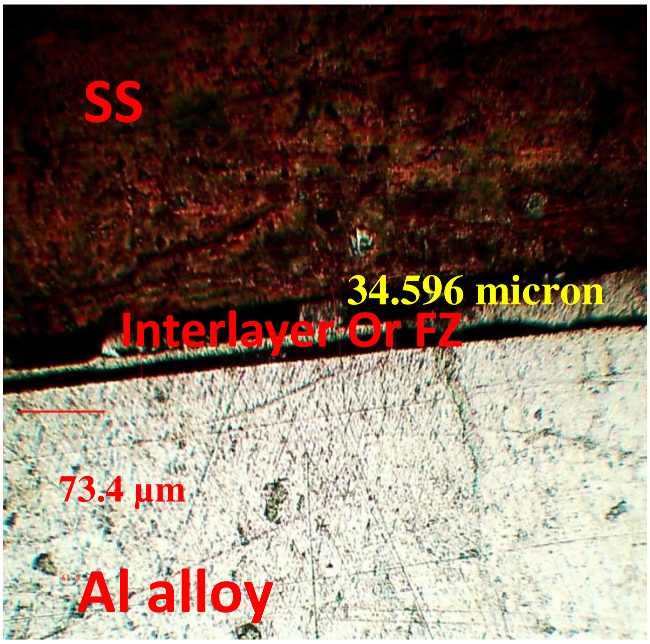


Figure 43: Weld at 5 kA and 18 milliseconds weld time reaction layer thickness approx. 34.596 micron

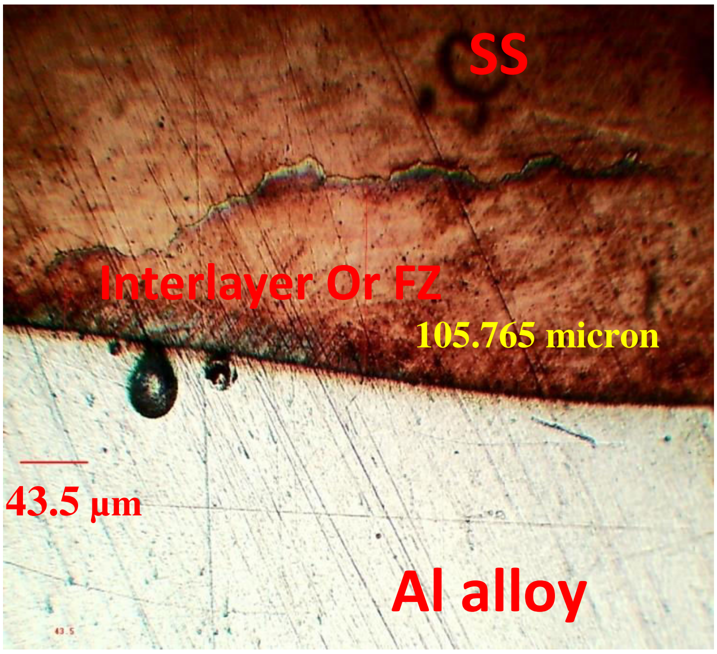


Figure 44: Weld at 6 kA and 18 milliseconds weld time reaction layer thickness approx. 105.765 micron

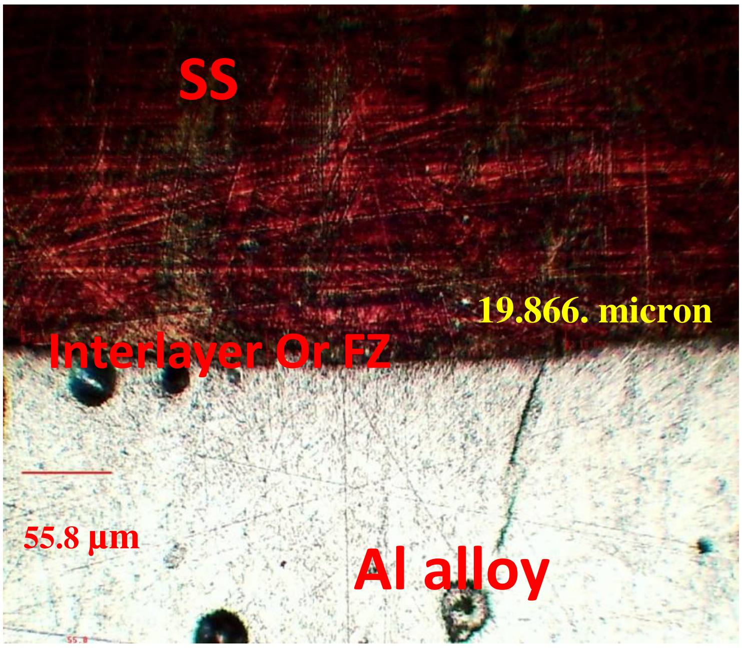


Figure 45: Weld at 5 kA and 15 milliseconds weld time reaction layer thickness approx. 19.866 micron

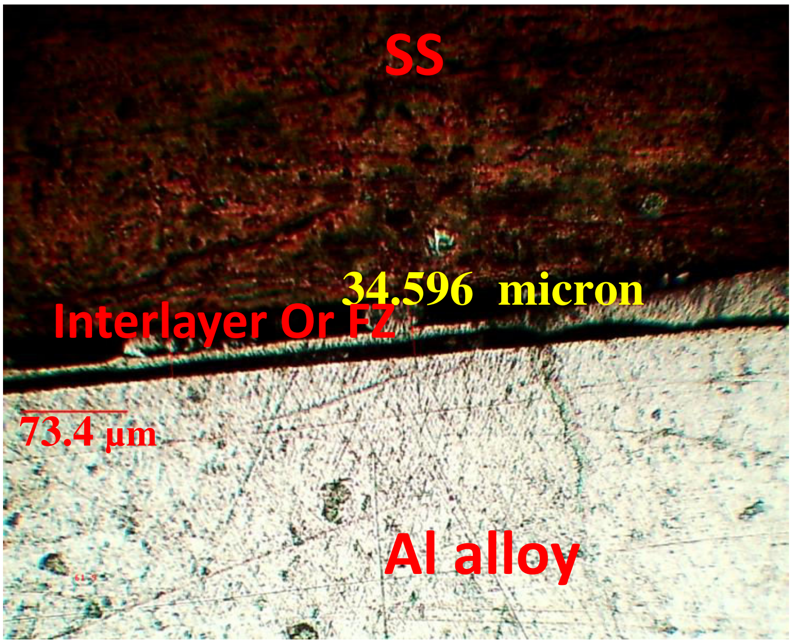


Figure 47: Weld at 5 kA and 18 milliseconds weld time reaction layer thickness approx. 34.596 micron

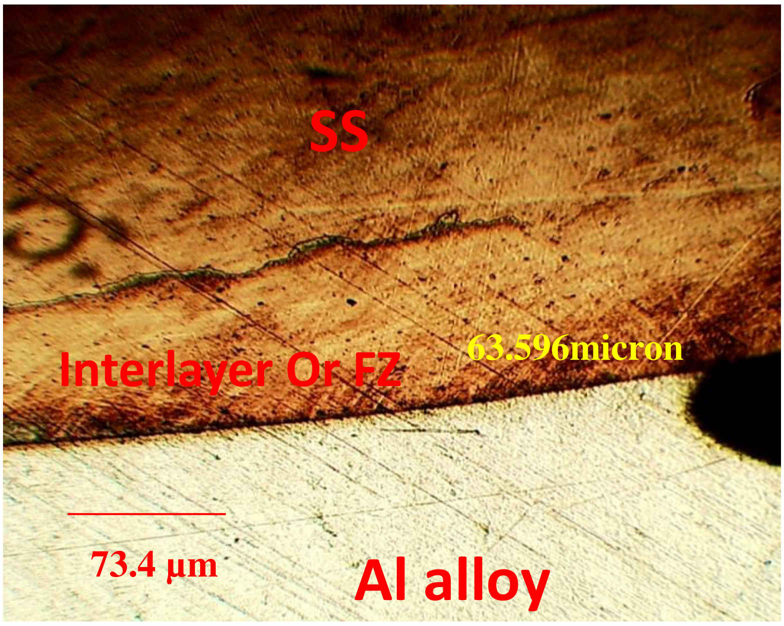


Figure 46: Weld at 5 kA and 21 milliseconds weld time reaction layer thickness approx. 63.596 micron

5.4 Tensile Test

A shear test was conducted and the fracture specimens are shown in Figures. Results show (Figure 48 to 53) that at constant welding cycle time an increase in welding current increases the maximum tensile load. Figure 53 shows at 6 kA welding current and 21 milliseconds welding time nugget has the maximum tensile strength. Increasing welding time and welding current tensile strength of welded sample increase. The maximum tensile shear load reached 953 N at 6 kA welding current and 21 milliseconds weld time. This is because the tensile shear load of the joint is influenced by nugget size bigger the nuggets size more the tensile strength.

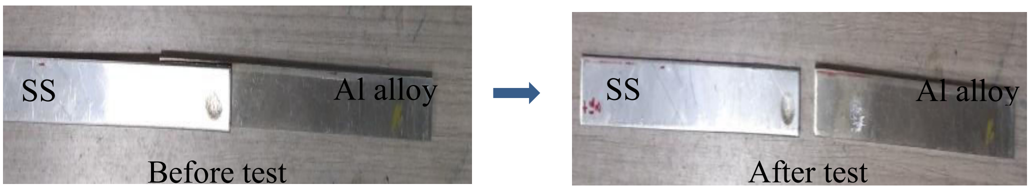
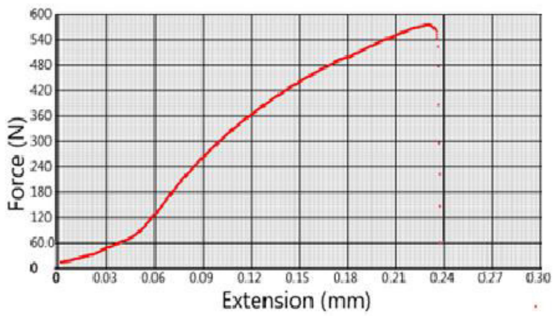


Figure 48: Tensile test specimen of stainless steel and aluminium alloy sample spot welded at 4 kA for 18 milliseconds



BREAK FORCE = 576 N

Figure 49: Force extension diagram of stainless steel and aluminium alloy sample spot welded at 4 kA for 18 milliseconds

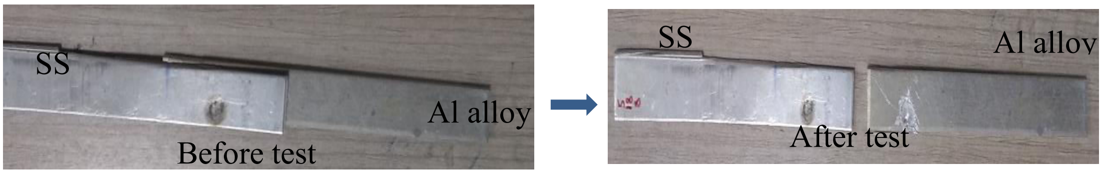
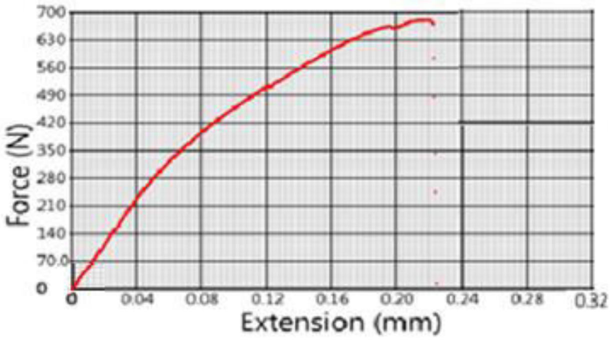


Figure 50: Tensile test specimen of stainless steel and aluminium alloy sample spot welded at 5 kA for 18 milliseconds



BREAK FORCE =682 N

Figure 51: Force extension diagram of stainless steel and aluminium alloy sample spot welded at 5 kA for 18 milliseconds

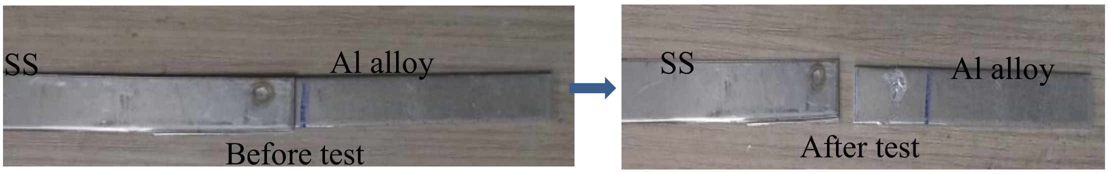
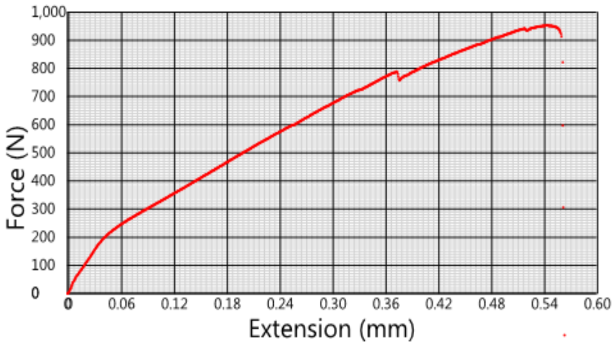


Figure 53: Tensile test specimen of stainless steel and aluminium alloy sample spot welded at 6 kA for 18 milliseconds



BREAK FORCE =953 N

Figure 52: Force extension diagram of stainless steel and aluminium alloy sample spot welded at 6 kA for 18 milliseconds

5.5 Hardness measurement

The hardness test was performed in a micro hardness testing machine. The detail test setup is given in previous chapter. Hardness value is measured in different section (base metal and at interlayer) around the weld nugget. From result we can say that hardness value of the interlayer is intermediate value in between Al alloy and SS hardness. Table 10 shows value of hardness at different zone.

Table 10: Hardness value of a sample weld at 6 kA and 18 milliseconds weld time at different zone

	Hardness value
SS	265±10 HV
Interlayer	218±10 HV
Al alloy	86±10 HV

Chapter 6 Conclusion and Scope for the Future Work

6.1 Summary and Conclusion

In this research work Resistance spot welding is done between two different types of sheet metals. Here mild steel and Al alloy or stainless steel and Al alloy sheets are used. Welding parameters are varied welding current and welding cycle time. After resistance spot welding, the size of the welding nugget is measured from macrograph and analyses the effect of welding parameters. Optical microscopy, EDX and SEM were taken at different location of the weld nugget. Various mechanical tests like micro hardness testing, tensile testing were performed to observe the effect of welding parameters. Lastly, we are trying to optimize the process parameter of the resistance spot welded dissimilar metal.
From this research work the following conclusion were made

1) Welding nugget

Weld nugget size increases at increasing welding current at constant welding cycle. So welding current and welding cycle is the important parameter for determining weld nugget size. It is also considered that higher heat input produce expulsion which make deformed weld nugget and not acceptable in working condition.

2) Macrograph

Asymmetrical weld nugget is found by welding of dissimilar materials. Final solidification line is shifted from sheet/sheet interface into the Al side side. The main reason of this properties is heat imbalance, this is because different heat conductivity, electrical resistivity and thermal expansion coefficient of sheets

3) Optical micrograph and scanning electron microscopy

In the microstructural observation section there are there are three different zones are found which is base metal, heat affected zone and fusion zone or weld nugget. Also after observing different microstructure images of welded sample at different parameter we can conclude that on increases the welding parameter like welding current and welding time reaction layer thickness increases. That means at higher heat input a thick IMC layer is formed

4) **Micro hardness test**

From result we can say that hardness value is a function of welding current and welding time. It can be seen that hardness of the interlayer increases as the Welding current increase, it is because of the formation of thick brittle intermetallic layer at high temperature.

5) **Tensile properties**

Tensile properties show that in case of mild steel and Al alloy weld strength increase upto certain limit but after it decrease but in case of stainless steel and Al alloy at higher welding current and higher welding cycle time makes higher strength of the welded coupon.

At the end of this research work we are trying to find optimum parameter of this welding process. By considering different results we conclude that

a) Optimum parametric combinations of welding current and welding time to obtain maximum strength joint for MS and Al alloy 6061 are (5 kA; 18 milliseconds).

b) Optimum parametric combinations of welding current and welding time to obtain maximum strength joint for SS and Al alloy 6061 are (6 kA; 21 milliseconds).

6.2 Suggestions for further studies

Based on the observations of the present work and literature review of past work, following points should be considered for future scope in this area of research:

- In this experiment we use maximum 6 kA welding current but for process optimization we can use more welding current.
- Welding force may be another process parameter.
- We can use any filler material in between sheet for better diffusion.
- Coated sample also help for improving joint strength.

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