EXPERIMENTAL STUDY OF MULTI-SHEET STACK-UP OF DISSIMILAR MATERIALS BY RESISTANCE SPOT WELDING

A THESIS

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BY

SOURJADEEP DASGUPTA

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UNDER THE SUPERVISION OF

PROF. AKSHAY KUMAR PRAMANICK

DEPARTMENT OF METALLURGICAL AND MATERIAL ENGINEERING

JADAVPUR UNIVERSITY

KOLKATA-700032

MAY 2019

JADAVPUR UNIVERSITY

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CERTIFICATE

This is to certify that the thesis entitled "EXPERIMENTAL STUDY OF MULTI-SHEET STACK-UP OF DISSIMILAR MATERIALS BY RESISTANCE SPOT WELDING" submitted by Sourjadeep Dasgupta (Exam roll no M4MET19004, Registration no14089 of 2017-2018) in partial fulfilment for the degree of Masters of Engineering in Metallurgical Engineering from the Metallurgical and Material Engineering Department, Jadavpur University, Kolkata-700032, is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other organization.

(Prof. Akshay Kumar Pramanick)

Thesis Advisor

Dept. Of Metallurgical and Material Engineering

Jadavpur University

Kolkata-700032

(Prof. Akshay Kumar Pramanick)

Head of Department

Dept. Of Metallurgical and Material Engineering

Jadavpur University

Kolkata-700032

Dean

FET, Jadavpur University

Kolkata-700032

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Name- Sourjadeep Dasgupta

Exam Roll no M4MET19004

Class Roll no 001711302012

Registration no 140895 of 2017-2018

Sinature---------------------------------

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(Sourjadeep Dasgupta)

M.E in Metallurgical Engineering

Metallurgical and Material Engineering Department

Jadavpur University

Kolkata-7000032

CONTENTS

List of figures

List of Tables

Chapter 1

INTRODUCTION

Chapter 1

INTRODUCTION

Resistance spot welding of multiple sheets is nowadays being inevitable in vehicle manufacturing and other fields. At present manufacturing of automobiles, resistance spot welding of three sheets stacks up constitutes approximately one-third of total welded joints [5]. One of the reasons for the need of multiple sheet welding is a continuous attempt to reduce the weight of vehicles in order to improve fuel efficiency. Another reason is the design complexity. As the design of modern automobile becoming more complex, multiple sheets joining is becoming inevitable [6]. For example, a door frame may consist of some steels that are of extremely high strength to resist an impact, and others that are of much lower strength to help create a crumple zone. To produce such customized components, multiple sheet stack-ups are often needed. Multiple sheets welds lead to improvement of design flexibility, lower cost and higher productivity compared to two sheets joining of automobile body panels.[1]

However, RSW of multiple sheets is very challenging compared to two-sheet spot welding, joining multiple sheets is significantly more complicated due to the addition of extra interfaces. Welding current flow throughout the joints is also complicated. The use of different material combinations and different sheet thicknesses further complicates the process [7]. The weld nugget quality has become a major concern. There is insufficient growth of the weld nugget, which has a detrimental effect on the crashworthiness of the vehicle. Moreover, the failure mechanism of three-sheet resistance spot welds is not well understood.[13] Despite the importance of multiple sheet spot welding, reports in the literature dealing with their welding behaviour and mechanical behaviour are limited.

In this thesis an attempt has been made to study the characteristics of four sheet dissimilar materials and dissimilar thickness resistance spot welds.

Chapter 2

LITERATURE REVIEW

Chapter 2

LITERATURE REVIEW

2.1. Definition of welding

A weld is defined by American Welding Society (AWS) as "a localised coalescence (the fusion or growing together of the grain structure of the materials being welded) of metals or non-metals produced either by heating the materials to the required welding temperatures, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler materials.[4]

2.1.1. Welding processes

According to the sources of heat, welding processes can be broadly classified as:

❖ Electric welding processes (heat source is electricity)
  Electric welding processes can be classified as
  - Electric arc welding
  - Electric resistance welding
  - Laser welding
  - Electron beam welding
  - Induction welding

❖ Gas welding processes (heat source is gas flame)
  Gas welding processes can be classified as
  - Oxy-acetylene gas welding
  - Oxy-hydrogen gas welding
  - Oxy-coal gas welding
  - Oxy-liquefied petroleum gas welding
  - Air acetylene gas welding

- The other welding processes are
    - Thermit welding
    - Forge welding
    - Friction welding
    - Ultrasonic welding
    - Explosive welding
    - Cold pressure welding
    - Plastic welding

2.1.2. Resistance Spot Welding

Electric resistance welding refers to a group of welding process in which parts to be welded are first heated to the fusion temperature by the resistance of workpiece to the flow of electric current and then squeezed by mechanical pressure to accomplish welding. No filler metal or flux is added in this process. [1]

This process can be further classified as:

- Spot welding
- Seam welding
- Butt welding
- Flash butt welding
- Projection welding

Above are a few types of resistance welding processes, but the most common and the subject of this thesis is **Resistance Spot Welding**.

Resistance spot welding is one of the types of spot welding processes which is used for making lap joints. The metal pieces are assembled and placed between two copper electrodes and then current is passed. The parts are heated at the area of contact by electrical resistance. The electrodes are simultaneously pressed against the metal pieces by mechanical or hydraulic pressure.

2.1.2.1. Principles of Resistance Spot Welding

In Resistance spot welding, two or more sheets of metal are held between electrodes through which current is supplied for a definite time keeping the workpieces under pressure between the electrodes. The welding cycle starts with the upper electrode moving and contacting the workpieces resting on the lower electrode which is stationary. The workpieces are held under pressure as shown in Fig 2.1 and only then heavy current is passed through the electrodes for a preset time. The temperature of the metal between the electrodes rises rapidly due to the resistance to flow of current through the contacting surfaces of workpieces (Joule Effect). The pressure between electrodes squeezes the hot metal together thus completing the weld. The weld nugget formed is allowed to cool under pressure and then pressure is released. This total cycle is known as resistance spot welding cycle.

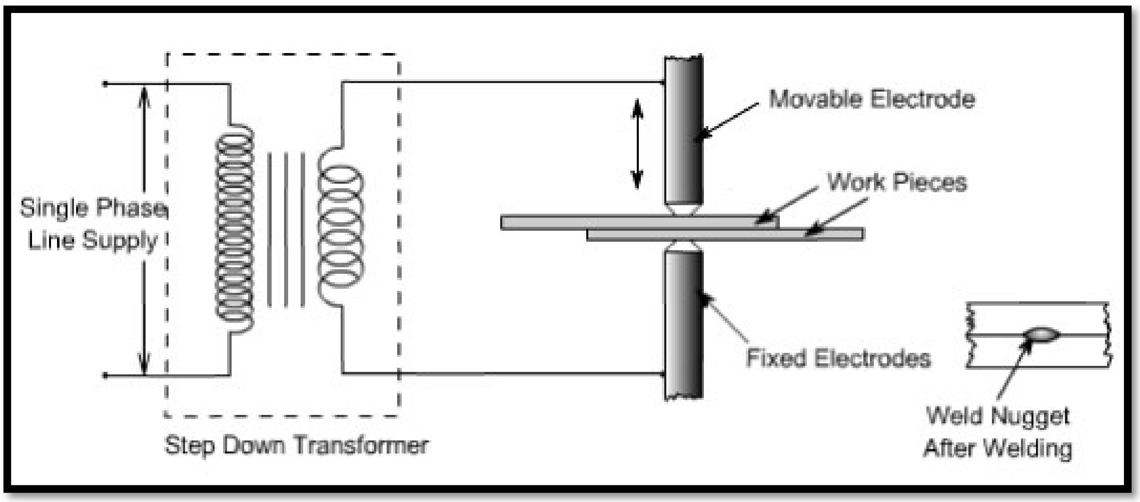

Fig 2.1. Principles of resistance spot welding

- Joule Effect: The physical principle for heat generation is defined by the Joule's Law, which in its simplest form can be expressed as…

$$H=I^2Rt$$

Where H is the weld heat input in Joules, I is the current in Amperes, R is the resistance in ohms and t is the time in seconds.

The actual resistance that causes heat generation can be considered as a series of resistance. The equivalent resistance can be expressed as…

$$R=R_1+R_2+R_3+R_4+R_5+R_6+R_7$$

Where R_1 = Bulk resistance of the upper electrode

R_2 = Contact resistance of the upper electrode and upper sheet

R_3 = Bulk resistance of the upper sheet

R_4 = Contact resistance of the upper and lower sheet

R_5 = Bulk resistance of the lower sheet

R_6 = Contact resistance of the lower sheet and the lower electrode

R_7 = Bulk resistance of the lower electrode … [2]

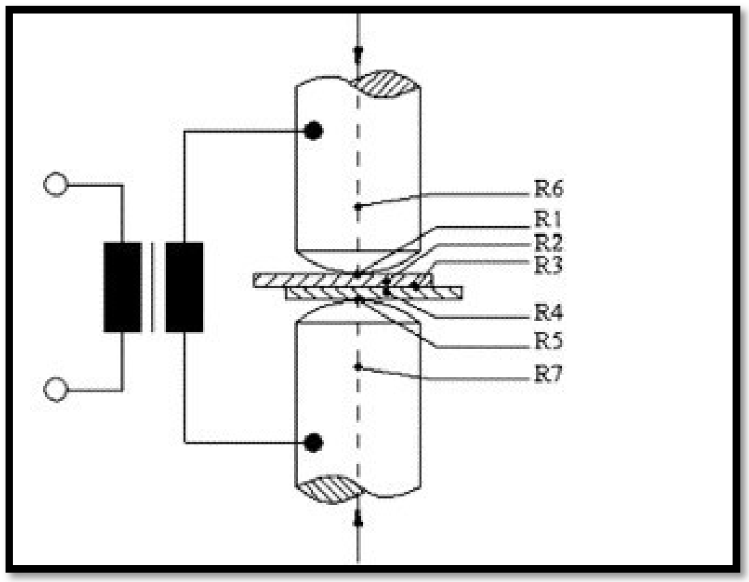

Fig 2.2. Effective resistances in RSW

2.1.2.2. Parameters in Resistance spot welding:

The main parameters that affect the weld quality the most are welding current, weld time and electrode force. The effects of these parameters are discussed below:

2.1.2.2.1. Welding current

The amount of weld current is controlled by two things: first, the setting of the transformer tap switch determines the maximum amount of weld current available; second, the per cent of current control determines the per cent of the available current to be used for making the weld. Low per cent current settings are not normally recommended as this may impair the quality of the weld. [3] Welding current is the most important parameter in terms of heat generation that has to be controlled precisely in order to get acceptable weld quality. Since heat generation is proportional to the square of the current, a small change in current results in much difference in heat generation.

2.1.2.2.2 Weld time

The time involved in a single weld in Resistance spot welding can be divided into three parts.

- **Squeeze time**: This time is the interval between the initial application of force by the electrodes and the initiation of current flow. During this period the sheets are held properly between the electrodes and the proper pressure is achieved between the electrodes.
- **Weld time**: This is the time during which the current is passed through the workpieces. During this period electrode pressure is maintained constant, the quantity of molten metal increases and fused metal spurts out and a series of peaks and valleys occur in a microscopic scale on the surfaces of the metal components. In addition to that, the HAZ (heat affected zone) extends.
- **Hold time**: This is the time between the termination of current flow and the pressure reduction. The hold time is essential to allow the weld nugget to solidify and to chill the weld with the help of the water-cooled electrode. [3]

2.1.2.2.3. Electrode force

The level of electrode force in Resistance spot welding plays a significant role in weld formation and therefore is considered a critical factor. Electrode force influences the magnitude of static contact resistance and thus the extent of initial heating in the sheet/sheet or electrode/sheet interface. Increase in electrode force results in smaller weld nuggets as a consequence of the reduction in initial heating and the average current density in sheet/sheet interface. Any decrease in pressure results in an increase in these resistances and thereby leading to more heat generation. However the resistance decrease as a consequence of a larger area due to electrode growth after a number of welds made. The final result is a balance between these two effects, the outcome of which would be highly dependent on the surface properties of the two materials being welded.

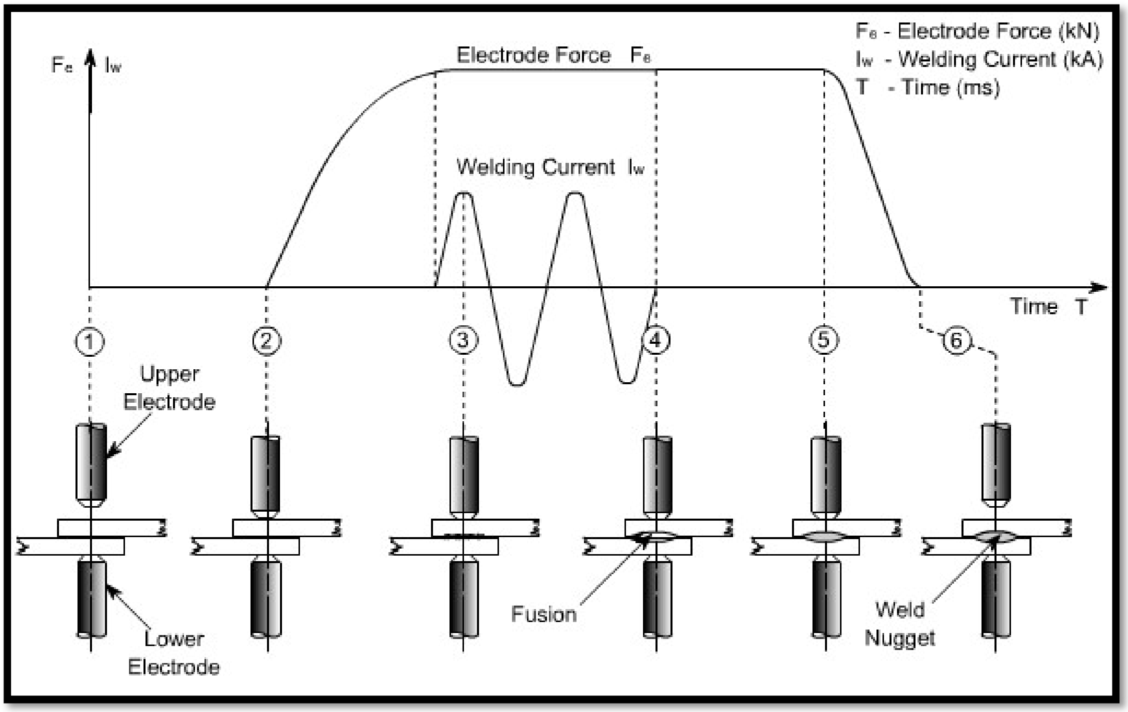

Fig 2.3. Electrode force during a single spot weld

2.1.2.3. Mechanism of heat generation and nugget growth

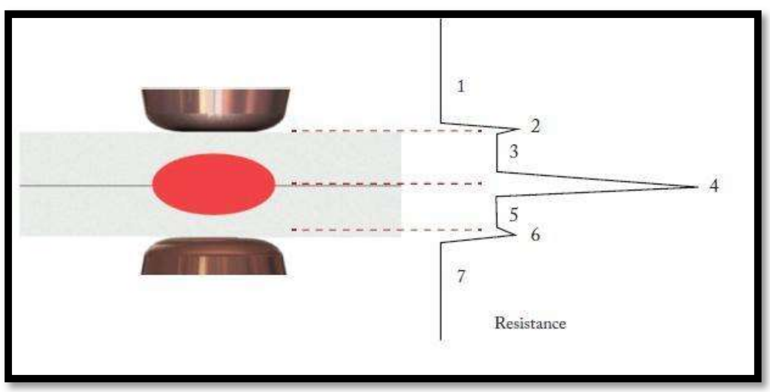

Fig 2.5 Resistance plot

Heat generation associated with the RSW process is more complicated than just the simple heating of a conductor associated with the passage of electrical current. Fig 2.5 shows the standard RSW arrangement including a plot of resistance across the electrodes that reveals a very important characteristic critical to most resistance welding processes, the contact resistance between the sheets being welded. As indicated in the figure, the highest resistance to the flow of current is where the sheets come into contact with each other. This fact allows a weld nugget to begin forming and grow exactly where it is needed-between the sheets.

In order to better understand the heat generation mechanism, the current path from one electrode to the other can be compared to an electrical circuit that contains seven "resistors" in series. In Fig 2.5, "resistors" 1 and 7 represent the bulk resistance of the copper electrodes, "resistors" 2 and 6 represent the contact resistance between the electrodes and the sheets, "resistors" 3 and 5 represent the bulk resistance of the sheets, and "resistor 4" represents the contact resistance between the sheets. It is important to point out that while the figure shows the location of a successful weld (called a nugget), the plot of relative resistance describes the situation at the very beginning of the weld, and prior to nugget formation. As described later, these resistances change rapidly during the short time of a single weld, a concept called dynamic contact resistance.[1]

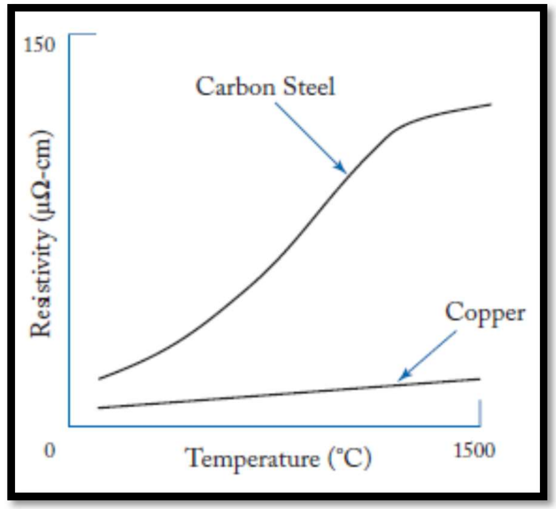

Fig 2.6 Effect of temperature on resistance

Another factor that works strongly in the favour of resistance welding of steel is that as steel is heated, its resistivity relative to copper increases dramatically, as shown in Fig 2.6. So, the initial contact resistance effectively heats the surrounding area, which is, in turn, heated more rapidly by the flow of current because its resistivity is higher due to the higher temperature. As a result, heating and weld nugget formation can occur quite rapidly.[1]

2.1.2.4. Effect of electrode force on contact resistance

All metals have some surface roughness that limits the contact area when the two sheets are brought together. As a result, when current is passed through the sheets, the electrons will be forced to flow through the narrow regions where the surface asperities touch. This creates localized extremes in current density that causes an increase in resistance. When electrode force is applied, surface asperities are collapsed and the contact resistance becomes less. This means that with RSW, higher forces will generally result in less heating due to reduced contact resistance. In addition to surface roughness, other conditions that increase contact resistance include oxides, rust, scale, grease/oil, and paint. Higher electrode forces will have the same

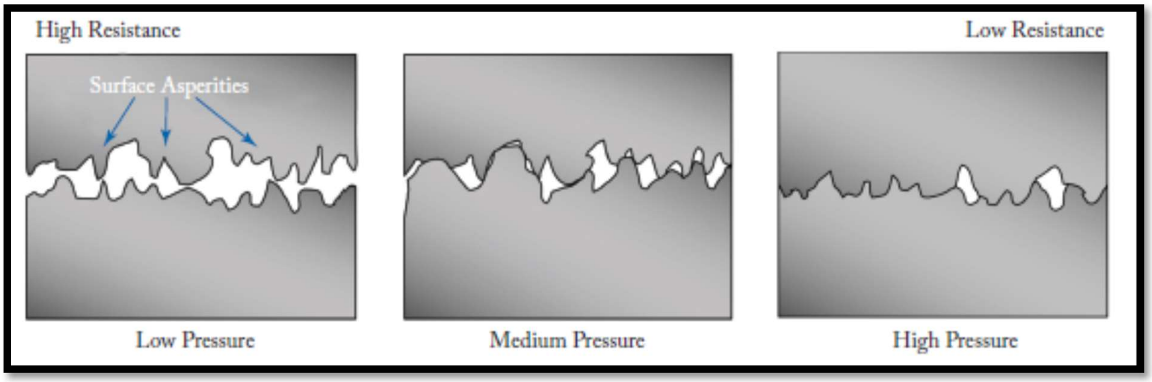

Fig 2.4 Effect of electrode force on contact resistance

effect of lowering the contact resistance by breaking up oxides and pushing out other surface contaminants. [1]

2.1.2.5. Dynamic Contact Resistance

The resistance across a spot weld during the time the weld is being made doesn't remain constant but changes rapidly, and therefore is considered "dynamic." By monitoring the

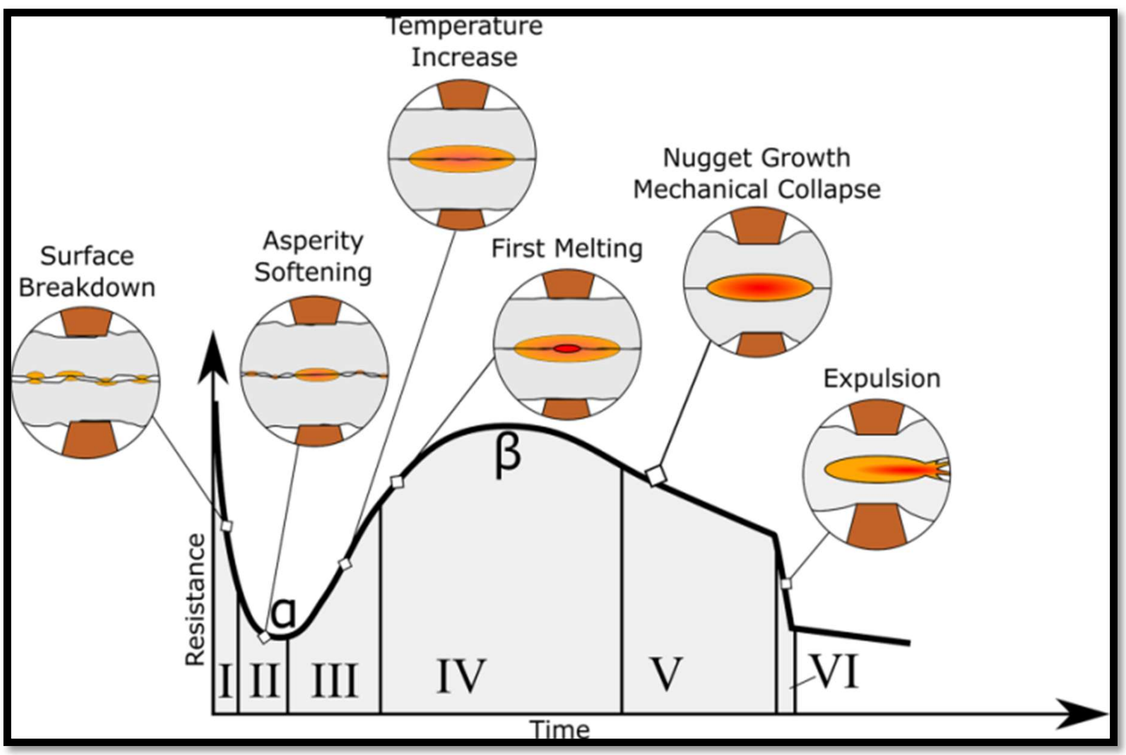

Fig 2.7 Dynamic contact resistance

resistance during a single spot weld, a plot of resistance vs. weld time can be generated. The result is known as a dynamic resistance curve since it reveals how much resistance changes over the course of a weld. A typical dynamic resistance curve for carbon steel is shown in Fig 2.7. As indicated on the left side of the figure, resistance starts out relatively high, drops, and then begins to rise again. This portion of the curve reveals the transition from contact resistance to bulk resistance. Initially, contact resistance remains high as surface oxides and surface roughness create greater resistance to the flow of current. With enough pressure and heat, the oxides are shattered and the surface asperity peaks collapse, thus lowering the contact resistance. The contact resistance heating rapidly heats the surrounding steel, which dramatically increases its resistivity, and bulk resistance of the sheets begins to dominate. The bulk resistance heating soon becomes large enough to begin forming a molten nugget. As the nugget grows, the current path becomes larger which reduces the current density, which causes the resistance to plateau and then drop. A further drop in resistance may occur if there is indentation since the length of the current path is reduced. If there is expulsion, a severe indentation may occur dropping the resistance even more.[1]

2.1.2.6. Weldability lobes

The main parameters, which can be controlled on a resistance-welding machine, are welding current, weld time and electrode force. The ability to make a weld, based on these parameters, under production conditions, is best defined in terms of a 'weldability lobe'. The weldability lobe defines the available tolerances for producing a weld of defined quality. By such means, it is possible to determine the

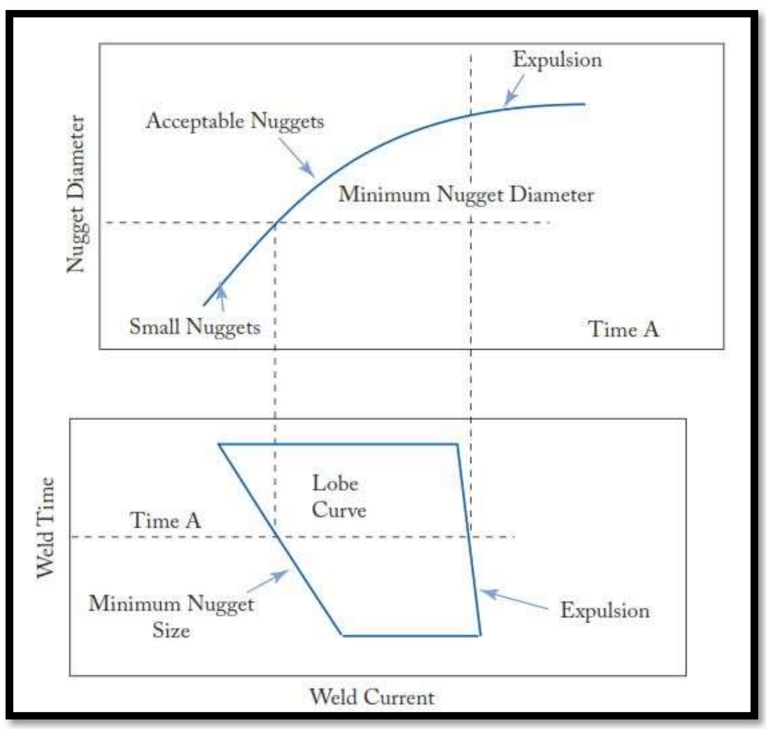

Fig 2.8 Current range curve and weldability lobe

welding parameters which give rise to an acceptable weld quality as defined by precise physical limits such as weld size.[2]

The current range curve shows the relationship between current and weld nugget diameter while the lobe curve shows a process window within which acceptable welds may occur. Since nugget (weld) size directly shows the weld quality or weld strength it is an important measure whether a weld is acceptable or not. A general rule of thumb is to produce a nugget diameter more than $4\sqrt{t}$ (where t is the sheet thickness), but this can vary depending on the materials being welded. The maximum nugget size is generally determined after which expulsion occurs and this can be shown by both the current range curve and the lobe curve. A typical lobe curve in fig 2.8 shows that a weld can be performed within a very short time which is the goal of the automotive production using a high amount of current. However excessively high current in a short time gives a narrow process window.[1]

2.1.2.7. Expulsion

A common phenomenon that occurs in resistance spot welding is Expulsion. When molten metal from the weld area is sprayed out or ejected during the weld time, it is called expulsion. Expulsion may occur at the sheet/sheet interfaces or electrode/sheet interfaces. The latter does not affect the weld quality severely as long it is confined to the surface area but can damage the electrode. Expulsion in the sheet/sheet interfaces is highly undesirable in terms of weld quality because in this case metal lost from the nugget area and the joint becomes insufficiently strong. There are two mechanisms associated with expulsion. The first mechanism occurs when the current supplied is high or the weld time is high, and the fusion zone gets too large for the pressure ring created by the electrodes, and the metal sprays out. The second mechanism may take place if the electrode force is not enough to withstand the force of volume expansion of the fusion zone due to liquefaction of metal. The sheets are simply forced apart and liquid metal gets ejected.

Fig 2.9 Expulsion

2.1.2.8. Weld strength test

Visual inspection is always an important and effective method, but in case of resistance spot welding, the nugget is hidden in between sheets. So mechanical testing is crucial in order to gauge the strength of weld joints. Some of the widely used tests are discussed below:

- Peel test

The main test by which weld nugget diameter thus the weld strength can be gauged is peel (destructive) testing. In this test, both sheets are torn away from each other by clamping one sheet usually in a vice and the other sheet is gripped with pliers and the load is acted in the direction perpendicular to its original orientation as shown in Fig 2.10. In this way, the weld nugget can be exposed and measured.

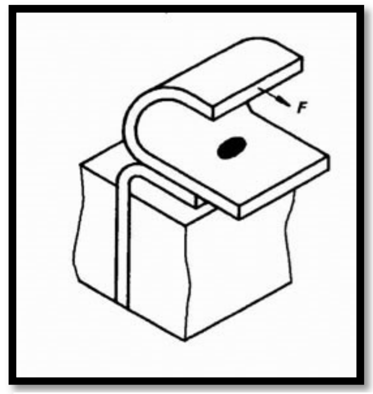

Fig 2.10 Peel test

- Shear tensile test

The shear tensile test is the most common test in determining the weld strength because of its simplicity. Sheet materials are spot welded at one end and dragged from either side till failure.

- Cross tension test

In cross-tension tests, two test strips measuring 150 mm long × 50 mm wide are positioned normal to each other with an overlap of 50 mm, and a spot weld is made at the centre of the overlapped region. In the cross-tension test, a tensile load is applied on the weld in a direction normal to the weld

The reason for the poor mechanical performance of Spot Welding is that the applied load is always concentrated along the perimeter of the weld nugget. Some loading condition is even more severe and produce more stress concentration than shear-tension, and lowers the load bearing capacity. Fig 2.11 compares three common loading conditions/test types for a spot weld—tensile shear, cross tension, and peel/chisel. As the fig 2.12 indicates, the severity of the loading condition is the least in tensile shear and the greatest in a peel or chisel condition. This figure also reveals that a spot weld loaded in shear performs better in a mechanical test, such as tension than one that is in a peel-type loading condition.[1]

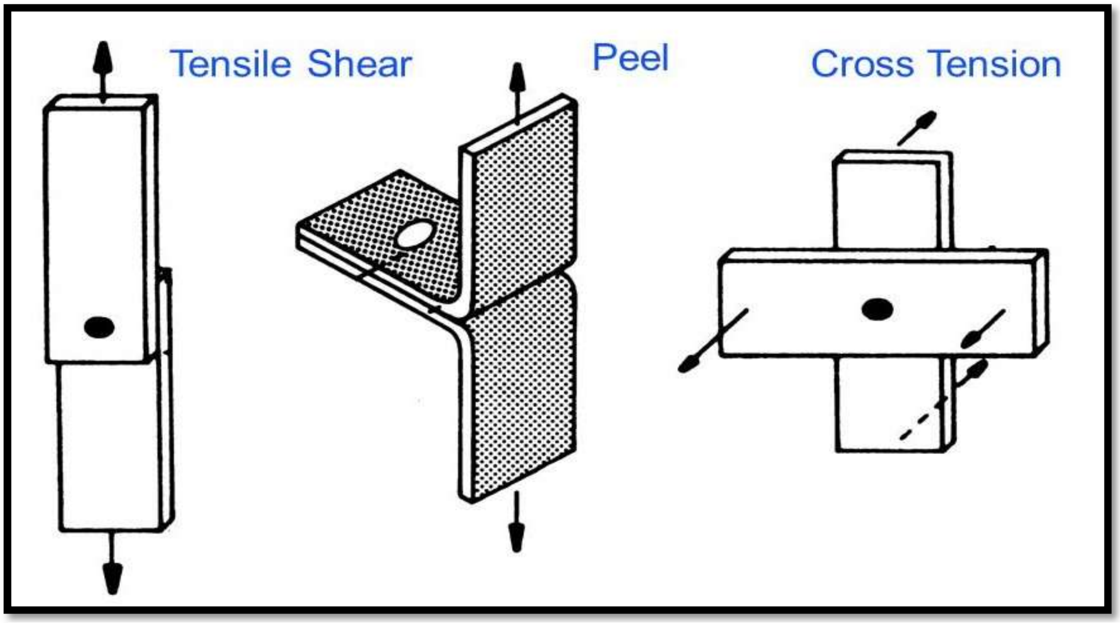

Fig 2.11 Loading directions

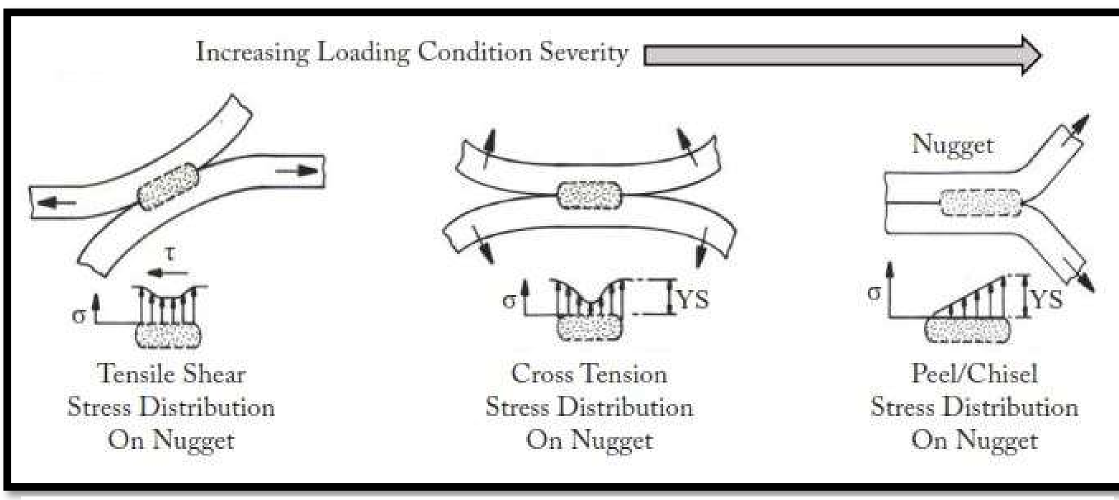

Fig 2.12 Effect of loading condition on nugget stress distribution

2.1.2.9. Failure modes of spot welds

As a result of peel test the following kinds of nugget or buttons may be obtained shown in Fig 2.12 [1] and depending on the shape, size of the nugget and nature of failure, a weld is generally determined to be of acceptable quality or not. Such tests have been used extensively over the years with conventional steels where it is a commonly accepted practice to base weld quality purely on whether or not a full button pull is achieved. However, testing has shown with modern high-strength materials, such as advanced high-strength steels, that fracture mode other than a full-button pull may produce acceptable mechanical properties.

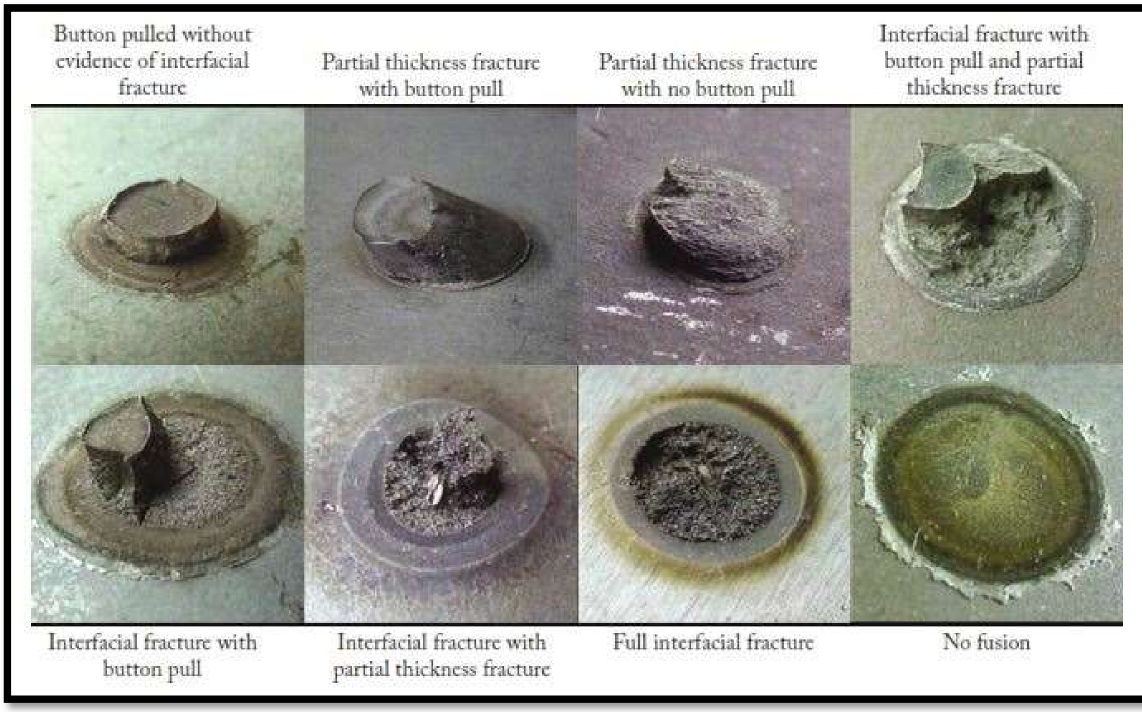

Fig 2.12 Variety of spot weld fracture modes

2.1.2.10. Multi-sheet stack-up RSW

The need for design flexibility and reduction of process time led to the practice of resistance welding of multiple sheet stackups. RSW of multiple sheet stackup is very challenging compared to two sheet RSW. Current flow through the increased number of contact surfaces is complicated. Use of dissimilar material and dissimilar thickness further complicates the process. Literature dealing with the characteristics of multiple sheet stackup is limited. Some of the important findings by the researchers in this topic is discussed in the next section.

2.2 Review of previous work

Over the year a lot of research has taken place in resistance spot welding, and interesting results has been brought up. This section brings into account some of the findings that are relevant to the subject of this thesis work.

N. Harlin investigated and compared the nugget growth characteristics on two sheet and three sheet stackups to ensure optimum welding conditions which ensure high levels of joint quality. In both the cases of double sheet joints and triple sheet joints the initial heat generation and the nugget formation was observed to occur where the resistance was high i.e. at the sheet to sheet interface. Because of the efficiency of the water-cooled electrodes, the effect of heat generation was pronounced at the sheet to sheet interfaces. But the incubation period to weld nugget formation was dependent on total joint thickness. A longer weld time was required for joints of greater thickness.[10]

Jie Shen developed a FEM model to analyse the weld nugget shifting phenomenon in Resistance spot Welding in multi stackup sheets. It was found that when the thickness of any of the outer sheets increases, the degree of weld nugget shifting becomes serious which leads to unacceptable weld nugget. [11]

Zhenzhen Lei developed an FE model with the help of ANSYS to analyse the transient thermal characteristics of Resistance Spot Welding with Three sheet stackups. In this study, it is concluded that the highest temperature begins at the two faying surfaces between sheet/sheet symmetric to the centre of the entire sheet stacks because of contact resistance and equal sheet thickness which differs from the temperature distribution of two sheet assembly.[5]

Jei Shen developed a finite element model to predict the weld nugget size for RSW of multiple stackup of steel sheets. The weld nugget on the faying interfaces of the steel sheet which has higher bulk and contact resistivity. [7]

M Pouranvari and Marashi investigated to find a critical sheet thickness for weld nugget growth during RSW of three sheet stackups below which FZ size at sheet/sheet interface is nearly equal to the FZ size at the geometrical centre of the joint. Increasing the sheet thickness beyond the critical sheet thickness caused a shift in the location of weld nugget formation to the sheet/sheet interfaces. Below the critical sheet thickness, the weld nugget growth at the geometrical centre of the joint is higher than that at the sheet/sheet interface.[9]

R. Chtourou proposed an experimental procedure to investigate the mechanical behaviour of multi-materials and multi-sheet RSW assemblies in pure and combined opening or shear modes. The results showed that the peak load and the energy absorbed increase with the nugget size of the spot welds especially for pure shear test characterized by an interfacial failure mode.[12]

Eizadi investigated the weld nugget development and mechanical properties of four sheet dissimilar thickness RSW. Lack of sufficient weld nugget penetration into the thin/thick interfaces is due to a large amount of heat dissipation from thick/thin interfaces into the water-cooled electrodes. Therefore, higher heat input is required to establish sufficient weld nugget size at thin/thick interfaces. [8]

A. Tavasolizadeh investigated the mechanical properties of three sheet stackups and concluded that the thickness of the middle sheet has an important role to play in nugget growth. Increase in nugget size results in increase in the peak load and the failure mode is determined by the nugget thickness in the sheet/ sheet interface.[16]

Kang et al. investigated the fatigue characteristics of three-sheets stack-up of DP600. The experiments were designed to investigate the effects of electrode tip geometries, surface indentation levels, and base metal strengths on fatigue life of the tensile shear spot welds. The fatigue test results showed scatter in the plot of the maximum applied loads versus cycles to failure of spot welds due to weld sizes and base metal strengths. Thus, a normalized structural stress parameter was proposed and correlated well to the fatigue test results.[17]

Pouranvari et al. investigated The effects of weld nugget size and expulsion on the performance of low carbon steel resistance spot weld. The results showed that although expulsion does not reduce the load carrying capacity of spot welds, it decreases their energy absorption capability which was attributed to the change of failure location due to excessive electrode indentation associated with expulsion.[18]

Wei et al investigated the macrostructure, splash situation, nugget diameter and tensile shear property of spot welds for similar and dissimilar combinations of galvanised DP1000, bare TRIP980 and bare TWIP980 steels were evaluated. It was found that for the dissimilar spot welding of galvanised DP1000, uncoated TRIP980 and uncoated TWIP980, the TRIP/TWIP/DP combination can obtain better weld quality than the other combinations.[19]

Chapter 3

EXPERIMENTAL PROCEDURE

Chapter 3

EXPERIMENTAL PROCEDURE

3.1. Materials

The materials selected for this project were 0.8 mm thick IF steel and 1.2 mm thick mild steel, chemical composition of which is given below in Table 4.1

Table 3.1: Chemical composition of base metals

Grade	Chemical Composition (wt. %)						Mechanical Properties (MPa)		Thickness of sheet (mm)
	C	Mn	Si	S	P	C.E	YS	UTS	
IF	0.043	0.188	0.021	.0073	0.016	0.054085	121.7	139.1	0.8
MS	0.065	0.181	0.103	0.011	0.012	0.07799	199	202	1.2

3.2. Setup

Spot welding was performed by CEA make Resistance Spot Welding machine interfaced with Mechelonic Engineer controller. Cold water circulating system was used to maintain the temperature of the truncated cone electrode at 20 degree Celsius. Electrode tip diameter of 6mm was used for the experiments based on BS 1140 specification taking the sheet thickness as 1.2 mm. Welds were carried out at different current levels at an interval of 0.5 KA roughly. Coupons were made for lap joints and MS sheets were kept in the middle in the stack and IF sheets were kept at the extremities as shown in Fig 3.2.

Fig 3.1 RSW setup

Fig 3.2: Configuration of joint

3.3. Parameters

Depending on the literature of the past researchers and trials with suitable parameters, Electrode force was kept constant at 2.5 KN and the weld time was chosen to be 14 cycles (28miliseconds) for the thesis work. Current level was varied from 5.0 KA to 8 KA.

Table 3.2: Weld parameters

Parameter level	Electrode force (KN)	Weld Time (Cycles)	Current (KA)
1	2.5	14	5.1
2			5.5
3			5.9
4			6.5
5			7.0
6			7.5
7			8.0

3.4 Mechanical testing

3.4.1. Microhardness

Microhardness survey was made on flat metallographic specimen across the joints in Vickers's microhardness testing machine as in Fig3.3 (*Make: LECO Co., USA; Model: LM248AT*). Indentations were taken with diamond indenter across the samples at an interval of 0.5mm.

Fig 3.3 Microhardness setup

3.4.2. Tensile testing

The shear-tensile tests were carried out in a Tinius Olsen (H50KS) made in UK, 48kN capacity tensile testing machine using 50kN Load cells. The tensile specimens were held in wedge grip and monotonous increasing loads were applied by the actuator. Tests were terminated when the joint has been failed, either a pullout failure or an interfacial failure.

Test samples has been made according to BS 1440 standards. Two types of configurations were used to study the load bearing capacity of joints. Fig 3.5. shows the two configurations.

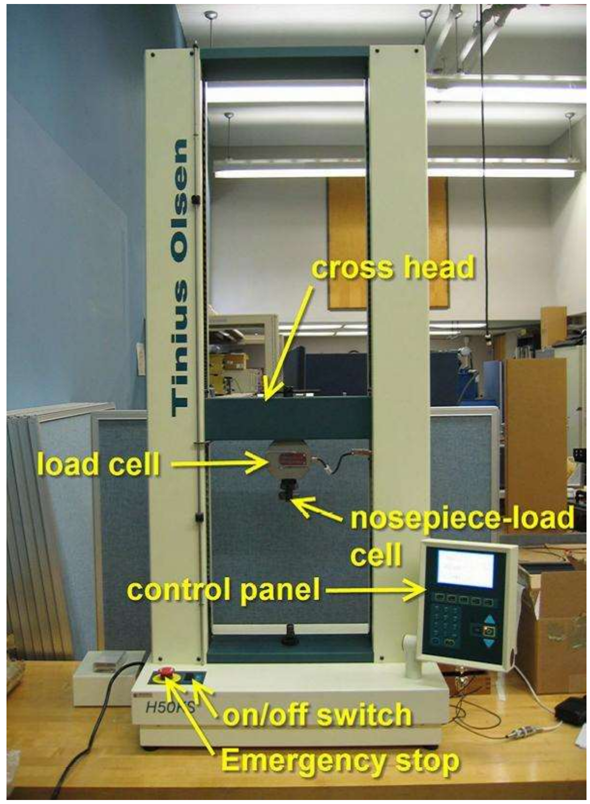

Fig 3.4: Tensile test setup

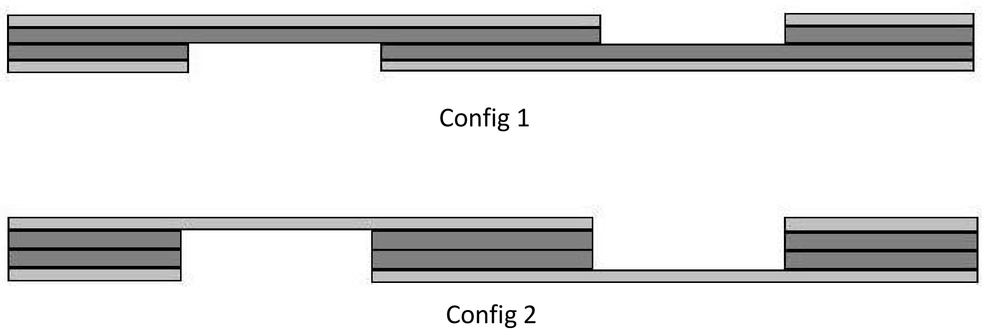

Fig 3.5: Configurations of Shear-Tension test samples

3.5. Metallography

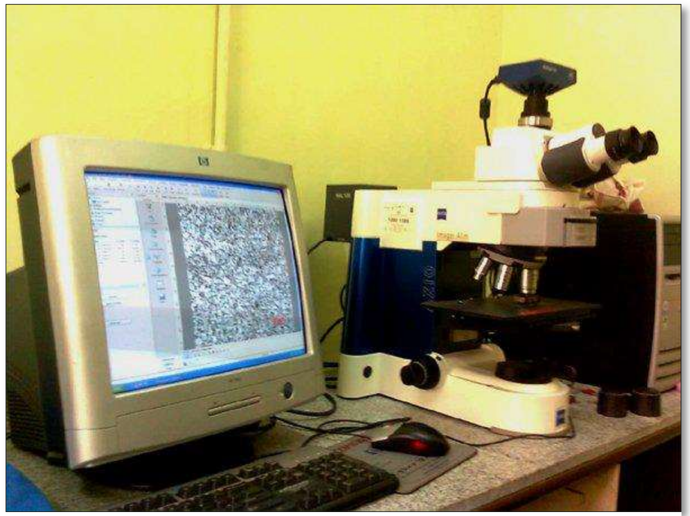

Fig 3.6: Optical micrograph setup

The weld nugget of specimens welded at different current level were cut using a BUEHLER make low speed saw. Then was polished using emery papers and finally cloth polished with alumina polishing agent in a BUEHLER make polisher. The specimens were then etched using picral (1g picric acid, 100ml ethanol) added wit 1 ml HCl.. Microstructural examination was carried out using a light optical microscope as shown in Fig---- (*Make: Carl ZEISS India Pvt. Ltd.; Model: Imager.A1m*) and the microphotographs were taken at different magnifications. For the macro-photographs a Canon scanner is used at 1200 dpi.

Chapter 4

RESULT AND DISCUSSION

Chapter 4

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4.1. Weld nugget characteristics

Width of the FZ i.e. the weld nugget size is an important factor affecting the weld quality. Nugget sizes at different current level were measured after the peel test and it was observed that current has an important role to play in nugget growth. As current is increased, the size of the weld nugget has increased steadily, the representation of which is shown in Fig 4.6.

- Below current of 4.2 KA, no nugget formation was observed and sheets could be separated without any essential load.

Fig 4.1 No nugget formation at below 4.2 KA

Fig 4.2 After peel test at 5.0 KA

Fig 4.3 After peel test at 5.9 KA

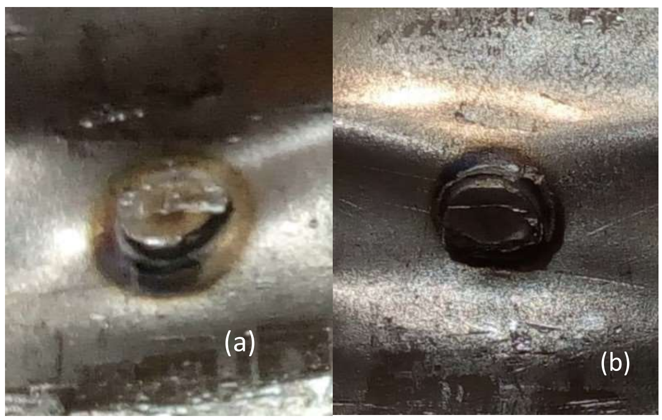

Fig 4.4 Nugget at 5.9 KA

Fig 4.5 Interfacial expulsion at 8 KA

- The mechanism of nugget growth depends on a balance between the heat generation and the heat dissipation. The heat generation is a function of welding parameters, contact resistance and bulk resistance. Whereas heat dissipation depends on joint configuration, the thickness of the base metals, and the effect of water-cooled electrodes. In the present configuration, the total thickness was 4 mm which resulted to be thick enough to make the effect of heat generation dominate in the two middle sheets and the effect of heat dissipation dominate in the outer sheets. As a result at 5.0 KA peel test showed that weld nugget was formed between the middle sheet interfaces and the sheets at the periphery were not fused properly. Due to the action of pressure and heat, the sheets at the periphery were attached to the other sheets. As shown in fig 4.2 there was no nugget formation on the outer sheets, but evidence of nugget in the middle sheet/sheet interface.

- At 5.5 KA nugget size was found to be 4.3 mm which is the lowest permissible nugget size in this configuration, i.e 4√t, where t is taken as 1.2mm.
- Welds were performed at 5.9 KA, 6.5 KA, 7 KA, 7.5 KA and nugget diameters were found inside the permissible range and the failure was 'pull out' type. In Fig 4.3 peeled off sample at 5.9 KA is shown. After step by step removal of the sheets in peel test, the following nugget was exposed. The whole nugget was attached to one of the middle sheets as shown in above Fig 4.3. The weld nugget consists of different steps as it was peeled off from different

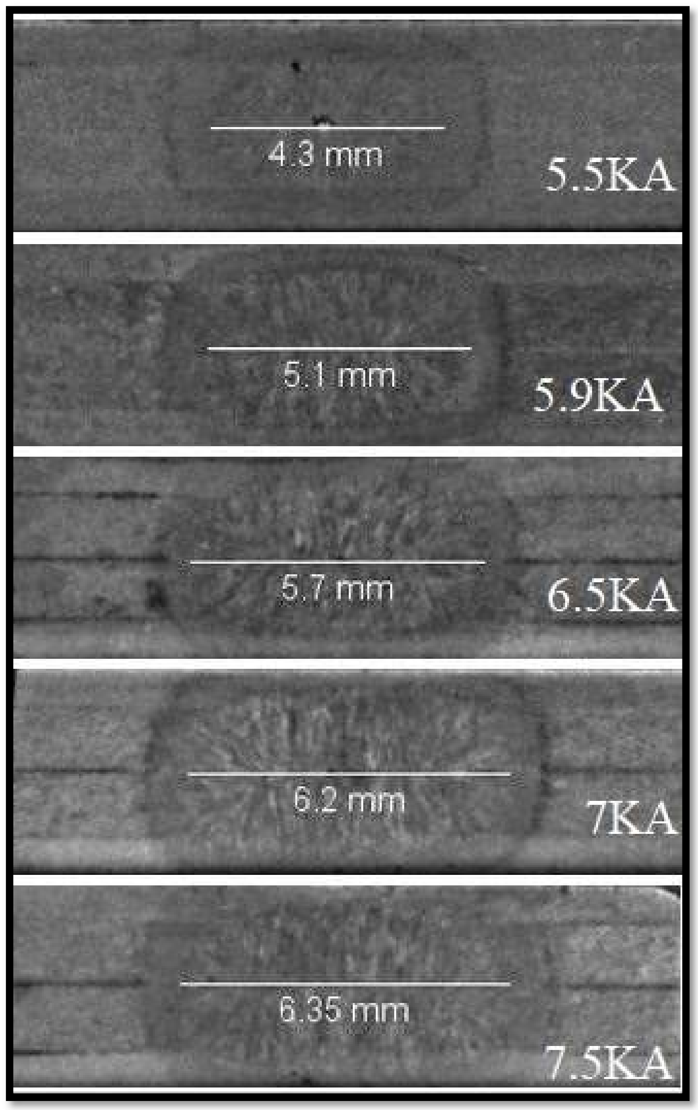

Fig 4.7 nugget growth with increase in current input

sheets. Fig 4.4 shows both the sides of the sheet containing the whole nugget for better understanding. In Fig 4.4 (b) two steps in the nugget can be
seen. The upper step peeled off from the outer sheet has less diameter compared to the lower step which was peeled off from the sheet in between. Fig 4.4 (a) contains the part of the nugget which was peeled from the outer sheet containing only one step.

- At 8 KA interfacial expulsion was observed and the current was not increased beyond this.
- In fig 4.7 macrostructure of the samples are shown, starting from 5.5KA to 7.5KA. It is evident that with an increase in current input, the fusion zone increases. The graphical representation of which is shown in fig 4.6.

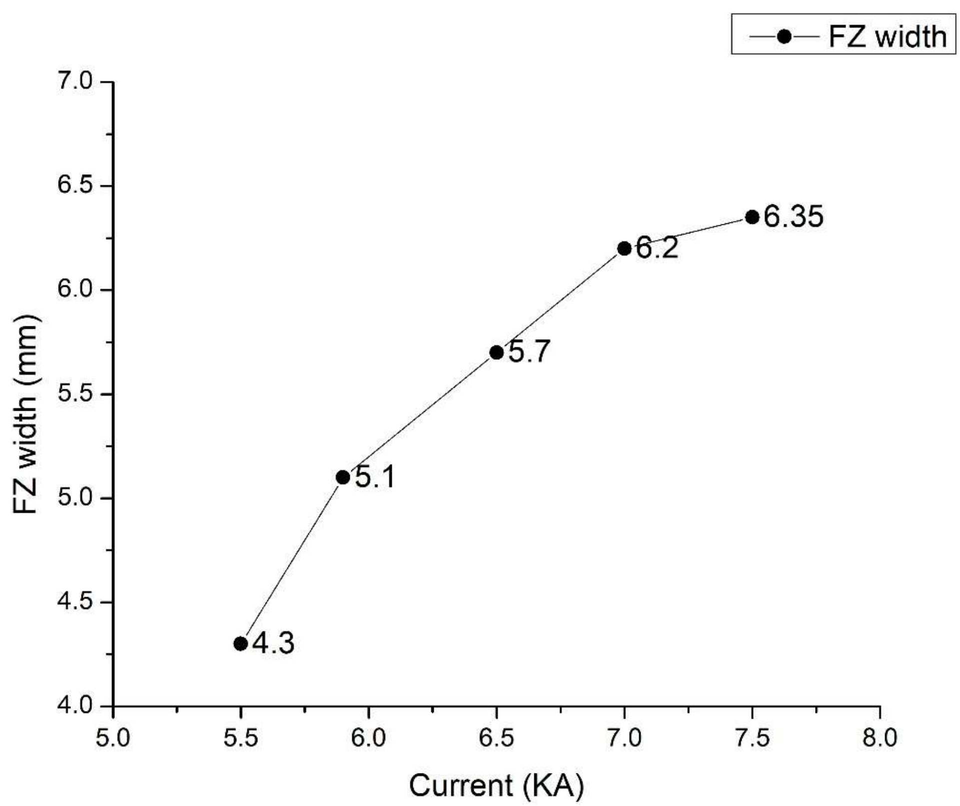

Fig 4.6 Variation of FZ width with Current

4.2. Microhardness distribution

Fig 4.8 shows the hardness profile of the sample welded at 6.5 KA. The indentations were taken at an interval of 0.5 mm with diamond indenter. The average hardness of the weld zone was found to be 240 HV. A rise in the hardness value is observed near the boundary of the fusion zone on either side. This may have happened because of the high cooling rate of that zone. The zone being near to the base metal has undergone high cooling rate and led to the formation of martensite. Hardness value gradually decreased through the HAZ and at base metal, it came to an average of 125 HV

Table 4.1 shows the hardness values of the weld zones at different current inputs starting from 5.5 KA to 7.5 KA.

Table 4.1 Microhardness of weld zone at different current inputs

Current	Hardness of weld zone (HV)	Average value of hardness (HV)
5.5	231.2	249
	227.8	
	287.8	
5.9	246.4	250.16
	244.5	
	259.6	
6.5	268.7	257.36
	260.3	
	243.1	
7	237.1	231.46
	226.7	
	230.6	
7.5	263.7	248.2
	237.1	
	243.8	

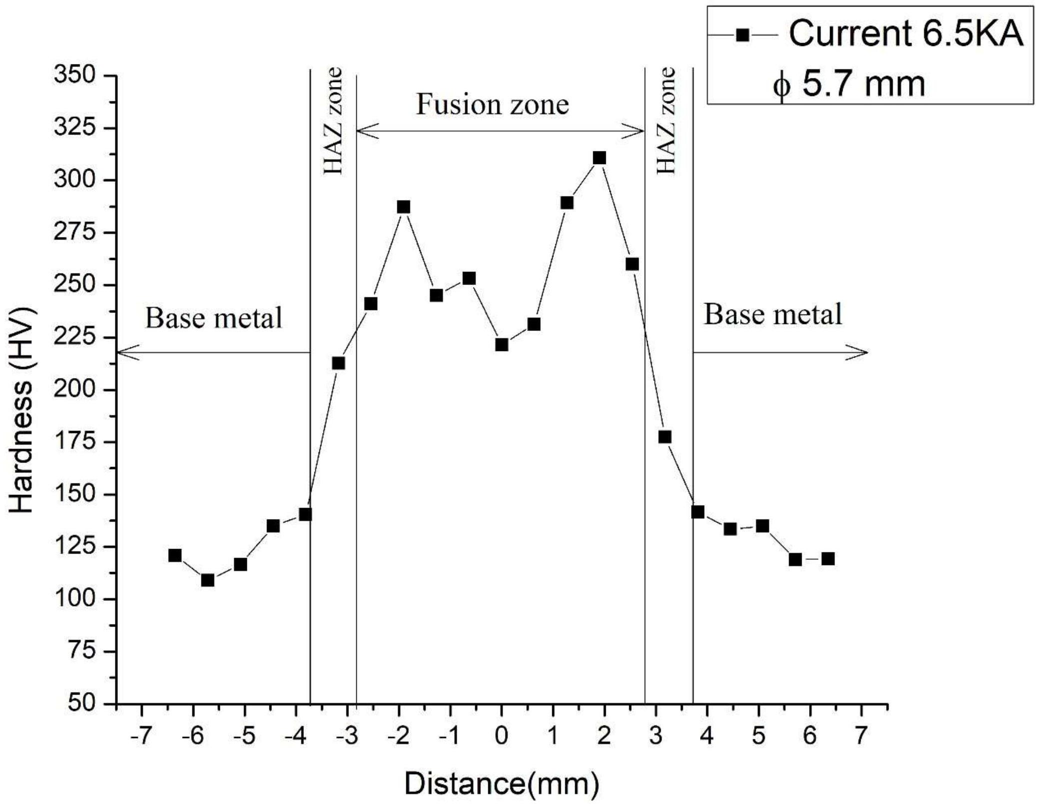

Fig 4.8 Hardness profile at 6.5 KA

4.3 Microstructure of weld zone

Fig 4.9 (a) shows macrostructure of fusion zone consisting of columnar grains. Fusion zone is melted and resolidified during welding process thus showing a cast structure. [15] Fig 4.9 (b) shows the microstructure of base metal which consists of ferritic grains and the corresponding hardness is about 125 HV. Fig 4.10 shows the microstructure of the weld zone that is composed mainly of lath martensite and proeutectoid ferrite. Martensite formation in FZ is attributed to the high cooling rate during RSW process due to the presence of water-cooled copper electrodes and their quenching effect as well as short welding cycle. [8] In coarse-grained HAZ, which is adjacent to the FZ, both high cooling rate and large grain size promote the formation of the martensite.

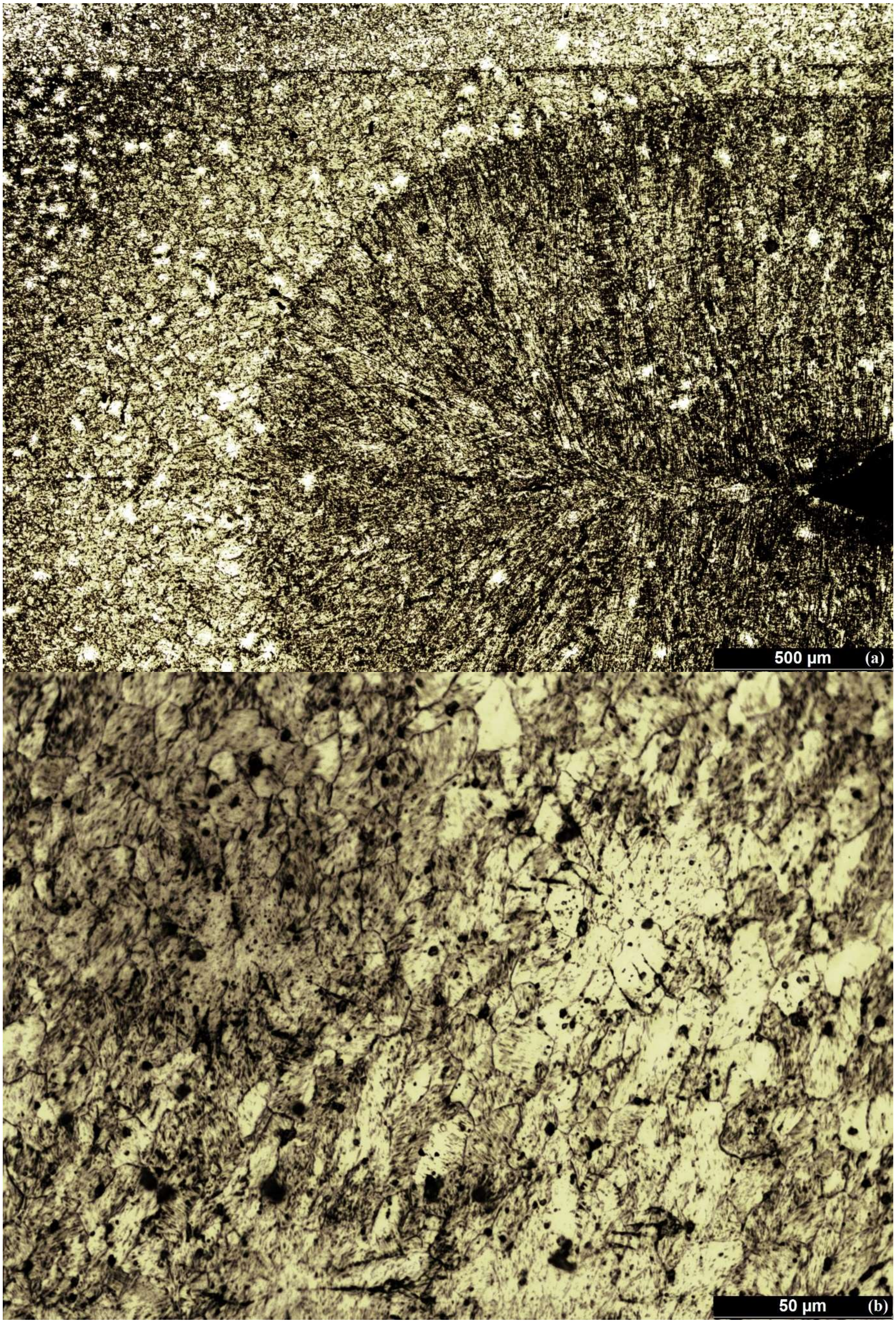

Fig 4.9 Macrostructure of partial fusion zone and HAZ (a), Microstructure of base metal(b)

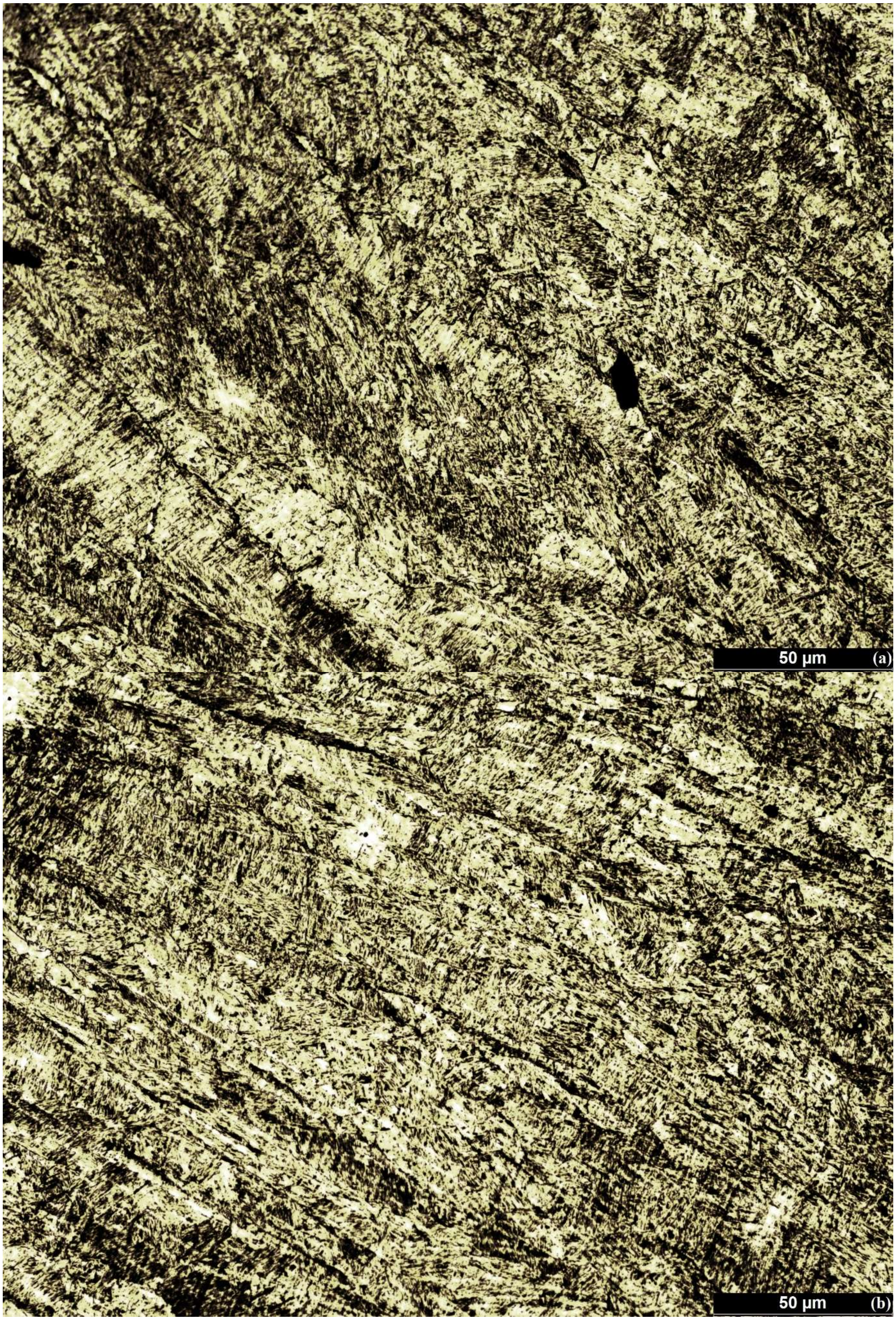

Fig 4.10 (a),(b) Microstructure of fusion zone

4.4 Load bearing capacity

The specimens for shear tension were prepared according to the BS 1140 taking the standard sheet thickness as 1.2 mm shown in fig 4.12. Quasi-static tensile–shear tests were performed at a crosshead speed of 2 mm/min with a universal testing machine. Peak load values were extracted from the load-displacement curve. The failure mode was determined from the failed samples and mentioned in table 4.2. Fig 4.11 shows specimens of two different configurations, as discussed earlier, after failure in shear tension test. In both the configurations nugget was pulled out from the specimens. In config 1 nugget was torn away from both the sheets exposing

Fig 4.11 Config1 and Config 2 after failure

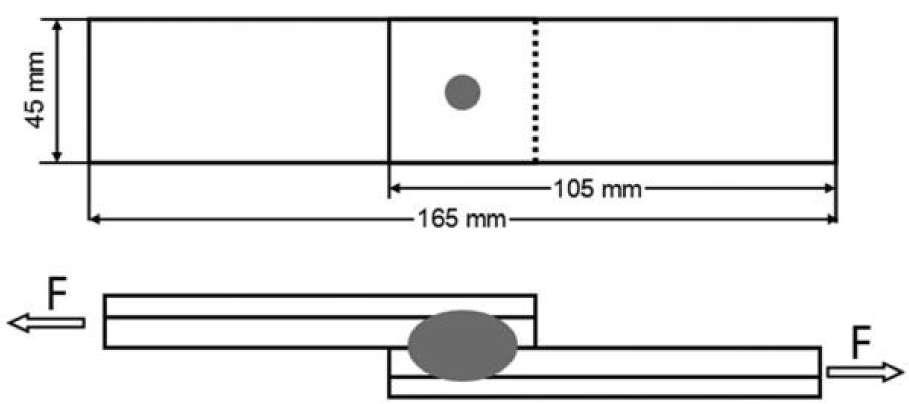

Fig 4.12 Tensile test specimen dimensions

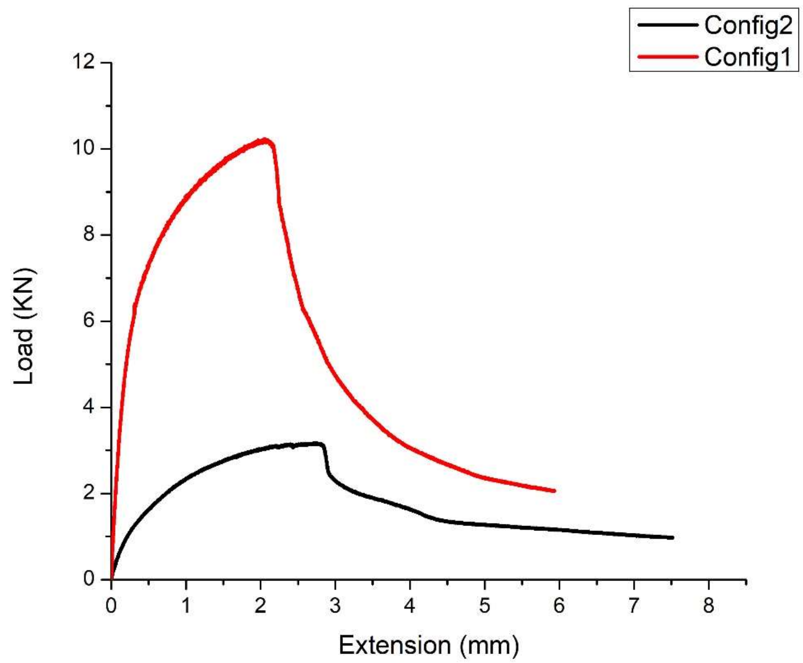

Fig 4.13 Load-Extension plot for Config 1 and Config 2

the full nugget, but in case of config 2 only the outer sheets were torn and the nugget was intact within the middle sheets, thus consuming less energy and evidently, config 2 has a lot less load-bearing capacity. The load vs extension plot for both the samples is shown in fig 4.13.

Thus, config 1 was chosen as the standard specimen for shear tension test. Table 4.2 shows the maximum load-bearing capacity of the specimens, weld at different current levels and also the type of failure occurred during the tests.

Table 4.2 Load bearing capacity and failure modes

Current (KA)	Maximum load (KN)	Average (KN)	Type of failure
5.9	9.06	9.43	Interfacial Failure
	9.8		
6.5	10.6	11.15	Pull out
	11.7		
7	11.9	12	Pull out
	12.09		
7.5	12.2	12.65	Pull out
	13.1		

Though the nugget size was inside permissible range at 5.5 KA, shear tension test was not performed at this level as at much higher current, i.e. 5.9 KA, interfacial failure was observed in shear tension test. Fig 4.14 shows a comparative representation of load-extension plots at different current input.

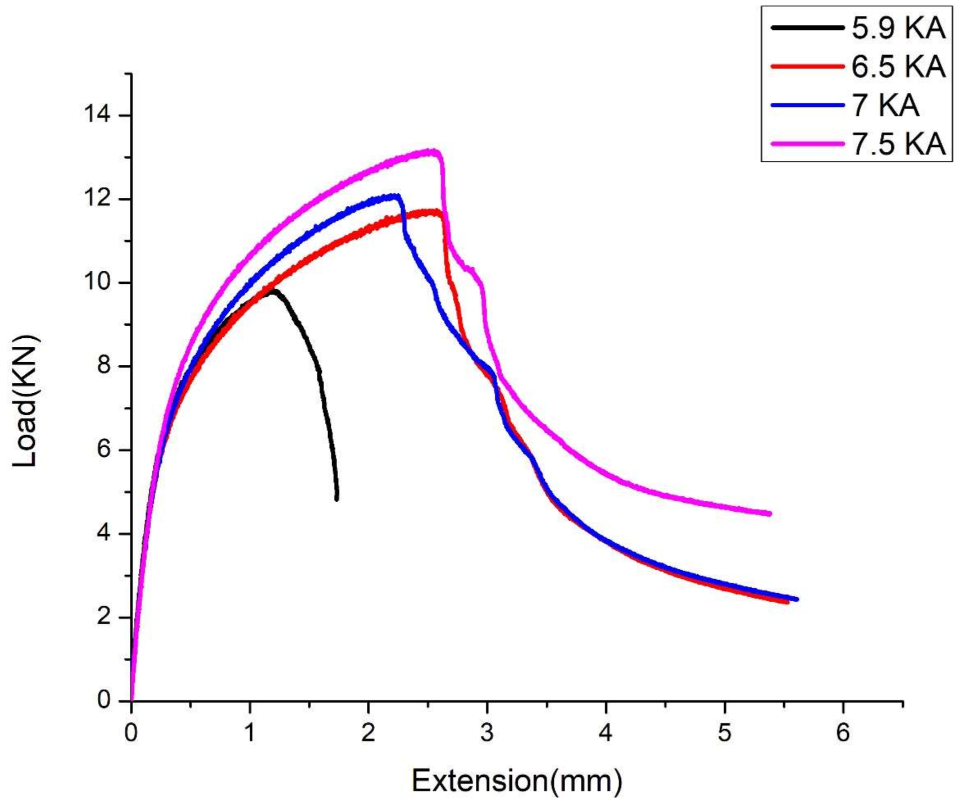

Fig 4.14 Tensile plots at different current inputs

Due to the fact that there are two sheets overlapped in the place of one sheet in the sample dimension according to the BS1140, the two sheets are strong enough to hinder the rotational movement that produces a mixed loading of shear and tension. When the nugget size is not large enough to withstand the minimum amount of force required to start the rotational movement of the overlapped section, it tends to fail interfacially. When the current was increased to 6.5 KA the nugget grows sufficiently to withstand the minimum force required, and the tensile force overcomes the hindrance to the rotational movement, mixed loading of tension and shear set in, leading the failure to 'pull out' type.

Chapter 5

CONCLUSION

Chapter 5

CONCLUSION

The weld nugget development and mechanical properties of four-sheet dissimilar thickness resistance spot welds were investigated. The following conclusion can be drawn from this study.

1. The mechanism of bonding depended on the heat input. The weld nugget was well developed at middle sheet/sheet interface for welding currents higher than a minimum value (i.e. 5.0 kA). There was no fusion at outer sheet/sheet interfaces when using low welding currents. However, metallurgical bonding was achieved by a solid-state mechanism at the outer interfaces. Increasing welding current beyond a critical value (i.e. 5.5 kA) led to penetration of weld nugget into both the outer sheet/sheet interfaces. At 8 KA interfacial expulsion was observed.
2. Absence of weld nugget at the outer sheet/sheet interfaces were caused by the quick heat removal by the water cooled electrodes. Therefore higher heat input was required in order to make the nugget penetrate in to all the sheets.
3. The fusion zone had a columnar dendritic structure that contained lath martensite and some amount of proeutectoid ferrite.
4. The failure mode was controlled by weld nugget size. Beyond a critical value of nugget size Pull out mode failure was ensured.
5. Due to the hindrance to moment formation during shear tension tests, shear stress was predominant leading to IF failure below a critical value. This made the current range even shorter from 6.5 KA to 7.5KA.

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