SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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PREDICTION USING REGRESSION MODEL FOR TENSILE SHEAR STRENGTH OF RESISTANCE SPOT WELDING 5052 ALUMINIUM ALLOY USING FULL FACTORIAL DESIGN MODEL

By

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DECLARATION

I hereby declare that I have conducted, completed research project and written the dissertation entitled **"Prediction Model for Tensile Shear Strength of Resistance Spot Welding 5052 Aluminium Alloy Using Full Factorial Design."** I also declare that it has not been previously submitted for award of any degree or diploma or other similar title of this for any other examining body or University.

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LIST OF ABBREVIATION

RSW	Resistance Spot Welding
FFD	Full factorial design
FZ	Fusion zone
HAZ	Heat affected zone
BZ	Base metal zone
DOE	Design of experiment
XRF	X-ray Fluorescence
AWS	American Welding Society

LIST OF SYMBOLS

kA	Kiloampere
ms	Milisecond
mm	Milimeter
MPa	Megapascal
HV	Vickers Hardness

RAMALAN MODEL UNTUK KEKUATAN TEGANGAN RICIH KIMPALAN RINTANGAN BINTIK ALOI ALUMINIUM 5052 MENGGUNAKAN REKA BENTUK FAKTORIAL PENUH

ABSTRAK

Coraza Systems Malaysia Sdn. Bhd. adalah syarikat berasaskan kepingan besi yang menghasikan produk seperti alat aeroangkasa, alatan elektrik dan perkakas rumah. Terdapat masalah mengenai kekuatan pada sambungan kimpalan untuk produk aloi aluminium 5052 yang dicantum menggunakan proses kimpalan rintangan bintik. Projek ini dijalankan untuk mengkaji faktor yang paling mempengaruhi dan untuk mengkaji tindakbalas terbaik antara parameter kimpalan rintangan bintik. Parameter proses kimpalan yang digunakan adalah arus elektrik kimpalan, dalam kA (20.0, 18.2, 16.3), masa kimpalan, dalam ms (0.2475, 0.2250, 0.2025) dan tekanan kimpalan, dalam bar (1.144, 1.040, 0.936). Reka bentuk faktorial penuh digunakan untuk menghasilkan reka bentuk matriks untuk penyelidikan ini. 11 eksperimen dijalankan berdasarkan reka bentuk matriks yang terhasil. Teknik analisis varians digunakan untuk mendapatkan faktor yang paling mempengaruhi dan tindak balas mereka terhadap kekuatan tegangan ricih berdasarkan nilai-P faktor tersebut. Faktor yang paling mempengaruhi untuk kimpalan rintangan bintik adalah arus elektrik kimpalan dengan nilai keberangkalian sebanyak 0.003 di mana nilai tersebut lebih rendah daripada 0.05. Model matematikal yang terhasil daripada ANOVA adalah Y= 209.018 -11.9395 C + 95.5389 T -291.238 P + 17.8590CP. Nilai koefisien R^2 yang dikira adalah 91.13% dimana nilai tersebut menandakan kesesuaian model terhadap keputusan eksperimen. Kekuatan tegangan ricih yang diperoleh adalah 63.61 MPa melebihi nilai kekuatan tegangan ricih kebiasaan parameter yang diguna di Coraza iaitu 41.05 MPa. Reka bentuk faktorial penuh adalah kaedah yang efektif untuk mendapatkan faktor yang mempengaruhi kekuatan tegangan ricih pada sambungan kimpalan rintangan bintik untuk aloi aluminium 5052.

PREDICTION OF MODEL FOR TENSILE SHEAR STRENGTH OF RESISTANCE SPOT WELDING 5052 ALUMINIUM ALLOY USING FULL FACTORIAL DESIGN

ABSTRACT

Coraza Systems Malaysia Sdn. Bhd. is a sheet metal company which produce sheet metal products such as aerospace part, electrical part and home appliance. There was a problem on strength of weld joint of 5052 aluminium alloy product which was assembled by RSW process. This project was conducted to study on the significant factor and to find the best interaction between resistance spot welding (RSW) parameters. The welding process parameters involved are weld current, in kA (20.0, 18.2, 16.3), weld time, in ms (0.2475, 0.2250, 0.2025) and weld pressure, in bar (1.144, 1.040, 0.936). Full factorial design (FFD) was employed for the development of design matrix for this research. 11 experiments were conducted based on the designed matrix. Analysis of variance (ANOVA) technique was applied to obtain the most significant factors and their interaction effect on tensile shear strength based on the P-value of the factors. The most significant factor found for RSW process was weld current with 0.003 probability value which was lower than 0.05. The linear-square model developed using ANOVA was Y= 209.018 -11.9395 C + 95.5389 T -291.238 P + 17.8590 CP. The coefficient of determination R^2 calculated was 91.13% which the value indicated that the compatibility of the model to the experimental result. The highest tensile shear test obtained from the experiment was 63.61 MPa which was higher compared to the typical used parameters at Coraza for 5052 aluminium alloy with tensile strength only 41.05MPa. The FFD employed in this project proved to be an effective tool to find the significant factors of RSW process which contribute to the tensile shear strength of 5052 aluminium alloy.

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

Resistance spot welding (RSW) is one of the metal joining method used in industries. RSW is a rapid joining method for sheet metal joining purposes in various application such as automotive parts, aerospace parts, home appliances and electronic parts. The advantages of using RSW method are it is a rapid joining process. There are no other consumables need to assist the welding process. RSW is a clean and environmentally friendly welding process. The strength of the joint also is reliable by electro-mechanical joint. A simple heat generation process occurs in RSW operation. The heat generates by the passage of current through resistance. The operation is almost the same as the heating coil. There are several parameters that need to be considered in RSW operation. There are weld current, weld time, weld pressure and electrode tip diameter. In industries, RSW process is perform using automated system of robot. Minimum skill requirements needed to perform this process. The disadvantage of the RSW technique are the capital cost for the equipment is high and the difficulty in disassembly the undesired welding joint (Sahota, Singh et al. 2013)

The typical configuration of the weld joint is lap joint between two sheets metal. RSW is the overlapping pieces of sheet metals at a spot by the application of pressure and electric current. Copper alloy is the common material to be used as the electrode of the spot welder machine. The copper electrode will then apply pressure to the workpieces and passed the electric current through it. The resistance between the upper electrode and lower electrode will generate heat at the workpiece and the heat will develop at the interface between the two sheet metal (Anas, 2014). At the sheets metal interface, weld pool is developed and with the assist of pressure by the electrodes the weld pool then cooled and form a joint called weld nugget between the workpieces material (Larry,2002).

Coraza System Malaysia Sdn. Bhd. is a company which providing excellent services in joining sheet metal parts. Spot welding process is one of the joining method that taken in Coraza Systems Malaysia Sdn. Bhd. in producing the sheet metals products that desired by the customer. Examples of products that produced by Coraza Systems Malaysia including CPU cover, medical machine cover, PECVD skeleton chamber and aerospace parts. Most of the products that Coraza Systems Malaysia Sdn. Bhd. made are sheet metal base material. The materials used include aluminium, stainless steel and cold-rolled steel (CRS).

The use of RSW in joining lightweight aluminium alloy is increasing (Rapp, Glumann et al. 1995). The usage of aluminium alloy is increasing due to its lightweight properties with significant mechanical properties which almost similar to steel. The demand on the lightweight materials in industries is high to decrease the power consumption, the load and the cost of the materials. In automotive industries, lighter materials need to be used as the automotive part which can reduce the load and enhance the fuel efficiency (Sun et al. 2007).

In resistance spot welding, the weld nugget starts to form when there is sufficient heat generated at work piece interface. The nugget formation largely depends on the resistance spot welding process parameters which are weld current, weld time, weld pressure and electrode tip diameter. The parameters need to controlled to prevent any weld discontinuities. It is important to choose and control the spot welding process parameters for obtaining optimal weld strength (Eşme 2009).

Design of experiment (DOE) method can be used to develop mathematical model. This mathematical models will undergo validation process to determine either the models are valid or not. Several DOE methods can be used such as Taguchi method, Full Factorial Design and Response Surface Methodology (RSM). The DOE methods are important in development, process improvement, optimizing parameters and improvement of existing product designs (Hinkelmann and Kempthorne 2012). Study on the optimization parameters of resistance spot welding has been made by Ugur Esme (2009) by using Taguchi method, one of the DOE method. Full factorial design was used to develop the design matrix of the experiments and the significant factor will be determined by the construction of ANOVA table. The validation of the model develop by ANOVA is validate by performing confirmation test base on the model of the experiment.

Several studies have been taken in determining the optimize parameters of resistance spot welding for materials such as aluminium alloy, stainless steel, cold rolled-close atmosphere steel and mild steel. The Design of experiments (DOE) technique have been adopted to determine the optimize parameters for RSW. Studies on the RSW of 5xxx series aluminium alloy was conducted by Han L.Thornton (2011) and optimizing RSW parameters of 1xxx series aluminium alloy by using response surface methodology (RSM) by Anas (2014). Prashanthkumar (2014) used full factorial design for parameter selection for resistance spot welding through the thermal analysis on the cold rolled closed annealed steel (CRCA) sheets metal with 2 mm thickness. The optimum process parameters for the spot welding process were obtained by comparing the experimental and the simulation result.

1.2 PROBLEM STATEMENT

In Coraza, 5052 Aluminium alloy with thickness 1.2 mm was joined together forming two layer of material by resistance spot welding process. The strength of the spot welding is likely depend on the quality of the weld nugget that form between two sheets of the material. The current problem on the resistance spot welding process in Coraza on 5052 aluminium alloy with 1.2 thickness has be found due to the formation of undersize weld nugget which the weld nugget size formed does not achieved the minimum requirement for 1.2 mm aluminium sheet metal by AWS D17.2 (American Welding Society) which is 4.57 mm. Undersized weld nugget lowered the tensile shear strength of the joint and reduced the weld quality. Thus, this study is taken to investigate the significant factor of the resistance spot welding parameters on the tensile shear strength of the welded joint which depend on the weld nugget size. Most common problem that occur in resistance spot welding is formation of undersized weld nugget. This problem occurs when the applied current is too low and the weld time for the welding process is too short. Undersized nugget will eventually lower the strength of the weld. Others welding surface problem such as burn marks due to high current, deep indentation mark due to too high weld pressure and weld splash that form on the surface of the test piece due to too high resistance between the joined materials.

Furthermore, factor that influence the problem in resistance spot welding (RSW) of 5052 aluminium alloy is the weak weldability of aluminium alloy (Anas,2014). Weak weldability of aluminium alloy cause it to have low strength at the welded area. Thus the reduced the weld quality. Different composition of aluminium alloy cause it to have different electrical conductivity and thermal conductivity (Hassanifard, Zehsaz et al. 2011). Thus, different series of aluminium alloy is likely to have different setting of parameters for RSW due to the different in the composition. Thus, there are several problems in determining optimal parameters of RSW for aluminium alloy due to its weldability (TAO, Liang et al. 2012). The composition of the aluminium alloy give different weldability of the aluminium alloy series.

In performing resistance spot welding process, several parameters need to be consider to produce high quality weld. Parameters of resistance spot welding are welding current, welding time, welding pressure and electrode tip diameter. In 2014, Anas has made a study on the effect of welding current, welding time and electrode diameter to the tensile shear strength of aluminium 1100. He has found that the weld nugget size is important in determining the tensile shear strength of the joint. Weld nugget size can be controlled by controlling the parameters of the resistance spot welding process. Different set of parameters produce different size of weld nugget. By using statistical mathematical method, the parameters of resistance spot welding can be optimized.

This problem can be solved by applying full factorial design (FFD) method to determine the most significant factors and interaction between parameters for the resistance spot welding process for 5052 series of aluminium alloy. The optimize outputs variables can be determined by generating mathematical models. Mathematical obtained can be used as the guideline for operators at Coraza Sytems Malaysia Sdn. Bhd. to set the parameters to a level which fulfilled the requirement from customer. The model developed also indicate the most significant factors in RSW process.

1.3 OBJECTIVES

1. To find the significant factors of resistance spot welding process based on three factors which are weld current, weld time and weld pressure.
2. To develop full factorial model for investigating the interaction between the factors for resistance spot welding by using full factorial design.
3. To investigate the effect of the most significant factor on the weld morphology, the tensile shear strength and the microhardness of the three zones (Fusion zone, heat affected zone and base metal zone).

1.4 SCOPE OF WORK

This project focused on the finding of the most significant factor of RSW process for 5052 aluminium alloy and measuring the weld nugget diameter for the spot welded 1.2 mm 5052 aluminium alloy. This step taken to ensure the weld nugget diameter achieve the minimum requirement diameter which was set by AWS D17.2 for 1.2 mm aluminium sheet thickness which is 4.57 mm of weld nugget diameter. 5052 aluminium alloy sheet metal with 1.2 mm thickness was used in this project. Material characterization such as X-ray fluorescene (XRF) was used to determine the chemical composition of 5052 aluminium alloy. The RSW parameters selected for this project were weld current, weld time and weld pressure. Full factorial design technique was used to develop design matrix of experiments with different set of parameters value. The tensile shear strength of the spot welded joint was investigated by using Instron Universal Testing machine at 10 mm/min of cross head speed. The tensile shear strength was performed three times for each set of parameters and the average value was taken as the final value so the value is more accurate. Mathematical model, contour plot and surface plot were generated from the analysis of variance table (ANOVA). Then, confirmation test was performed by selecting five set of parameters from the contour plot to be tested. Microstructure evaluation on the three zones (fusion zone, heat affected zone and base metal zone) was performed by ground the mounted samples with silicon carbide paper and polished using diamond paste. Etchant used was 5% of hydrofluoric acid (HF). The microstructure was observed by using optical microscope (OM) to investigate the behaviour of the weld morphology. The hardness of weld area was measured by Vickers hardness (HV) technique.

CHAPTER 2

LITERATURE REVIEW

2.1 ALUMINIUM IN INDUSTRIES

Nowadays, aluminium is used widely in variety of application. The combination of high strength and low density caused aluminium to be used in many applications such as in aerospace, automotive, food packaging and electronic parts. The corrosion resistance properties of aluminium to the atmosphere are also desired at various application. Aluminium oxide thin film forms over the aluminium surface to protect it from corrosion. Aluminium can be produce in various form either in sheet, bulk, film or even powder (alumina powder).

2.2 ALUMINIUM ALLOYS

Aluminium is one of the most abundant metal in the earth. Aluminium alloys is a family of aluminium which classified in series. Aluminium alloys are alloys in which the predominant metal is aluminium. In alloys, there are several alloying elements that added into the predominant metal to either increase the properties of the predominant metal or to lowered its properties depends on purposed use of the aluminium alloys. The typical alloying elements in aluminium alloys family are magnesium, copper, manganese, tin, zinc and silicon. Aluminium alloys also are classified base on two group which are casting alloys and wrought alloys. Both of casting alloys and wrought alloys are subdivided into two categories which are non-heat treatable and heat treatable. Most of the aluminium is used for the wrought product besides that cast aluminium has much lower melting point which likely to yield cost-effective products. By comparing the tensile strength between wrought aluminium alloys and cast aluminium alloys, wrought aluminium alloys generally have higher tensile strength compare to cast aluminium alloys.

The high level composition of silicon in cast aluminium alloys is one of the important alloying system (Al-Si) which give the excellent casting characteristics. In industries or engineering component or structures light weight metal and a good corrosion resistance metal are desirable (Polmear 1995). Thus, aluminium alloys becoming one of the popular choice for having those characteristics and properties.

2.3 ALUMINIUM ALLOYS DESIGNATION SYSTEMS

It is so important to understand the aluminium alloys designation system in order to classify the types of aluminium alloys based on their group either wrought aluminium alloys or cast aluminium alloys. Each group of aluminium alloys are then subdivided based on the series of the aluminium alloys. The Aluminium Association Inc. is the one which is responsible for the registration and classification of aluminium alloys. There are over 200 form of casting and ingots of aluminium alloys and over 400 wrought aluminium alloys registered with Aluminium Association. Aluminium alloys classified into numbers of group. These groups are based on either particular material's characteristics such as the aluminium alloys ability to respond to mechanical or thermal treatment or the aluminium alloys are classified based on the primary alloying element that is added into the predominant aluminium.

The identification systems used to classify the types of aluminium alloys is the numbering system and is also known as series system. Each cast aluminium alloys and wrought aluminium alloys have different styles of numbering system for the identification. The cast aluminium alloys having 3-digit and 1-decimal place system. The examples series of cast aluminium designation system are 1xx.x, 2xx.x, 3xx.x, 4xx.x, 5xx.x, 6xx.x, 7xx.x, 8xx.x and 9xx.x. While, the wrought aluminium alloys system is a little bit different from cast aluminium alloys system. The wrought aluminium alloys having 4-digit systems to classify the alloy series for wrought aluminium alloys. The examples of series of wrought aluminium designation system are 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, 7xxx and 8xxx. Table 2.1 shows for the cast aluminium alloys designation system.

Table 2.1: Cast aluminium alloys designation system (Polmear, 1995)

Alloy Series	**Principal Alloying Element**
1xx.x	99.00% minimum Aluminium
2xx.x	Copper
3xx.x	Silicon, Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused Series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other elements

The cast aluminium alloy designation system having three digits and one decimal digit. The specific alloys used in the series is indicated by the second and the third digits. The number is then followed by the decimal point which indicates whether the alloy is a casting or an ingot. The casting aluminium alloy will indicated by the zero digit (.0) while for an ingot aluminium it is indicated by number 1 and 2 (.1 or .2).

The modification on the cast aluminium to a specific is also indicated by a capital letter prefix. For an example, A356.0 is a cast aluminium alloy. The capital A indicates the modification of the 356.0 alloy. The first digit which is number 3 indicates the presence of silicon and copper or/and magnesium in the aluminium alloy. The first digit indicates the series of the aluminium alloy. The second and the third digits which is 56 for A356.0 cast aluminium alloy indicates the aluminium alloy is within 3xx.x series. Lastly, the zero decimal (.0) will indicates the final shape of the cast aluminium is in casting not in ingot form. Different from the cast aluminium alloy designation system, wrought aluminium alloy designation system used 4-digit identification system. Table 2.2 shows the wrought aluminium alloy designation system.

Table 2.2: Wrought aluminium alloy designation system (Polmear, 1995)

Alloy Series	**Principal Alloying Element**
1xx	99.00% minimum Aluminium
2xx	Copper
3xx	Silicon, Copper and/or Magnesium
4xx	Silicon
5xx	Magnesium
6xx	Unused Series
7xx	Zinc
8xx	Other elements

The wrought aluminium alloy designation system is different from the cast aluminium alloy designation system. The first digit of the series indicated the added element in the aluminium alloy and the series of the wrought aluminium alloy. For the second digit, it indicates a modification of specific alloy in the series if the second digit is not a zero. For an example, Aluminium alloy 5052, the first digit which is 5 indicates that the wrought aluminium alloy is from the magnesium alloy series. The second digit is zero, indicates there is no modification made to the aluminium alloy and lastly the 52 identifies it in the 5xxx series. There is an exception to the numbering system for 1xxx series of wrought aluminium alloy where the last 2 digits indicates the minimum aluminium percentage above 99.00% for an example for wrought aluminium alloy 1350 series the minimum aluminium is 99.50%.

2.3.1 Aluminium 5052

Aluminium alloy 5052 is from 5xxx series alloys from wrought aluminium alloy. The principal alloying element for 5xxx series is magnesium. The magnesium additions ranging from 0.2% to 6.2%. This alloys have the highest strength of the non-heat treatable alloys. Aluminium alloys 5xxx series is also readily weldable. A good weldability properties cause this aluminium alloy series to be used widely in variety of application such as automotive parts, shipbuilding, aerospace parts, pressure vessels and buildings. This 5xxx aluminium alloys series are widely being used in the structured which required low-temperature properties and high corrosion resistance (Mondolfo 1976).

2.4 RESISTANCE SPOT WELDING IN INDUSTRIES

Resistance spot welding (RSW) has been widely used in automotive and aerospace industries. The ability of the resistance spot welding to joint sheet metal make it as one of predominant joining technologies. This technology is applied to assembly sheet metal parts such as car body, aerospace, electronics and electrical appliances parts. Furthermore, resistance spot welding is one of the cost saving welding process. Most of the spot welders are automated. Thus, it can promote the accuracy and the consistency of the welding process. Resistance spot welding also do not need any extra materials or fillers to complete the welding process. Resistance spot welding also is widely used in electronics and electrical industry for joining various type of components.

2.5 RESISTANCE SPOT WELDING OVERVIEW

Resistance spot welding (RSW) is a process which two metal surface joint together by the heat generated from the resistance between two electrodes (Larry, 2002). In resistance spot welding, the weld nugget of the welded part is not visible outside the work piece or the product. The work pieces are held together by the force from both electrodes. The process of resistance spot welding involving the thermal, mechanical, electrical and metallurgical factors (Li, Lin et al. 2007).The interaction between mechanical, electrical, thermal and metallurgical is important in determining the process parameters of the resistance spot welding. Typically, the metal sheets thickness range is from 0.5 mm to 3.2 mm. Copper alloy electrode is used as the electrodes. Two copper alloy electrodes are usually used to concentrate the welding into a small spot on the work pieces and to simultaneously clamp two work pieces together. Resistance spot welding joint to sheet metal together by overlapping two sheet metal then the heat generated from the resistance between two copper electrodes will form a fused nugget between the work pieces. The weld nugget form from the resistance between two copper electrode inside or between the two sheet metal interface. The amount of heat deliver to the materials is depending on the resistance between the electrodes and magnitude and duration of the applied current.

There are several parameters that need to be considered in the resistance spot welding process such as weld time, weld current, air pressure, electrodes tip diameter, material thickness, squeeze time and hold time. The required amount of time current flows in the joint is determined by material thickness and type of materials, the amount of current flowing, and the cross-sectional area of the welding tip contact surfaces. Figure 2.1 show the schematic of resistance spot welding and the weld nugget form after the welding process.

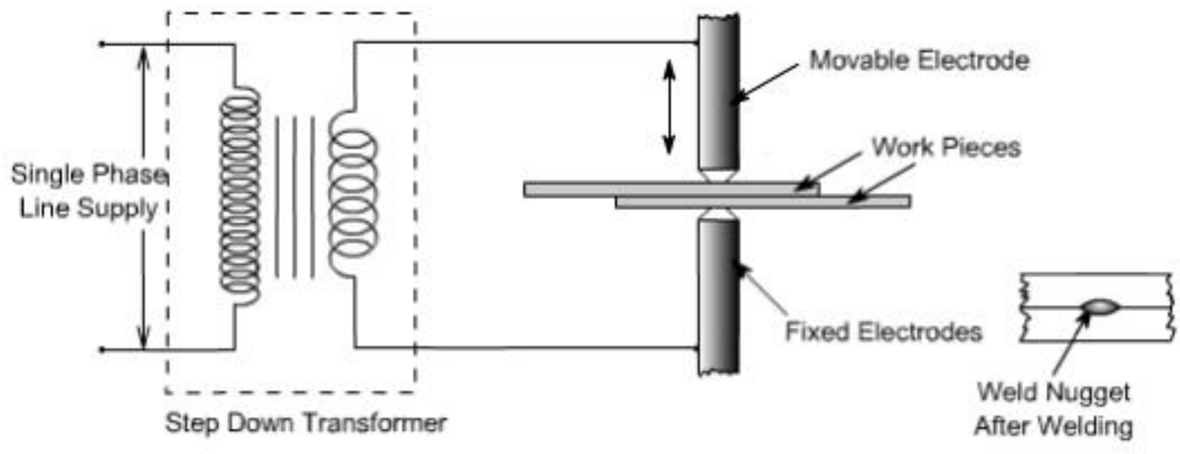

Figure 2.1: Schematic of resistance spot welding (Millers handbook, 2010)

2.6 ADVANTAGES AND DISADVANTAGES OF RESISTANCE SPOT WELDING

Resistance spot welding (RSW) is one of the metal joining process which used resistance between two electrodes to form weld nugget between the work pieces. Joining two work piece of metal can be quick and efficient by spot welding process. The advantages of resistance spot welding process are the process of RSW is comparatively low cost compare to other welding processes. Handling a spot welder machine does not need highly skilled worker. Thus, it can actually lower the labour cost. The process of resistance spot welding can be done either automatic or semi-automatic. In a car body assembly factory, spot welder machines can produce up to 200 spot in six second. Furthermore, the range of thickness of the work piece can be as thin up to 0.5mm sheet thickness. Multiple sheets metal can be join at one time.

However, there will still have disadvantages from resistance spot welding process. For resistance spot welding, the initial equipment cost of spot welder machine is the higher that others conventional arc welding machine (Pires, Loureiro et al. 2006). Resistance spot welding also can only create localized joint, which the welded zone is only at one spot. The joint might not be particularly strong. The spot welded joint is highly depended on the parameters of the spot welding machine and the cleanliness of both the work piece and the electrodes. The maximum sheet metal can be spot welded is 4 mm. Thus, resistance spot welding not suitable for thick materials.

2.7 RESISTANCE SPOT WELDING PARAMETERS

In resistance spot welding, the parameters of the welding process are important in determining the weld quality and the weld nugget formation. There are several process parameters that need to be considered during the welding process. Parameters in resistance spot welding process will determine the strength and quality of the welded work piece. The three main parameters in resistance spot welding are welding current, welding time and electrode force which also known as the welding pressure. Other parameters such as squeeze time, hold time and diameter of the electrode contact surface only plays minor role in the resistance spot welding process. All these parameters can be controlled on the resistance spot welding machine (Williams and Parker 2004). Determination of optimized welding parameters is a complex issue. In resistance spot welding, a change of one parameter might affect other parameters.

2.7.1 Weld Current

In resistance spot welding, welding current is one of the most important parameter in determining the quality of the weld. The weld current is the current that being used during welding process and usually the unit used is kilo-Ampere (kA). Weld current determine the heat generation during the welding. The principle of resistance spot welding is the Joule heating law. The heat generated is highly depending on the current (I), resistance(R) and time (t). The equation 2.1 shows the Joule heating law is expressed in the formula below:

$$Q = I^2Rt \qquad \text{(Eq 2.1)}$$

Q : Heat generation

I : Current supply

R : Resistance of materials and the contact interfaces

T : Time of current flow

The amount of weld current can be controlled by adjusting the value or percentage that will be given to complete the welding process. The value of weld current is different for each material. Each material has different electrical conductivity and thermal conductivity. Thus, different amount of current is needed to generate sufficient heat to complete the welding process. In resistance spot welding, low amount or percentage of current are not recommended because it might reduce the quality of the weld (Aslanlar, Ogur et al. 2008). The weld nugget size is increases rapidly by the increasing in the weld current during the welding process. Large weld nugget size will give a significant strength to the welded zone but too much current supply might result in deterioration of the electrode and other type of undesired welding defects such as burn marks, spatter and expulsion. Thus, constant current control usually used in welding production to control the size of weld nugget formation and the to obtain a steady process (Zhou and Cai 2013). The typical types of welding current used in resistance spot welding are alternate current (AC), condensator discharge (CD) and middle frequency inverter DC. The most current supply used in the production is alternate current (AC). Figure 2.2 shows the typical type of current used in the resistance spot welding process in industry.

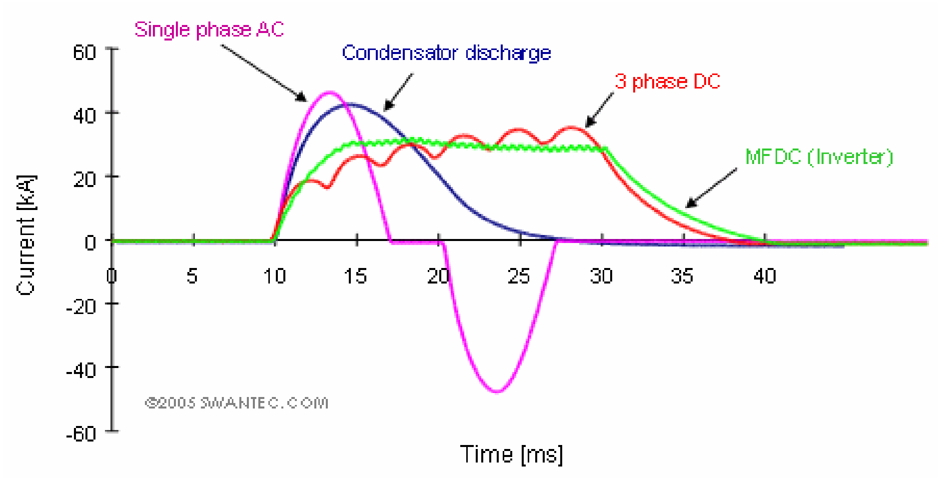

Figure 2.2: Type of currents use in resistance spot welding production (Swantec.com. 2005)

2.7.2 Weld Time

During the resistance spot welding process, the weld time is the time during the weld current is applied to the metal sheet from the copper electrode. The typical units use for weld time are millisecond (ms) or cycles. From the Equation 1 above, time or weld time is directly proportional to the heat generated for the welding process. The welding current (I) and the welding time (t) together will produce the amount of heat energy delivered for the welding process. Too high welding current or too long welding time might promote internal expulsion and oversize weld nugget while too low welding current and too short welding time will reduce the quality of the weld and may induce undersize weld nugget. Prolonged welding time also may induce several weld defects such as indentation mark, weld splash and burn marks or the electrode might stick to the work piece.

2.7.3 Pressure/Welding Force

Welding pressure or welding force may not be included in the Equation 2.1 but it still plays an important role for the resistance spot welding process. The pressure supresses the contact between the surface of the workpieces by the lower and upper electrodes. This force or pressure can induce significant effects on the welding quality. The welding force or pressure influences the resistance spot welding process by the effects on the contact resistance. For the welding process to be completed, the workpieces must be compressed sufficiently with specific pressure to enable the flow of the current through the weld zone. As the same effect as weld current and weld time, too large pressure also can induce internal expulsion from the weld zone. The ejection of molten metal from weld nugget during the welding process due to the weld nugget growing outside the area of the spot where the pressure is given by the electrode (Dennison, Toncich et al. 1997). If the welding process is provided with high welding current, too long welding time and low pressure might induce undesired expulsion. This is because when low pressure given for welding process the contact between two workpieces are not stable. Thus, will create unstable current density distribution on the surface between the workpieces.

2.8 WELDING MORPHOLOGY

During the resistance spot welding process, the workpiece will absorb heat that generated from the current and resistance with sufficient time and pressure weld nugget will form between the interface of the workpieces. In resistance spot welding there are three different welding zone that can be observed under the metallograpy testing. Figure 2.3 shows clearly the separation between fusion zone (FZ), heat affected zone (HAZ) and base metal zone (BM) (Aravinthan and Nachimani 2011). Figure 3 shows the metallographic sample from resistance spot welding study. The metallographic samples were produced using standard procedure with an optical microscope.

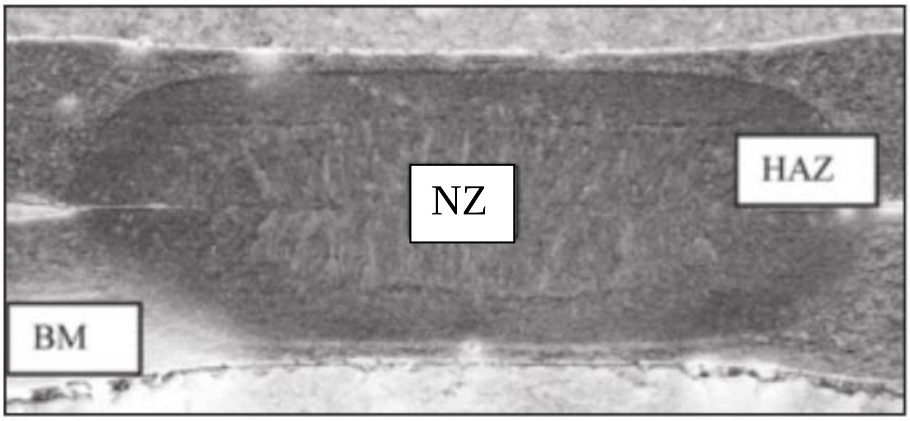

Figure 2.3: Different areas of test sample, nugget zone (NZ), heat affected zone(HAZ) and base metal(BM) (Aravinthan and Nachimani, 2011).

2.8.1 Fusion Zone / Nugget Zone

The fusion zone (FZ) is the melted zone between the interface of the workpieces which is melted during the welding process. The melted fusion zone then is re-solidified and form microstructure which different from the base metal (BM), likely the combination of two workpiece. Columnar grains at the fusion zone can be observed clearly in the Figure 2.3 The fusion zone has different in mechanical properties from the heat affected zone and the base metal zone.

2.8.2 Heat Affected Zone (HAZ)

The heat affected zone (HAZ) is located around the fusion zone. Heat affected zone not involve in melting but still undergoes microstructural changes due to sufficient heat energy for the microstructure to change. The heat affected zone has the same chemical composition as the base metal but the microstructural and the properties of this zone is different from base metal due to the zone has been heat treated. Typically, the results on mechanical properties of heat affected zone is negative compared to fusion zone. The amount of alteration from the heat treatment on HAZ depends on several factors such as the time of the metal being exposed to high temperature, the cooling rate of the process, the distance of the HAZ from fusion zone and the metal's thermal conductivity.

2.8.3 Base Metal Zone

Lastly for the weld zone morphology, the base metal zone (BM). The base metal zone is the original appearance of the materials welded. It has no microstructural or properties changes (Rhodes et al. 1997). The base metal zone located at the outer layer of the weld nugget area.

2.9 DESIGN OF EXPERIMENTS (DOE)

Design of experiments (DOE) is a mathematical and systematic method that used to determine the interaction between variables and thereby determining the optimal parameters and variables of specific process (Goupy and Creighton, 2007). Design of experiments also used to study the relationship between the variables and the responses. The interaction between the cause and effect of the process also can be obtained by using DOE method. Thus, by DOE method the overall process parameters or variables can be optimized and thereby enhanced the performance and productivity of the process. There are various types of DOE method of obtaining desired response from simple DOE to complex method. Optimization method such as Taguchi Method, Artificial Neural Network and Response Surface Methodology can be used to predict the optimized parameters for welding process thereby can give positive effect on the performance and productivity of the welding process.

2.9.1 Design of Experiment Terms and Concepts

There are several terms and concepts that being used in DOE method. There are controllable factors, uncontrollable factors, responses, hypothesis testing, blocking, replication and interaction. These terms and concepts are used through the modelling process until the end of the experiments. Controllable input factors which usually known as *x* factors are the input parameters/variables that can be altered before or during the experiments or process. As for example, the controllable input factors for resistance spot welding process are weld current, weld time and weld pressure. All these factors can be control by adjustment and setting on the spot welder machine. Figure 2.4 shows the process factors and responses of a process.

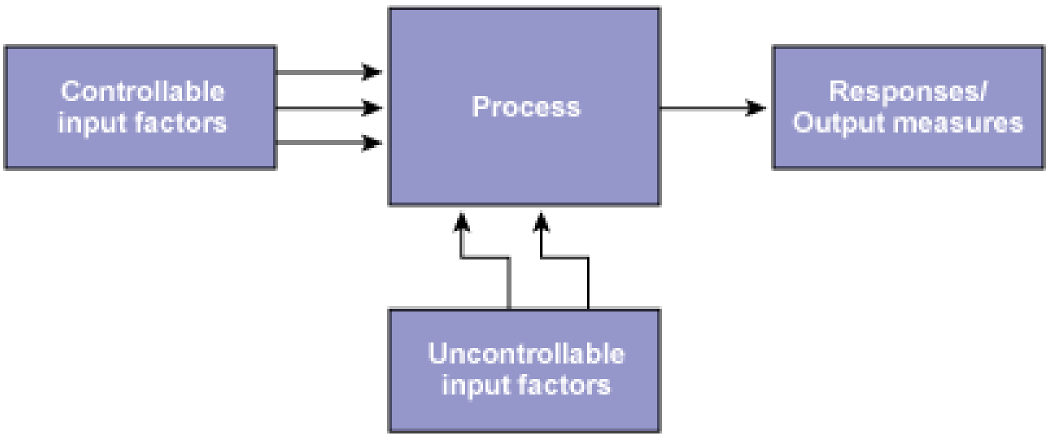

Figure 2.4 Process factors and responses (John Wiley and Sons, 1997)

The uncontrollable input factors are the parameters that cannot be changed. For the resistance spot welding process, the uncontrollable factor of the process is the environment temperature (Productivity Inc, 2000). Since, the process taken at open space area. Thus, the temperature of the cannot be controlled.

The aim of using DOE method is to achieve output(s) that will give the positive impact for the overall experiments or process. Response(s) or output(s) measures are the elements of the outcome of the process or experiments. For resistance spot welding, the desired response is the tensile strength of the welded test pieces. The results from the tensile testing will be used for the optimizing the parameters of the resistance spot welding.

In determining the significant factors of the process or experiments, hypothesis testing is used in DOE. The significant factors of the process can be determined by using statistical method such as Analysis of Variance (ANOVA). In a process or experiments the unwanted variation may exist either by the variation of the equipment or by the human error. These possibilities can be reduced by blocking and replication of the experiments. Blocking and replication used in DOE to reduce the unwanted variation during the process or the experiments. Replication of the experiment also can improve the accuracy of the results. When there are two or more variables in the experiments or process the interaction or relationship between the variables is important in obtaining a good response. The interaction between two variables may effects the response of the experiments or process.

2.9.2 Full Factorial Design

Full factorial design is one of mathematical and systematic from Design of Experiments methods. When a process encountering two or more factors, full factorial design is one of the best method to be used to study the significant factor that effect the overall process or the responses. Full factorial design work by investigating the combination of all factors that exist in the experiments. Full factorial experiments are the only means to completely and systematically study the relationship between the factors and identifying the significant factors of the experiments. The factors being investigated separately by one factor at a time and keeping the remaining factors to be constant (Ronald,1926).

Full factorial design in two levels is typical experimental design with all the factors are set at two levels which is high and low (+1, -1). This two levels factorial is called 2^k Full Factorial Design. The number of experiments or runs are depending on the number of factors of the experiments. Table 2.3 shows the number of runs for 2^k full factorial design.

Table 2.3: Number of runs for 2^k Full Factorial

Numbers of Factors	Runs
2	4
3	8
4	16
5	32
6	64
7	128

The numbers of runs are increases as the number of factors of the experiment increase. Thus, in full factorial design, when the number of factors is too big it is not recommended to proceed with full factorial design because of the experimental design need a large number of runs and it is not very efficient. There are several steps in Full factorial design method to be followed during the analysis:

i. Learning the most from as few runs as possible
ii. Determine the most significant factors which affect the mean, variation and determine the interaction between factors