EFFECT OF RESISTANCE SPOT WELDING PARAMETERS ON COPPER AND BRASS

by

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Master of Science

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the thesis entitled "Effect of Resistance Spot Welding Parameter on Copper and Brass". I also declare that it has not been previously submitted for award for any degree or diploma or other similar title for any other examining body or University.

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LIST OF ABBREVIATIONS

RSW	:	Resistance spot welding
SSRSW	:	Small-scale resistance spot welding
ECAP	:	Equal channel angular pressing
USA	:	United States of America
CDA	:	Copper Development Association
WME	:	Weld metal expulsion
ESS	:	Electrode-sheet sticking
HSLA	:	High-strength low-alloy
BM	:	Base metal
HAZ	:	Heat affected zone
FCC	:	Face centered-cubic
BCC	:	Base centered-cubic
SEM	:	Scanning electron microscope
EDX/EDS	:	Energy Dispersive X-Ray Spectroscopy
UTS	:	Ultimate tensile strength
HV	:	Vickers hardness
$FeCl_3$	:	Ferric chloride
HCl	:	Hydrochloric acid
PVC	:	Polyvinyl chloride pipe
Cu-Zn	:	Brass (copper-zinc) alloy
AC	:	Alternate current
DC	:	Direct current

LIST OF SYMBOLS

Q	:	Heat
I	:	Current
R	:	Resistance; Resistivity
t	:	Time; Thickness
E	:	Voltage drop across the electrodes
Hz	:	Hertz
%	:	Percent
ºC	:	Degree celsius
σ	:	Shear stress
α	:	Alpha
β	:	Beta
A	:	Area
N	:	Newton
F	:	Force
kgf	:	Kilogram-force
nm	:	Nanometre
ms	:	Millisecond
mm	:	millimetres
kA	:	Kilo amperes
GPa	:	Gigapascal
µm	:	Micrometre
Amps	:	Amperes

KESAN PEMBOLEHUBAH KIMPALAN RINTANGAN BINTIK TERHADAP KUPRUM DAN LOYANG

ABSTRAK

Kimpalan rintangan bintik adalah kaedah biasa yang digunakan untuk kimpalan logam. Kebanyakan kajian dalam teknik ini hanya tertumpu kepada bahan-bahan terpilih dan hanya sedikit maklumat boleh didapati mengenai tindakbalas dan tingkah laku kuprum dan aloi kuprum. Oleh itu, kajian ini bertujuan untuk mengkaji kesan pembolehubah kimpalan rintangan bintik ke atas kuprum dan aloi loyang. Kuprum dan loyang yang dikimpal melalui teknik kimpalan rintangan bintik di bawah perbezaan arus kimpalan dan tekanan beban telah dikaji. Pengukuran nuget menunjukkan pengaruh beban (60 N, 65 N, 70 N dan 75 N) dan arus kimpalan (5.50 kA, 6.00 kA dan 6.50 kA) pada kedua-dua kawasan pelakuran dan keliangan dalaman. Diameter nuget meningkat pada kadar arus kimpalan rendah dan tinggi, tetapi terhad kepada nilai maksimum pada peringkat pertengahan arus kimpalan. Di samping itu, penyambungan kuprum menunjukkan pembentukan oksida dan retak berlaku, manakala penyambungan loyang menunjukkan lebih pembentukkan liang dan penembusan yang berlebihan di kawasan pelakuran. Oleh itu, arus kimpalan ditingkatkan kepada 8.00 kA, 8.50 kA dan 8.90 kA, manakala pembolehubah beban kenaan adalah malar pada 60 N, 65 N, 70 N dan 75 N yang diambil sebagai nilai optimum untuk memperbaiki penyambungan kimpalan. Sifat-sifat mekanikal dan mikrostruktur kimpalan kuprum dan loyang juga diperincikan. Spesimen pada arus kimpalan tinggi menghasilkan lebih tinggi hasil kekuatan tegangan ricih daripada arus kimpalan rendah. Mod kegagalan diperincikan dengan pemerhatian permukaan patah kimpal. Korelasi antara logam asas dan kekerasan zon pelakuran dihasilkan.

Penyambungan loyang memberikan nilai kekerasan yang tertinggi pada nugget kimpal kerana penghalusan struktur bijian dan ini diikuti oleh HAZ dan asas logam asal. Manakala penyambungan kuprum menunjukkan nuget kimpal memberikan nilai kekerasan terendah daripada logam asas asal disebabkan pelembutan penyepuhlindapan dominan menyebabkan pengasaran struktur bijian.

EFFECT OF RESISTANCE SPOT WELDING PARAMETERS ON COPPER AND BRASS

ABSTRACT

Resistance spot welding is the most commonly used method for joining sheet metals. Most studies in this technique were focus on selected materials and little information is available regarding the response and behaviour of copper and copper alloy. Thus, in this research is purposed to study the effect of resistance spot welding parameters on copper and brass alloy. The copper and brass welded by resistance spot welding technique under varied welding currents and applied loads has been investigated. A nugget measurement looked at the influence of loads (60 N, 65 N, 70 N and 75 N) and weld currents (5.50 kA, 6.00 kA and 6.50 kA) on both fusion area and internal porosity. Nugget diameter increased at low and high-level of welding current, but significantly restricted to a maximum value at intermediate level of welding. Furthermore, copper joints revealed more oxide formation and crack development, while brass joints revealed some pores and excess penetration in the fusion area. Thus, the weld currents were increased up to 8.00 kA, 8.50 kA and 8.90 kA, while applied load parameters were kept constant at 60 N, 65 N, 70 N and 75 N to which taken as optimised values to improve the weld joined. The mechanical properties and microstructure of these welded copper and brass was detailed. Specimens joined at higher welding current yielded higher tensile-shear strength results than those joined at lowest welding current. Failure modes are detailed by observing weld fracture surfaces. A correlation between base metal and fusion zone hardness is produced. The hardness of brass joints gave the highest hardness values due to grains refinement resulted from the weld nugget zone and this was followed

by HAZ and original base metal. While copper joints revealed the weld nugget gives the lowest hardness values than the original base metal due to annealing softening was dominant caused coarsening grain structures.

CHAPTER 1

INTRODUCTION

1.1 Resistance spot welding in general

Resistance spot welding (RSW) is the most commonly used method for joining sheet metals. Spot welding is a widely used in joining process for fabricating sheet metal assemblies such as automobiles, truck cabins, rail vehicles and home applications due to its advantages in welding efficiency and suitability for automation (Hou et al., 2007). For example, modern auto-body assembly needs 7000 to 12, 000 spots of welding depending to the size of a car (Huh and Kang, 1997). Resistance spot welding is also suitable for small batch production because the method is flexible, equipment simple and the welding process is easy to control (Rautaruukki, 2009).

Work stages in resistance spot welding are very fast. Resistance welding methods are inexpensive and efficient, which has made them highly popular in the making of sheet joints. Resistance spot welding is a process in which faying surfaces are joined in one or more spots by resistance to the flow of electric current through worksheets, which are held together under force by electrodes. The contacting surfaces in the region of current concentration are heated by a short-time pulse of low voltage, high-amperage current to form a fused nugget of weld metal. When the flow of current ceases, the electrode force is maintained while the weld metal rapidly

cools and solidifies. The electrodes are retracted after each weld, which usually is completed in a fraction of a second (Neville and Bristish, 1993).

There are three stages in making spot weld are illustrated in Figure 1.1. First the electrodes press the welded worksheets together and decrease the transfer resistance of worksheets between the electrodes, which allows directing welding current through the desired route. Then, the welding current is connected after termination of the squeeze time. Welding current produces heat at the faying surfaces and thus creates a weld pool between the worksheets. This is followed by the third or hold time, which welding current is switch off as the weld time ends, but electrode force still presses the worksheets together and electrodes cool the weld down. The hold time forges the worksheets while it is cooling, where the weld pool must solidify and must achieve sufficient strength properties during the hold time (Rautaruukki, 2009).

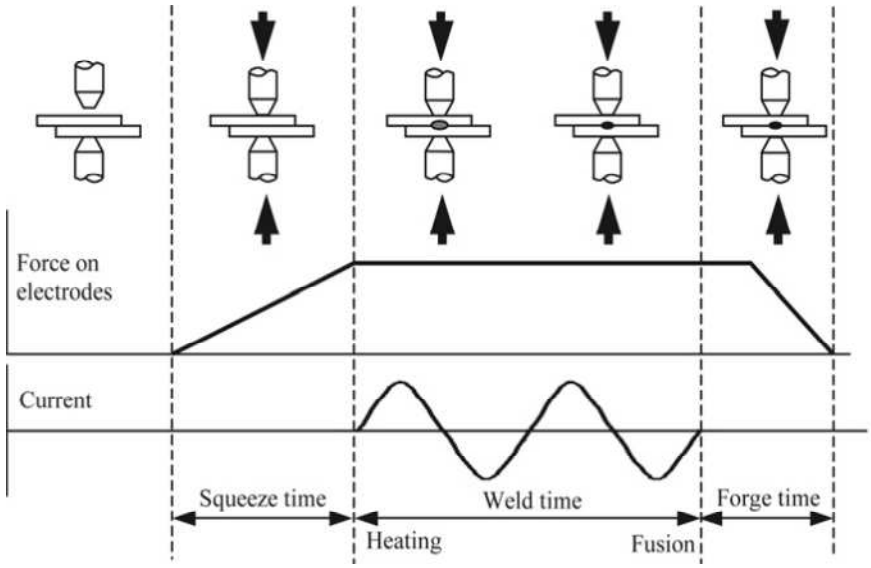


Figure 1.1 Typical spot welding cycle (Kahraman, 2007)

The key variables that must be controlled to achieve consistently acceptable welds are the welding energy used to generate heat, the amount of time that the energy is applied, the physical weld force that is applied and the quality of the materials being joined, including metallurgic properties, resistance, thickness, configuration and coatings (www.mddionline.com)

Factors affecting the amount of heat being generated by a given weld current for a unit of time are; the electrical resistance of the materials being welded, the electrical resistance of the electrode materials, the contact resistance between the parts as determined by surface conditions, scale, welding pressure and the contact resistance between the electrodes and parts as determined by surface conditions, area of electrode contact and welding pressure. In most resistance welding machine, welding current is adjusted as a percentage of the nominal power of the machine, although in some equipment adjustment is made by changing the transformation ratio of the welding transformer (Rautaruukki, 2009).

Mechanical testing is an important aspect of weld ability study. Such testing is either for revealing important welds characteristics, such as weld nugget diameter or weld button size, or for obtaining and evaluating the quantitative measures of weld's strength. Mechanical testing of a weldment can be static or dynamic test and among the static test, tension shear or tensile shear testing is commonly used in determining weld strength or the tensile strength of the welded joints because it is easy to conduct the test and the specimens for the test is simple in fabrication.

1.2 Problem statement

The resistance spot welding process is a very useful way of joining galvanised steels sheets, cast iron, nickel, aluminium and others. In the past, steel is the major material encompassing over 70% of all joining materials in resistance spot welding (Ta-chien, 2003). Most studies in RSW method were focus on selected materials and little information is available regarding the response and behaviour of copper and copper alloy.

Thus, in this research, pure copper and brass (Cu-Zn) alloy were chosen as a base material for joining due to these alloys are typically more difficult to be resistance spot welded. Although copper and copper alloys can be joined by most of the commonly used methods such as gas welding, arc welding, resistance welding, brazing and soldering, the joining of copper is usually difficult by conventional fusion welding methods because copper has a thermal diffusivity of about 401 W/mK, which is almost the highest among all the metallic materials. During welding, much higher heat input is required due to the rapid heat dissipation into the worksheets and the welding speeds are therefore quite low. In addition, the serious oxidation at melting temperature and the thermal crack in the joint are also a stubborn problem and will inevitably deteriorate the mechanical properties of the copper weld (Lee et al., 2003). In addition, different material may show the different effects to the nugget diameter. Copper and brass alloy were chosen in term of its electrical resistivity, thermal conductivity and melting points and these properties would affect the physical and mechanical properties.

On the other hand, extensive research and development work has been carried out on the effects of welding parameters such as welding current, welding time, electrode force, etc. However, most of this work is limited to sheet metals of similar joining of copper-copper sheets and brass-brass sheets by RSW method. The determination of appropriate welding parameters for spot welding is a very complex issue. The welding parameters play an important role on the quality of weld. In addition, controlling a small change of one parameter will affect all the other parameters .Thus, welding current and applied welding load (electrode force) was chosen depends on the material to be welded. In addition, the parameters were selected for relatively thick sheet of copper (0.5 mm thickness) and brass (1.0 mm thickness) used. One problem, though, is that the size of the contact surface will increase during welding. To keep the same conditions, the electrode force needs to be gradually increased. As it is rather difficult to change the electrode force in the same rate as the electrodes are "mushroomed", usually an average value is chosen (Aslanlar, 2006). However, more work is required in order to understand the effects of RSW parameters on these materials before further implementation can occur.

The aim of this research is to study the effect of RSW parameters on similar joining of copper-copper sheets and brass-brass sheets, also with different thickness. Nugget characteristics, weld nugget sizes, peel off, tensile-shear strength, hardness and metallographic evaluations were considered and each of them has been investigated in details.

1.3 Research objectives

The main focus of the research:

i. To study the effect of RSW parameters on similar joining of copper-copper sheets and brass-brass sheets metal and their welding performance.
ii. To study the relationship between welding currents and applied welding load to the nugget diameter and their nugget characteristics for each welded specimens.
iii. To examine the effect of welding parameters on hardness test and microstructural evaluations on the base metal (BM), heat affected zone (HAZ) and nugget area.
iv. To analyze the shear-strength of the tensile test properties, the fracture surface and impact performance of spot welded specimens.

1.4 Scopes

In this research, resistance spot welding method was used to study the effect of welding parameters on similar joining of copper-copper sheets and brass-brass sheets metal. Various welding parameters were applied to the specimens. Physical and mechanical properties, microstructural characterization and nugget characteristics with different nugget diameter were evaluated. Three different mechanical testing were conducted, which are peel off test, hardness test and tensile test. Figure 1.2 illustrates the scope in this research.

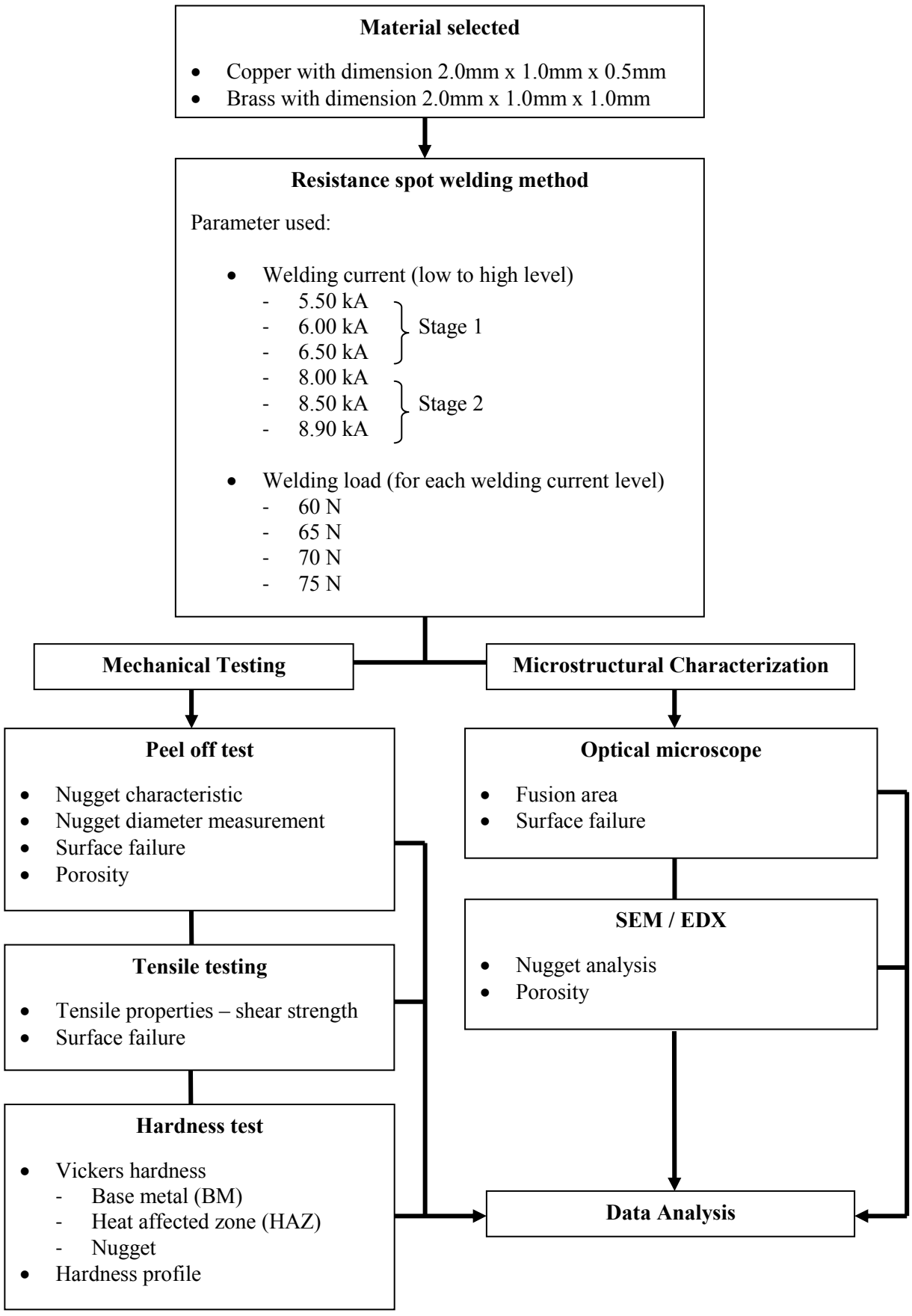


Figure 1.2 Schematic representations of the whole experimental procedures

CHAPTER 2

LITERATURE REVIEW

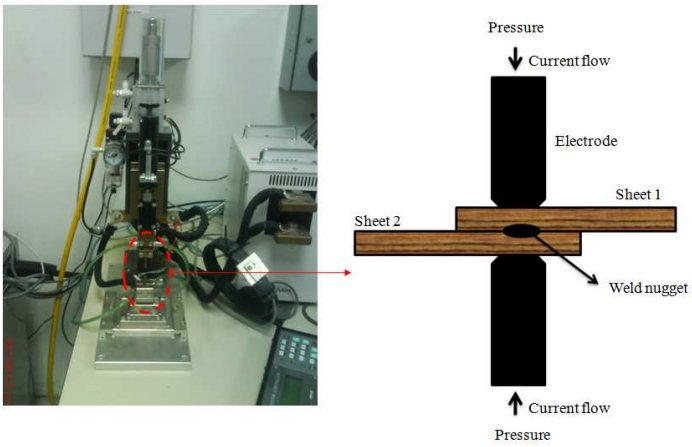
2.1 Resistance spot welding (RSW)

Spot welding is one of a group of resistance welding processes that involve the joining of two or more metal parts together in localise area by the application of heat and pressure. The resistance involves electrode and sheet bulk resistances as well as electrode-sheet and sheet-sheet contact resistances.

Spot welding produces single spot like welds, which are called nugget. The spot weld nugget is formed when the interface of the weld joint is heated due to the resistance of the joint surfaces to electrical currents flows. Welding current is directed to the specimens through electrodes, which hold the part to be welded in close contact before, during and after welding. The welding current depends on the material to be welded and specimen thickness. Spot welding also can be used for joining several metallic materials and sheets of different thickness together without large deformation (Rautaruukki, 2009).

The process is used for joining sheet materials and uses shaped copper alloy electrodes to apply pressure and the electrical current flows through the work pieces. Heat is developed mainly at the interface between two sheets, eventually causing the materials being welded to melt, forming a molten pool, a weld nugget. The size and shape of the individually formed welds are limited primarily by the size and contour

of the electrodes faces. Figure 2.1 shows the micro spot welder machines and the spot weld illustration.



(a) (b)

Figure 2.1 Schematic figures of (a) micro spot welder machines and (b) the spot weld illustration

2.2 Principle of operation resistance spot welding

The heat required for any resistance spot welding process is produced by the resistance offered to the passage of an electric current through the worksheets. Since the electrical resistance of metals is low, high welding currents are required to develop the necessary welding heat. Typically the currents are in the range of 1000's of amps, while the voltage is at the level of a few volts only.

The rate of heat generation depends upon the flow of current, in amperes, through the resistance offered by the materials. Other electrical factors, such as voltage, frequency and power factor, enter into consideration only with respects to their uniformity. They affect only the value of the current.

According to Ohm's law:

$$I = \frac{E}{R} \tag{2.1}$$

Where *I* is the current, *E* is voltage drop across the electrodes and *R* is the resistance through the metal. R is the summation of the contact resistance and the resistance of the work to be welded. Therefore, for a given value of *R*, the magnitude of *I* is determined by *E*. Current to the primary of the transformer is controlled which determines the current delivered to a weld of a given resistance. The principle of resistance spot welding is the Joule's heating law, where the heat is generated depending on three basic factors. It can be expressed by equation:

$$Q = I^2Rt \tag{2.2}$$

Where *Q* is the heat generated (Joule), *I* is the current (amperes), *R* is the resistance (ohms) of the base metals and the contact interfaces and *t* is the duration of current flow (seconds). From the equation, it can be shown that the current, resistance and time are key parameters for heat generation and hence the quality of the weld.

2.2.1 Welding current

The welding current is the most important parameter, in order to form a nugget between two metal sheets. A larger amount of heat must transmit to the spot in very short period time. Equation 2.2 shows the welding current has more influence than resistance, R or time, t, since it has a square power influence. On the other

words, if current is doubled, the heat amount will be equal to four times of the previous value (Guangqian, 2007).

To create the heat, a very high alternative current (AC) or direct current (DC), usually thousands of amperes must be applied. The heat generated depends on the electrical resistance and thermal conductivity of the metal and the time that the current is applied (Guangqian, 2007). The sizes of the weld nugget increase rapidly with increasing welding current, but too high current will results in expulsions and electrode deteriorations.

For example, studied on weldability of thin sheet metals during small-scale resistance spot welding using an alternating-current power supply by Zhou et al. (2000) who figured out the welding current (kA) values for 0.4 mm diameter nugget, weld metal expulsion (WME) and electrode-sheet sticking (ESS) for sheet metals of brass and copper as shown in Table 2.1, which indicated that the welding current having the strongest effect.

Table 2.1 Welding current (kA) for 0.4 mm diameter nugget, WME and ESS (Zhou et al., 2000)

Sheet metals	Electrodes	Minimum	Expulsion	Sticking	Suggested range
Brass	Class 2	1.6	2.0	2.6	1.6 - 2.6
	Class 14	1.2	>1.8	~1.4	1.2 - 1.4
Cu	Class 2	≥3.5	3.8	2.8	-
	Class 14	≥2.2	-	2.0	-

* The minimum current is determined to produce 0.4mm diameter of weld nuggets. Electrode force is 4.5 kg and weld time is 8 cycles

2.2.2 Welding force (electrode force)

The force is one of the main parameters. The influence of force on the quality of the spot welds is important. The purpose of the electrode force is to squeeze the metal sheets to be joined together. The force supplied to the work to be welded, the method of application and the inertia of the moving parts, will greatly influence the quality of the spot weld. It is known that the bearing capability of joints will decrease under too large or too small electrode force (Ao et al., 2008).

However, the force must not be too large as might cause others problems. It presses the metal sheets to be welded together and restricts the passage of current to this area. It also reduces the formation of porosity and cracks in the welded area. A smaller force maintains a low value of contact resistance between the welding tips and sheets to be welded, reducing the tendency of sticking or alloying of the electrodes to materials being welded.

2.2.3 Welding time (welding cycles)

Welding time is the time during which welding current applied to the sheets metal. The heat generation is directly proportional to the welding time. The time is expressed in cycles. The weld time is measured and adjusted in cycles of line voltage as are all timing functions. One cycle is 1/50 of a second in a 50 Hz power system.

In a real environment, when the heat is transferred from the weld zone to the metal sheets, a portion of heat will be lost to the surrounding environment, the

amount of lost is proportional to the welding time, to reduce heat lost and improve welding efficiency, welding applications usually adopt short welding time with high current combination to control the welding machine (Guangqian, 2007).

Resistance spot welding depends on the resistance of the base metal and the amount of current flowing to produce the heat necessary to make the spot weld. To make good resistance spot welds, it is necessary to have close control of the time the current is flowing.

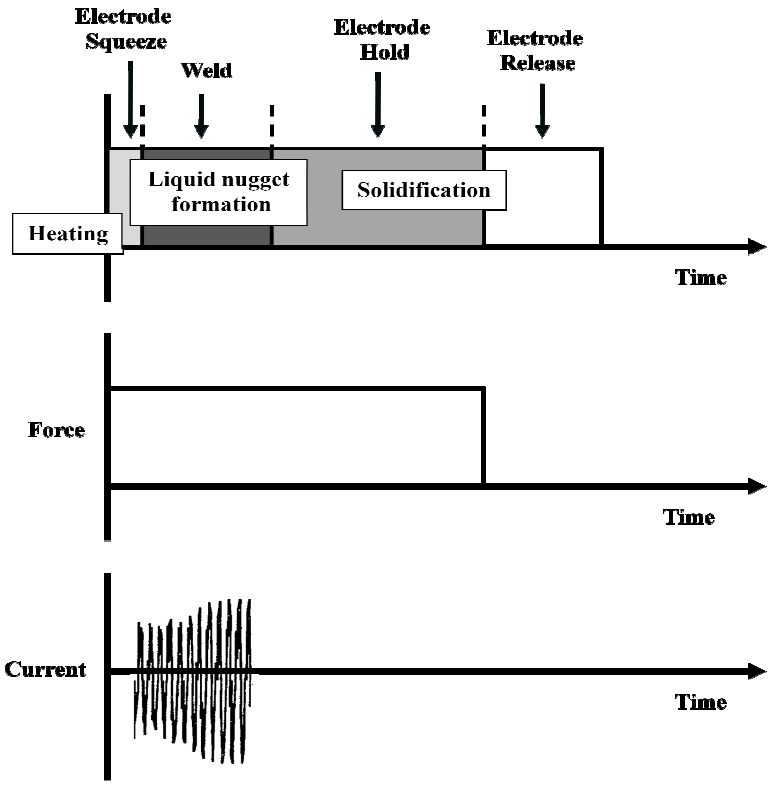


Figure 2.2 Four stage of spot welding process and weld nugget formation (Michelle, 1992)

A spot welding process normally includes four stages which are schematically illustrated in Figure 2.2. During process, the worksheets are squeezed together by a pair of electrodes. Then, electrical current flows through sheet metal. Since the electrical resistance at sheet to sheet (faying surface) is high at the beginning of the weld stage and the heat concentrates around the surface. When the temperature at the faying surface exceeds the melting point of metal, a molten nugget forms at the surface and grows. After the current terminates, the nugget cools down and consolidates, forming a solid spot joint. The weld stage is the most important to weld nugget formation and the hold stage is also important to the solidification of liquid nuggets.

2.3 Properties and characteristics of copper and copper alloys

Copper and copper alloys have been used to make a very wide variety of products that depends on their usefulness on combinations of such properties, strength, ductility, and hardness and corrosion resistance. Copper and copper alloys are classified according to a designation system administered by the Copper Development Association (CDA). In this system, numbers from C100 through C799 designate wrought alloys and numbers from C800 to C999 cast alloys. Within these two main classes, the system is divided into groups and subgroup (William, 2004).

Table 2.2 Copper and copper alloys are classified according to a designation system administered by the Copper Development Association (CDA)

	Wrought alloys
C1xx	Coppers[1] and high-copper alloys[2]
C2xx	Copper-zinc alloys (brasses)
C3xx	Copper-zinc-lead alloys (leaded brasses)
C4xx	Copper-zinc-tin alloys (tin brasses)
C5xx	Copper-tin alloys (phosphors bronzes)
C6xx	Copper-aluminium alloys (aluminium bronzes), copper-silicon alloys (silicon bronzes) and miscellaneous copper-zinc alloys
C7xx	Copper-nickel and copper-nickel-zinc alloys (nickel silvers)
	Cast alloys
C8xx	Cast copper, cast high-copper alloys, the cast brasses of various types, cast manganese-bronze alloys and cast copper-zinc-silicon alloys
C9xx	Cast copper-tin alloys, copper-tin-lead alloys, copper-tin-nickel alloys, copper-aluminium-iron alloys and copper-nickel-iron and copper-nickel-zinc alloys

[1] "Coppers" have a minimum copper content of 99.3% or higher
[2] High-copper alloys have less than 99.3% Cu, but more than 96% and do not fit into the other-copper alloy group

2.3.1 Copper

The basic properties of copper alloys are largely influenced by the properties of copper itself. These are high thermal conductivity, excellent ductility and toughness over a wide range of temperatures and excellent corrosion resistance in many different environments. All of the three qualities above are directly related to the structure and behaviour of copper's structure on an atomic scale. The copper atom is quite similar to an atom of gold or silver, which together with copper make up group in the periodic table of the elements. Solid copper can be described as the arrangement of copper atom in a face-centered-cubic (FCC) configuration.

There was only limited success in RSW of copper. The reasons are that the power required is very high due to very high thermal conductivity and low electrical resistance of copper and the high heat generation causes severe electrode-sheet sticking or even welding between the copper sheets and electrodes. Copper is one of those metals that are the least suitable for RSW because of its low electrical resistivity and high thermal conductivity. There is now an increased demand for a copper based material having both high electrical conductivity and high mechanical strength at elevated temperatures.

2.3.2 Brass (Cu-Zn) alloy

Brass alloy widely used as engineering materials in industry because of their high strength, high corrosion resistance, and high electrical and thermal conductivity. They are easily shaped and they posses nice appearance. Brass alloy, as known are copper (Cu) and zinc (Zn) alloys. The copper-zinc brasses consist of a series of alloys of copper with up to about 40% Zn. As the percentage of zinc changes, the properties of the Cu-Zn alloys change also. Copper-zinc brasses containing additional elements such as tin, aluminium, silicon, manganese, nickel and lead are referred to as “alloy brasses”. The alloying additions, which rarely exceed about 4%, improve some of the properties of the strength Cu-Zn brasses so they can be used for other applications (William, 2004).

The main problem with these alloys is the evaporation of zinc during the welding process. After welding, the weld metal becomes porous. Moreover, since the amount of zinc in the alloy is reduced due to evaporation, the brass material loses the

physical and chemical properties which it normally possesses. Studies on weldability of brass materials are very few. There is very little information concerning the weldability of brass materials in the literature and general definitions are often seen.

Brasses are used in applications such as blanking, coining, drawing, piercing, springs, fire extinguishers, lamp fixtures, flexible hose and the base for gold plate. Brasses have excellent castability and a good combination of strength and corrosion resistance.

2.3.2.1 Structure with Cu-Zn phase diagram

The phase diagram for the copper-zinc system is shown in Figure 2.3. Zinc has extensive solid solubility in copper and forms α-solid solutions with up to 39% Zn at 456°C. With increasing zinc content, a second solid solution of zinc in copper is formed which is designated the β phase. The α-solid has the FCC structure. The β phase has the BCC crystal structure and transforms upon cooling through the 468°C to 456°C temperature range from a disordered β phase structure to an ordered β' structure. With more than about 50% Zn, the γ-phase solid solution forms, this has a complex structure and which is very brittle. Copper- zinc alloys containing the brittle γ-phase are of little engineering use (William, 2004).

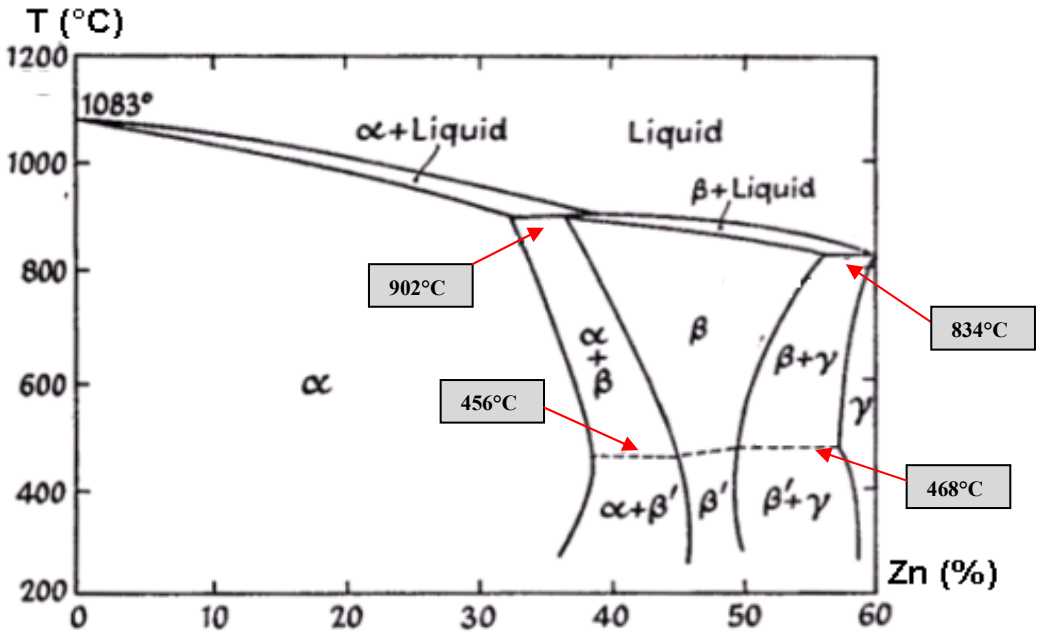


Figure 2.3 Schematic figure of constitutional phase diagram of the Cu-Zn alloy (www.keytometals.com)

The addition of zinc to copper results in the formation of a series of solid solutions which, in accordance with usual practice, are referred to in order of diminishing copper contents as the α, β, γ, etc constituents. The diagram may be summarized as follows:

Table 2.3 Table of further changes in percentage composition of copper and zinc (www.keytometals.com)

Percentage composition		**Constituent just below the freezing point**	**Constituent after slow cooling to 400°C**
Copper	**Zinc**		
100 to 67.5	0 to 32.5	α	α
67.5 to 63	32.5 to 37	α + β	α
63 to 61	37 to 39	β	α
61 to 55.5	39 to 45.5	β	α + β'
55.5 to 50	45.5 to 50	β	β'
50 to 43.5	50 to 56.5	β	β' + γ
43.5 to 41	56.5 to 59	β	β' + γ

The important alloys of copper and zinc from an industrial point of view are the brasses comprised within certain limits of zinc content. If the alloy composition is exactly equal to peritectic composition, α-phase and liquid phase are consumed completely in the peritectic transformation (peritectic reaction).

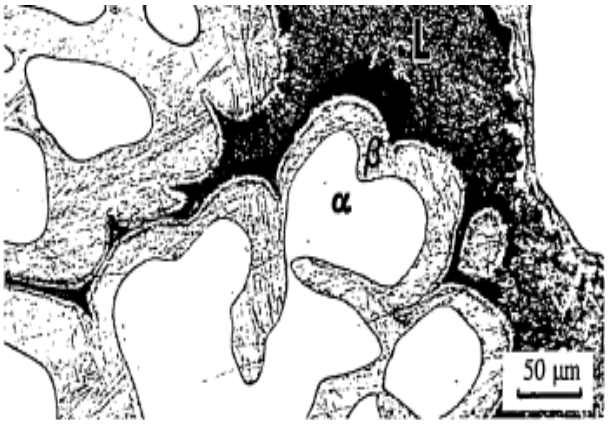


Figure 2.4 Classic microstructure of peritectic alloy, showing rim of β-phase separating primary α-phase from (darker) former liquid phase, in Cu-20wt-% Sn (Kerr and Kurz, 1996)

Figure 2.4 shows an example microstructure of peritectic alloy, showing rim of β-phase separating primary α-phase from (darker) former liquid phase, in Cu-20 wt-% Sn. In other words, the peritectic phase tends to form a rim around the primary solid α-phase (Kerr and Kurz, 1996).

2.3.2.2 Phase transformation

An example of a phase diagram with peritectic transformation is shown in Figure 2.5. Consider solidification of an alloy with concentration C. When the alloy temperature is higher than T_L, single liquid phase exists (point M on the diagram). When the temperature reaches the value T_L (point M_1 on the liquidus curve)

solidification starts. According to solidus curve (point $N_{1)}$ the first solid crystals (primary crystals) of the α-phase have composition C_1.

Further cooling of the alloy causes changing of the liquid phase composition according to the liquidus curve and when the alloy temperature reaches a certain intermediate value T (position M_T), liquid phase of composition C_y and solid α-phase of composition C_x are in equilibrium. At the temperature equal to T_P (peritectic temperature) formation of the α-phase crystals stops and the remaining liquid phase, having composition C_L reacts with α-phase crystals , forming β-phase of composition C_P (peritectic phase transformation). At this temperature remaining α-phase crystals have composition C_α and all crystals of β-phase have composition C_P (peritectic composition).

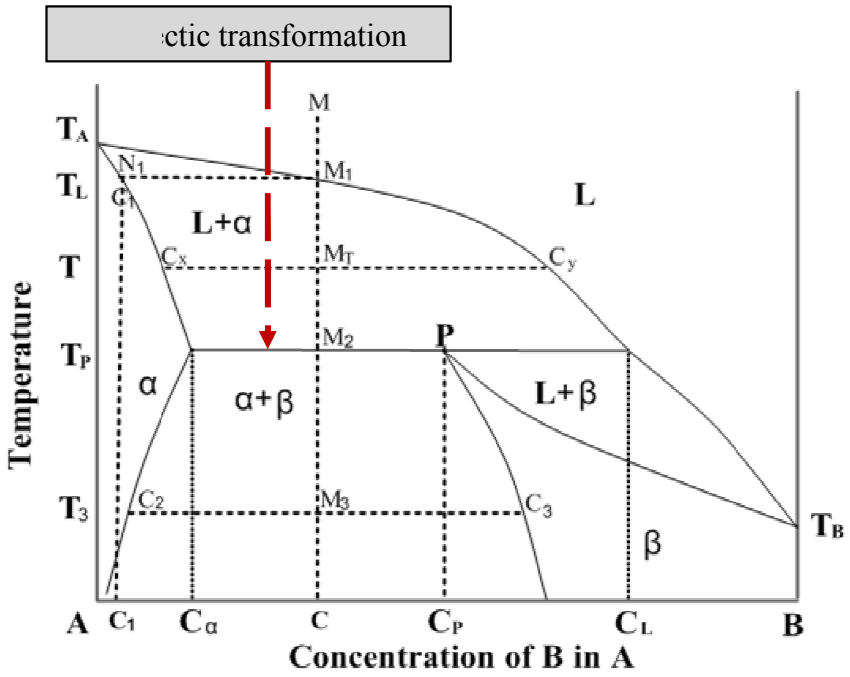


Figure 2.5 Example of a phase diagram with peritectic transformation (www.substech.com)

2.4 Nugget formation and their characteristics

The formation, size and growth rate of weld depend on the welding parameters used. During the RSW process, resistance at the faying surface generates heat which can cause peak temperatures to exceed liquidus. The nugget in a properly formed spot weld is round or oval in shape. Figure 2.6 shows an example of micrograph of the spot welded region; (a) weld nugget, (b) heat affected zone (HAZ), where the welding process has affected the materials properties and (c) base metal.

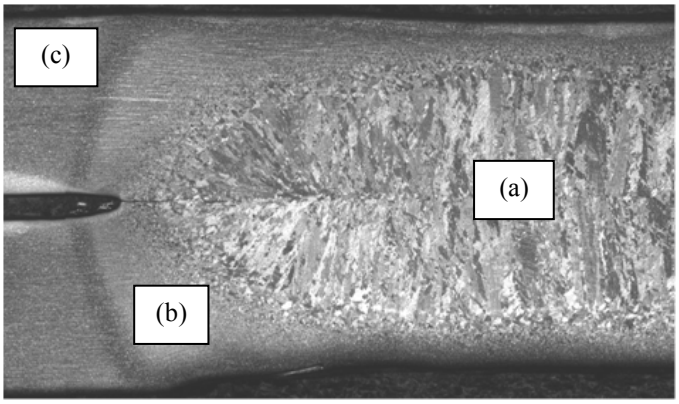


Figure 2.6 Micrograph of the spot welded region, (a) weld nugget, (b) heat affected zone (HAZ) and (c) base metal (Khan, 2007)

The HAZ is the portion of the material which has not been melted, but whose microstructure and mechanical properties are altered by the heat of welding. The nature of the thermal cycle at any position within the HAZ can be characterized by two parameters, the peak temperature *Tp* and the time period $\Delta t_{8\text{-}5}$. Both of these parameters increase with the heat input q:

$$Tp \ \alpha \ \frac{q}{r} \tag{2.3}$$

$$\Delta t_{8\text{-}5} \alpha q^n \quad (2.4)$$

where *r* is the distance from the fusion boundary and *n* has a value (1 or 2) which depends on whether the component being welded is thick compared with the size of the weld bead (Weisman, 1981).

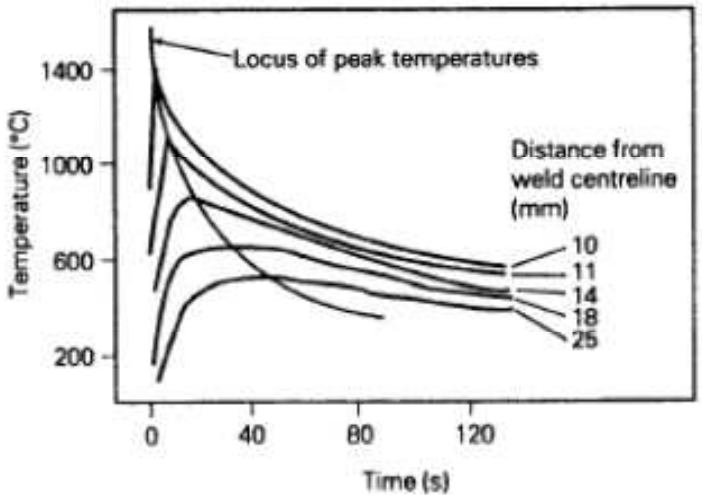


Figure 2.7 Temperature-time curves representing typical thermal cycles experienced in the HAZ of a weld (Weisman, 1981)

Effect of different weld current used for joining on the microstructure of weldments was studied by Dursun (2009). He was reported that the effect of heat input related with weld current on the microstructure of welded materials. It was found that the grain size of weld nugget and HAZ of welded materials were increased by raising the heat input. As seen from Figure 2.8, an increase in welding current from (a) 4 kA to (b) 7 kA and (c) 9 kA caused coarsening of structure. This figure illustrates a difference in microstructure of weld nugget due to different welding current.

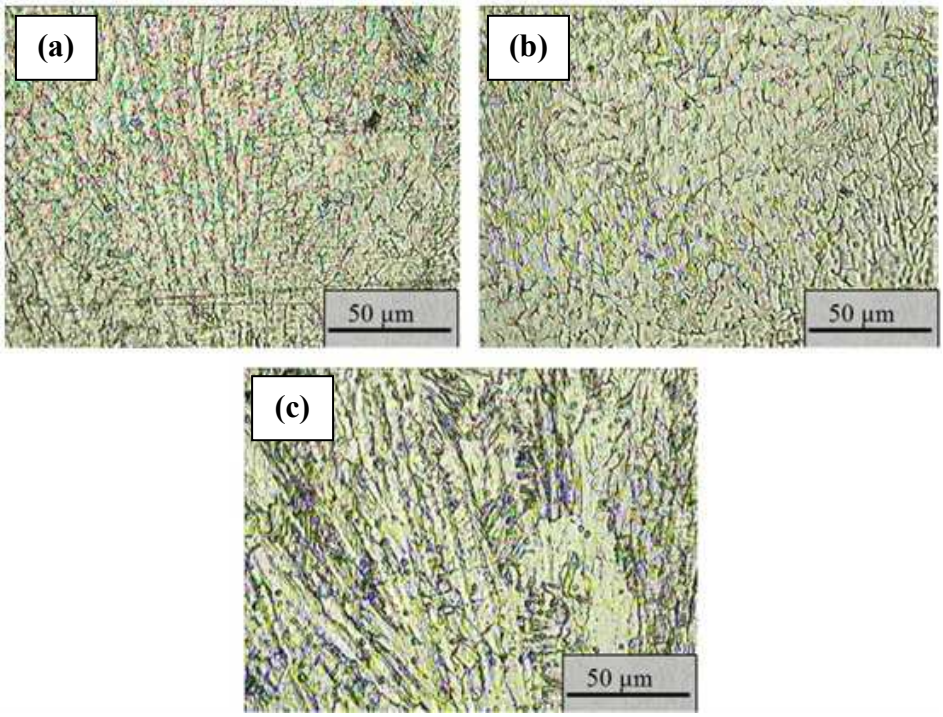


Figure 2.8 Samples, welded in atmosphere and then cooled in atmosphere, show microstructures of weld nugget coarsening by increasing weld current from (a) 4 kA to (b) 7 kA and (c) 9 kA (Dursun, 2008)

Harlin et al. (2003) reported on the studies of weld growth mechanism of resistance spot welds in zinc coated steel. Studies shows that the zinc coated steel melts at the faying surface and increasing the electrode force had major effects on the location of heat development and weld nugget formation. Furthermore, the increase electrode force provided improved consolidation of the molten weld pool such that internal weld porosity was reduced. Variation in electrode force indicated flexibility in the selection of welding conditions to produce an acceptable weld quality. Figure 2.9 shows an examples of typical micrographs illustrating the location of weld nugget, whilst the location of initial heat development and weld nugget formation in the coated stack was different to that in the uncoated variant, the weld quality was unaffected.

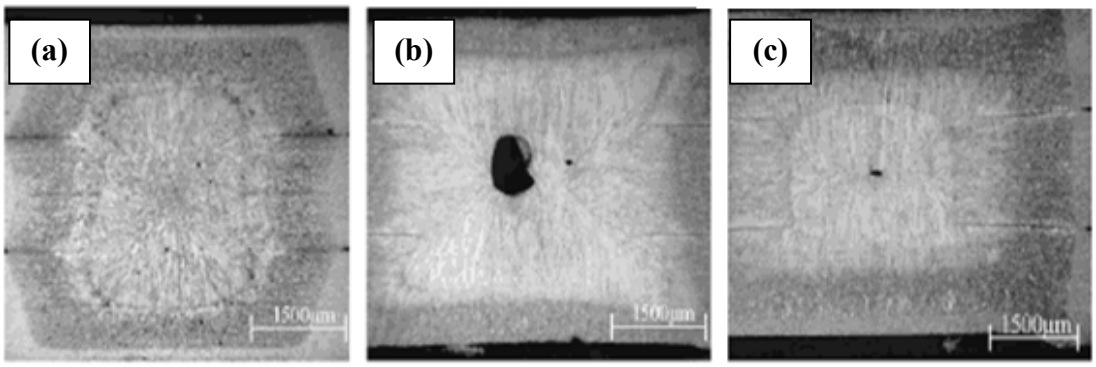


Figure 2.9 Typical micrographs illustrating the location of weld nugget after (a) 9 cycles of current flow in the uncoated stack with an electrode force of 2.1 kN, (b) 10 cycles of current flow in the coated stack with an electrode force of 2.1 kN, and (c) 16 cycles of current flow in the coated stack with an electrode force of 6.0 kN (Harlin et al., 2003)

Rautaruukki (2009) studied that the minimum acceptable diameter of weld nugget is considered to be $3.5\sqrt{t}$, where t is the thickness. Weld nugget which have a smaller diameter do not have sufficient penetration and the size is not enough to bear the calculation loads. A recommended weld diameter is $5\sqrt{t}$. This value is usually achieved slightly under the splash limit, where the weld nugget growth is stabilised and small variation in the welding current or workpiece surface quality do not significantly change the size of the weld.

Figure 2.10 shows how the weld nugget diameter increases rapidly at the beginning of the process, and the growth slows down at the end of the curve. This is because the nugget is too large for the electrodes to hold the weld pool between the welded sheets, which causes a burst of molten metal (Rautaruukki, 2009).

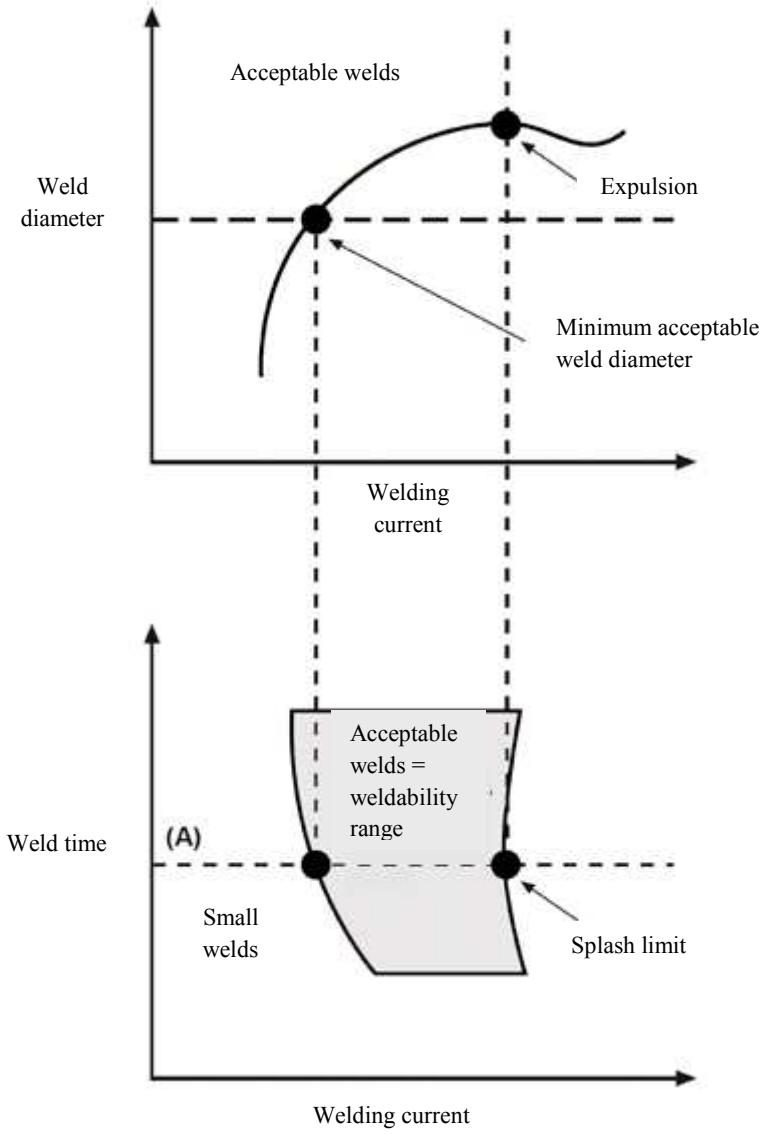


Figure 2.10 Weld nugget growth curve and weldability range (Rautaruukkki, 2009)

Numerical study of nugget formation in resistance spot welding by Mohsen and Hamed (2008) shows that as electrode force increased, contact radius increased. It can be seen in Figure 2.11 (a) and due to Joule' heat effect, as contact area enlarged, the generated heat at interfaces reduced and nugget size decreased as shown in Figure 2.11 (b). They noted that with reduction of force, for increasing nugget size, expulsion phenomenon occurs.