Investigation Parameters of Resistance Spot Welding For AA1050 Aluminum Alloy Sheets

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Abstract

The parameters of resistance spot welding (RSW) performed on low strength commercial aluminum sheets are investigated experimentally, the performance requirements and weldability issues were driven the choice of a specific aluminum alloy that was AA1050. RSW aluminum alloys has a major problem of inconsistent quality from weld to weld comparing with welding steel alloys sheet, due to the higher thermal conductivity, higher thermal expansion, narrow plastic temperature range, and lower electrical resistivity. Much effort has been devoted to the study of describing the relation between the parameters of the process (welding current, welding time, and electrode force) and weld strength. Shear-tensile strength tests were performed to indicate the weld quality. A weld lobe diagrams were constructed to evaluate the weldability of three sheet thicknesses of this alloy. Most appropriate welding time and electrode force are 5 cycles and 1.75-2.25 kN respectively. The ranges of the weldability are 14-28, 18-30, and 22-32 kA for 0.6, 1.0, and 1.5 mm sheet thicknesses respectively. A statistical regression analysis was used to demonstrate the relationship of the process parameters and the strength of the weldments. Two empirical equations for each thickness were proposed to estimate the shear tensile strength of the weldments, one for quadratic and the other linear relationship between the process parameters and the strength. There are no significant differences between the equations when applied to the available data.

Keywords: Commercial Aluminum alloys RSW Welding Parameters Regression Analysis

أستقصاء متغيرات لحام مقاومة النقطة لصفائح سبيكة الالمنيوم AA1050

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الخلاصة:

تم التحري عملياً عن متغيرات لحام المقاومة النقطي على الصفائح المصنوعة من الالمنيوم التجاري واطئ القوة، ولمتطلبات الأداء وقابلية اللحام وجودته اختيرت سبيكة الالمنيوم AA1050. للحام المقاومة النقطي لسبائك الالمنيوم مشكلة كبيرة في استقرارية جودة اللحام من لحام ولحام آخر مقارنة بلحام صفائح سبائك الفولاذ، وذلك للموصلية الحرارية والتمدد الحراري

العاليين، قصر المدى الحراري اللدن، والمقاومة الكهربائية المنخفضة لسبائك لالمنيوم عن سبائك الفولاذ. كُرس الكثير من الجهد لدراسة العلاقة بين متغيرات عملية اللحام (تيار اللحام، زمن اللحام، وقوة ضغط الاقطاب) مع قوة الملحومات. أُجريت فحوصات القوة (قص شد) لبيان جودة اللحام. شكلت مخططات متغيرات اللحام Lobe Diagram لتقييم قابلية اللحام ولثلاثة مقاطع من صفائح سبيكة الالمنيوم المذكورة. أفضل حالة لزمن اللحام هي 5 دورات وقوة ضغط الاقطاب هي 1.75 ـ 2.25 كيلو نيوتن. مدى قابلية اللحام هي 14- 28 ، 18- 30 ، و 22 - 32 كيلو أمبير للصفائح 0.6 ، 1.0 ، و 1.5 ملم على التوالي. تم استخدام تحليل الانحدار الاحصائي لتوضيح العلاقة بين متغيرات عملية اللحام ومتانة قوة الملحومات. تم اقتراح اثنين من المعادلات التجريبية لكل سمك لتخمين متانة قوة اللحام العلاقة الاولى من الدرجة الثانية والاخرى علاقة خطية بين متغيرات عملية اللحام ومتانة قوة الملحومات. وظهر عدم وجود فروقات جوهرية بين العلاقة الخطية والدرجة الثانية عند تطبيقها على البيانات المتاحة.

الكلمات الرئيسيه :

تحليل الانحدار　　متغيرات اللحام　　لحام مقاومة النقطة　　سبائك الالمنيوم التجارية

Introduction

RSW has been the dominant process in sheet metal joining, particularly in automobile industry in spite of consumer goods. Modern small vehicles contain (2000-5000) spot welds [Chao 2003]; therefore, each welded spot has its own importance not only with regard to quality but also for production issue. Automobiles manufacturers trend to make lighter vehicles with intensive use of aluminum in order to reduce fuel consumption and CO_2 emission.

A better understanding of aluminum spot welding processes has become necessary. Steel and aluminum alloys share many of the same process attributes for RSW. However, the productivity of aluminum spot welding is lower than of steel especially those alloys with low strength (series 1xxx), This is because aluminum alloys have higher thermal and electrical conductivity, higher coefficient of expansion, narrow plastic temperature range, and oxide film problems which forms on the surface of the aluminum and has high electrical resistance and a high melting temperature (2050℃), as the oxide film grows the effective contact resistance of the aluminum changes. Therefore, the control of weld quality is much more difficult and requires tighter controls [Kim and et. al 2009].

In general, aluminum's high thermal and electrical conductivity require higher current, shorter weld time, about (2-3) times the amount of current and ¼ weld time compared to spot welding steel. Accurate control and synchronization of current and electrode force is required due to the narrow plastic temperature range [RWMA 2003].

Most of the previous researches on aluminum RSW were concentrated on the high strength aluminum alloys such as series (2xxx), (5xxx), (6xxx), and (7xxx), since these alloys are less difficult of RSW than those low strength alloy series (1xxx), and definitely by manufacturer demand, but the required for low price product and higher resistance of corrosion will increase the demand on aluminum alloys series (1xxx) especially in sheet metal products.

Weld lobe diagrams are usually developed in a lap environment with nominal process setting and then extended to production. It is a graph indicating the evaluation on RSW weldability that shows the appropriate welding range by changing two factors with fixing one factor among three factors of RSW such as electrode force, weld time, and weld current [Cho and et.al. 2006]. In this work, the lobe diagram of weld current-weld time was used, with fixing the electrode force. The left boundary line of the lobe diagram was decided by low limit tensile strength of the welded thin aluminum sheet, and the right boundary line was decided where expulsion occurred [Zhang and Senkara 2006].

Expulsion, which can be observed frequently during RSW, happens at either the faying surfaces or the electrode/work piece interfaces. The latter may severely affect surface quality and electrode life, but not the strength of the weld if it is limited to the surface. The risk of expulsion is especially high in spot welding of aluminum alloys due to the very dynamic and unstable character of the process, relating to the application of a high current in a short welding time as compared to welding steels. Expulsions usually occur at the later stage of welding, as a nugget needs time to grow to a certain size. However, observations have shown that expulsion may also happen at early stages of welding when the size of the molten metal is considerably smaller than that of the compressive force supplied by the electrodes.

Expulsion in welding is determined by many factors involving electrical, thermal, metallurgical, and mechanical processes. Although there are many complicated causes of expulsion, its basic process can be described by the interaction between the forces from the liquid nugget and its surrounding solid containment. Based on this understanding, a general model of expulsion is proposed. The criterion can be stated as: Expulsion occurs when the force from the liquid nugget onto the solid containment equals or exceeds the effective electrode force [Senkara, Zhang, and Hu, 2004].

In this work, the relationship of RSW parameters and the quality of weld represented by shear-tensile test of aluminum welds were developed by using the charts indicating this relationship and the multiple power regressions using linear and quadratic model to construct mathematical empirical equations in order to estimate the strength of welds depending on the process parameter as an input values.

Experimental Procedure

The experiments were performed at Technical University of Denmark (DTU), using 0.6, 1.0, and 1.5 mm sheet thicknesses of low strength aluminum alloy AA1050 on a TECNA 8106 AC spot welding machine, the specifications of the welder are listed in **Table 1**. The Controller of the welder type is TE-180 with 16 functions.

The electrodes used during the experiments were type A0 according to ISO 5821-2009. They were made of Zirconium copper alloy (Cu Cr Zr) with the following chemical composition Cr 0.7-1.2%, Zr 0.06-0.15%, and the reminder Cu.

The configuration of electrodes is radius, 16 mm diameter with a spherical end surface of 40 mm radius. Welding current measured by a Rogowski coil together with TECNA-1430 conditioner instrument and a piezoelectric force sensor with Kistler type 5015 transducer for measuring the electrode force. And both these instruments connected to the Electrostatic Sensitive Connectors National Instruments model BNC-2110.

A LabVIEW version 8.6 software program from national Instruments was used to calculate the RMS of current and voltage, and the electrode force during welding. The properties and nominal compositions (performed by spectrum analyzer) of the sheets are shown in **Table 2**, the samples were cut from the sheets into 16 × 115 mm, the rolling direction with the longitudinal dimension and they joined as lap joining as shown in **Fig. 1**, to prepare the shear-tensile tests. A hard wood fixture was used to fix the samples in a good alignment with electrodes of welder.

The strength of weldments was performed in lap shear-tensile test on a 100 kN AMSLER universal testing machine. The effect of RMS current I (A), welding time C (cycle), and the electrode force P (kN) on the weld strength S (N) were investigated and evaluated. There were not used up/down-slope of the current and electrode force in all experiments. The experiments were designed as a general factorial with three replicates per condition. The factors and their associated values are given in **Table 3**.

Fig. 2 shows the macro/micrographs of the welding strips of 1.0 mm thick which was welded with 29 kA and 5 cycles. The nugget seems clearly with suitable size due to the sufficient welding parameters.

Results and Discussion

Lobe Diagram

A lobe diagram is a two dimension graphical representation of ranges of welding parameters for a specific material and its thickness to compare and evaluate the weldability and has been used for many years. The weldability of a material in RSW is determined by two main factors. Firstly, the width of the lobe curve, which shows the permissible weld current range at a constant weld time and secondly the wear of the electrodes [Kim and Eagar 1988].

The allowed welding range is obtained by fixing one parameter and changing two remaining parameters among electrode force, weld time and weld current. In this study, weld current-weld time has been used to represent the welding lobe, with fixing electrode force. The horizontal and vertical axes were set to weld current and weld time respectively. The value of the preselected electrode force was not originally planned, but during the experiments was performed, and it was selected about 2 kN, since this force give more weldability of the soft aluminum alloy than the other three values which were used in this work.

The width of lobe diagram depends on many variables such as weld current, weld time, electrode force, thickness of the sheet, and electrode shapes, but the dominant influence of the lobe width is the material properties and the surface contaminations of the sheets.

The oxide film is a dominant factor affects the weldability especially when welding aluminum sheets, since it causes many problems due to its high electrical resistance, high melting point (2050℃), and tenacious non-uniform nature of breaking during spot welding. Thereby it is difficult to construct the same lobe diagram for the same aluminum alloy and the same sheet thickness even though it selects the same welding parameters due to the largely variations of the oxide film growth.

Fig. 3 shows the weld lobe diagram as mentioned above with three sheet thicknesses. The lower limit (left line) of the diagram had been set to 435, 725, and 1100 kN for 0.6, 1.0, and 1.5 mm sheet thicknesses respectively. These values were calculated as the minimum shear tensile strength required for acceptable welding strength. On the contrast, the upper limit (right line) was decided by whether an expulsion (splash) occurred or not [Kim and Eagar 1988].

The wider area of all lobe diagrams located nearly at 5 cycles as welding time and showing good agreement across the investigated aluminum alloys which required minimum welding time, since any increasing of welding time cause expulsion and more distortions in the sheets because of the amount of excess heat generated.

The differences of the weldability between the thicknesses of the sheets as showing in lobe diagrams do not look much as it was expected and this is due the probability that all sheets have the same thickness of the oxide layer being of the same batch production.

The ranges of the appropriate welding condition are 28-14 (14), 30-18 (12), and 32-22 (10) kA of 0.6, 1.0 and 1.5 mm sheet thicknesses respectively. So, this could be conclude that the relationship between the weldability and thickness of sheets of this type of alloys as an inverse relationship. And the reasons that increasing the volume of the strip and surface area means more heat dissipated due to the thermal properties of the metal, in addition of more expulsions occur.

Weld Strength

RSW involves complicated interaction between the physical and metallurgical properties of the materials and electromagnetic and mechanical phenomena of the process. In this work, much effort has been devoted to the study of describing the welding parameters and the weldability of the soft aluminum alloy to obtain good weld qualities and in the same time improve the production stability without severe expulsion while maintaining a longer lifetime of electrodes. This will need not only better understanding of the weldability of the materials, but also more optimization of the welding process parameters which will need numerous welding experiments and destructive tests.

Shear tensile tests were done on the welding strips to demonstrate the strength of the welding quality and finding the relationship between the parameters of the RSW process and the strength. **Fig. 4, Fig.5, and Fig.6** show the effect of the welding current (percentage of the machine) and welding time (cycles) on the shear tensile force (N) for the 0.6, 1.0, and 1.5 mm sheet thicknesses, while the pressure was fixed of the pneumatic system of the welder at 1/8 bar which is nearly to the (1.75-2.25) kN electrode force, since the electrode force measured and calculated dynamically by the force sensor and the assistance of the LabVIEW program.

The charts confirm that increasing the welding time will decrease the shear tensile force due to the expulsions occur at these stages, and there are optimum values of welding current for each thickness. The small amount of the current density will form insufficient nugget size and the large amount of the current density will expulsion occur causing decrease of the electrode life. The relationship between the shear tensile strength and the parameters of the RSW process with three sheet thicknesses is shown in **Fig. 7**, and it is quite natural that the high values of shear tensile force exist with a thickness of 1.5 mm because of the large size of the nugget that bear higher load than the smaller nugget.

For the purpose of giving a clear picture of the process and their parameters, other experiments were performed by increasing the electrode pressure to the 1/4 bar (2.25-3.00 kN), 1/2 bar (3.00-3.50 kN), and 3/4 bar (3.50-4.00 kN). The charts of the influence of increasing the electrode force on the relationship between the RSW process parameters and their strength were shown in **Fig. 8**. The electrode force is the critical factor that influences the weldability.

There are a number of important observations by studying the charts, can summarize by the following:

- Sheet 1.5 mm
  i. The best strength of the welding had performed at 2.25-3.00 kN electrode force, and 22-27 kA welding current.
  ii. At lower electrode force (1.75-2.25) kN, it is required a large welding current value more than 27 kA to form the same nugget

iii. Size, since the contact resistance will be increased as the electrode force decreases.
iv. The best welding time is 9 cycles for all electrode force values. But there is a strange observation of a lower strength of the weldments at the time of 7 cycles even with all electrode force values. Probably this case occurred because of the critical value of heat dissipated related with size of the welding strips.

- Sheet 1.0 mm
  i. The behavior of the relationship between the welding strength and the parameters of the RSW process nearly as same as the sheet of 1.5 mm.
  ii. The best welding time is 5 cycles.
- Sheet 0.6 mm
  i. Better welding strength was occurred at the lower electrode force.
  ii. The best welding time is 2 cycle.

Generally, increasing electrode force will be decrease the welding strength for the soft aluminum alloys. Moreover, it will be decrease the welding range, and increase the separation of the strips, in addition of increasing the internal stresses that cause the indentation of the cracks at the nugget and the heat affected zone (HAZ).

Regression Analysis

Since there are a little published paper investigated the RSW relevance with a low strength commercial aluminum alloys and based on the experimental of this work, empirical equations were proposed to calculate the minimum shear tensile strength for a specific of the aluminum alloy AA1050.

There were several attempts to find the best proposed equations to estimate the welding strength. One of this attempt was three order power equation, but most of the proposed equations were inaccurate, therefore the focus was only on the below equations. The following equations are proposed for estimating the shear-tensile strength of the RSW process, one for a quadratic relationship (eq. 1) and the other for a linear relationship (eq. 2).

These equations were constructed from the available data of this experimental work using the

LabVIEW software program to calculate the RMS of current (I) and voltage, welding time (C), and the electrode force (P) during welding and the tests performed of the shear-tensile strength (F) to the weldment strips, and assistance with numerical solution in curve fitting which are demonstrated in the appendix.

$$F = a_0 + a_1 I^2 + a_2 I + a_3 C + a_4 P \qquad (1)$$

$$F = a_0 + a_1 I_i + a_2 C_i + a_3 P_i \qquad (2)$$

And the solutions of the above constants (a's) for each thickness are;

Sheet 0.6 mm:

$$F = 7 - 0.4I^2 + 54I - 17C - 144 \qquad (3)$$

$$F = 169 + 36.5I - 17C - 145P \qquad (4)$$

Sheet 1.0 mm:

$$F = 252 + 0.2I^2 + 48I - 10C - 264P \qquad (5)$$

$$F = 183 + 54I - 10C - 264P \qquad (6)$$

Sheet 1.5 mm:

$$F = -2425 - 0.3I^2 + 240I + 8C - 265P \qquad (7)$$

$$F = -980 + 113I + 7.3C - 260P \qquad (8)$$

When implementation the above empirical equations on the data of the experiments of this work was noted the absence of a large difference between linear equations and the quadratic equations. So, it will be suggest applying the linear equations because they are easier and will be quite sufficient to estimate the values of the welding strength.

Conclusions

It is important to know and evaluate the influence of the RSW process parameters on the welding strength especially where welding low strength of aluminum alloys since these alloys are very difficult to resistance welding due to the high thermal conductivity, low electrical resistance, the oxide film problems, and the low strength.

The most important conclusions can be summarized as follows;

1. The differences of the weldability between the thicknesses of the sheets were little, and the range of the weldability are 14, 12, 10 kA for the 0.6, 1.0, and 1.5 mm sheet thickness respectively. So, it shows inverse relation between the weldability range and the sheet thickness of a specific this alloy.
2. The best welding times are 2, 5, and 9 cycles for the 0.6, 1.0, and 1.5 mm sheet thickness respectively.
3. The range of the appropriate welding condition is large in the 5 cycles of a welding time.
4. Resistance spot weldability of AA1050 aluminum alloy is influenced greatly by the electrode force. When a lower electrode force is applied, the acceptable current range is the widest. The best amount of the electrode force is (1.75-2.25) kN.
5. The proposed empirical equation with linear relationship is quite enough to estimate the strength of the weldments.

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Appendix

Multiple power regressions for the variables of shear tensile strength parameters;

$$f\,(F, I, C, P) = 0 \qquad \text{(A1)}$$

Where:

F: Shear tensile strength in (N)

I: Welding current in (kA)

C: Welding time in (Cycles)

P: Electrode force (kN)

$$F \propto I, C, P \qquad \text{(A2)}$$

$$F = f(I, C, P) \qquad \text{(A3)}$$

Modified eq. (11) for the power relationship related variables, therefore:

$$F = a_0 + a_1 I^2 + a_2 I + a_3 C + a_4 P \qquad \text{(A4)}$$

Or:

$$F = a_0 + \sum_{i=1}^{n} a_i x_i \qquad \text{(A5)}$$

The best values of a's are determined by setting up the sum of squares of residual error.

$$Sr = \sum \left(F_i - a_0 - a_1 I_i^{\,2} - a_2 I_i - a_3 C_i - a_4 P_i\right)^2 = Min. \qquad \text{(A6)}$$

$$\frac{\partial Sr}{\partial a_0} = -2\sum\left(F_i - a_0 - a_1 I_i^{\,2} - a_2 I_i - a_3 C_i - a_4 P_i\right) = 0 \qquad \text{(A7)}$$

$$\frac{\partial Sr}{\partial a_1} = -2\sum\left[\left(F_i - a_0 - a_1 I_i^{\,2} - a_2 I_i - a_3 C_i - a_4 P_i\right) I_i^{\,2}\right] = 0 \qquad \text{(A8)}$$

$$\frac{\partial Sr}{\partial a_2} = -2\sum\left[\left(F_i - a_0 - a_1 I_i^{\,2} - a_2 I_i - a_3 C_i - a_4 P_i\right) I_i\right] = 0 \qquad \text{(A9)}$$

$$\frac{\partial Sr}{\partial a_3} = -2\sum\left[\left(F_i - a_0 - a_1 I_i^{\,2} - a_2 I_i - a_3 C_i - a_4 P_i\right) C_i\right] = 0 \qquad \text{(A10)}$$

$$\frac{\partial Sr}{\partial a_4} = -2\sum\left[\left(F_i - a_0 - a_1 I_i^{\,2} - a_2 I_i - a_3 C_i - a_4 P_i\right) P_i\right] = 0 \qquad \text{(A11)}$$

Alternatively:

$$n a_0 + \sum a_1 I_i^{\,2} + \sum a_2 I_i + \sum a_3 C_i + \sum a_4 P_i = \sum F_i \qquad \text{(A12)}$$

$$\sum a_0 I_i^{\,2} + \sum a_1 I_i^{\,4} + \sum a_2 I_i^{\,3} + \sum a_3 C_i I_i^{\,2} + \sum a_4 P_i I_i^{\,2} = \sum F_i I_i^{\,2} \qquad \text{(A13)}$$

$$\sum a_0 I_i + \sum a_1 I_i^{\,3} + \sum a_2 I_i^{\,2} + \sum a_3 C_i I_i + \sum a_4 P_i I_i = \sum F_i I_i \qquad \text{(A14)}$$

$$\sum a_0 C_i + \sum a_1 I_i^{\,2} C_i + \sum a_2 I_i C_i + \sum a_3 C_i^{\,2} + \sum a_4 P_i C_i = \sum F_i C_i \qquad \text{(A15)}$$

$$\sum a_0 P_i + \sum a_1 I_i^{\,2} P_i + \sum a_2 I_i P_i + \sum a_3 C_i P_i + \sum a_4 P_i^{\,2} = \sum F_i P_i \qquad \text{(A16)}$$

In matrix form:

$$[\mathbf{A}]\,\bar{\mathbf{a}} = \bar{\mathbf{b}} \qquad \text{(A17)}$$

And the matrix to find (a's) is;

$$[\mathrm{A}] = \begin{bmatrix} n & \sum I_i^{\,2} & \sum I_i & \sum C_i & \sum P_i \\ \sum I_i^{\,2} & \sum I_i^{\,4} & \sum I_i^{\,3} & \sum C_i I_i^{\,2} & \sum P_i I_i^{\,2} \\ \sum I_i & \sum I_i^{\,3} & \sum I_i^{\,2} & \sum C_i I_i & \sum P_i I_i \\ \sum C_i & \sum I_i^{\,2} C_i & \sum I_i C_i & \sum C_i^{\,2} & \sum P_i C_i \\ \sum P_i & \sum I_i^{\,2} P_i & \sum I_i P_i & \sum C_i P_i & \sum P_i^{\,2} \end{bmatrix}$$

Where n is the repeated experimental test.

To resolve the matrix to find (a's) values multiple by $[A]^{-1}$

$$[A]^{-1}\,[A]\,\bar{a} = [A]^{-1}\,\bar{b} \qquad \text{(A18)}$$

Where:

$$\bar{a} = \begin{pmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix} \qquad \& \qquad \bar{b} = \begin{pmatrix} \sum F_i \\ \sum F_i\, I_i^{\,2} \\ \sum F_i\, I_i \\ \sum F_i\, C_i \\ \sum F_i\, P_i \end{pmatrix}$$

By the same procedure that is shown above, the linear relationship between the related variables is:

$$F = a_0 + a_1 I_i + a_2 C_i + a_3 P_i \qquad \text{(A19)}$$

And the matrix to find (a's) is

$$[A] = \begin{bmatrix} n & \sum I_i & \sum C_i & \sum P_i \\ \sum I_i & \sum I_i^{\,2} & \sum I_i C_i & \sum I_i P_i \\ \sum C_i & \sum C_i I_i & \sum C_i^{\,2} & \sum C_i P_i \\ \sum P_i & \sum P_i I_i & \sum P_i C_i & \sum P_i^{\,2} \end{bmatrix}$$

$$\bar{b} = \begin{pmatrix} \sum F_i \\ \sum F_i\, I_i \\ \sum F_i\, C_i \\ \sum F_i\, P_i \end{pmatrix}$$

Table 1 Resistance spot welder (TECNA-8106) Specifications

Specification	**Value**	**Specification**	**Value**
Supply Voltage	380 V	Phases	1
Frequency	50 Hz	Max. welding Power	810 kVA
Nominal power at 50%	250 kVA	Max. welding current	68 kA
Max. welding force	18.85 kN	Electrode force per 1 bar	3.14 kN
Supply pressure	6.5 bar	Water cooling	12 ℓ / min
Throat depth	250 mm	Net weight	1000 kg

Table 2 Strip material specifications

Trade name	**Thickness** (mm)	**Tensile** (MPa)	**Hardness** (HV)	**Nominal composition** (wt-%)				
				Fe	Si	Mn	Others	Al
1050A	0.6	105	30	0.255	0.173	0.021	0.051	99.5
1050A	1.0	105	30	0.378	0.100	0.018	0.004	99.5
1050A	1.5	127	45	0.350	0.070	0.010	0.070	99.5

Table 3 Experiments setup (factors and their associated values)

Factors	**Values**	**Units**
Sheets thicknesses	0.6, 1.0, 1.5	mm
Current (RMS)	10 ~ 30	kA
Welding time	1 ▯ 13	cycle
Electrode force	1.75 ▯ 4.00	kN

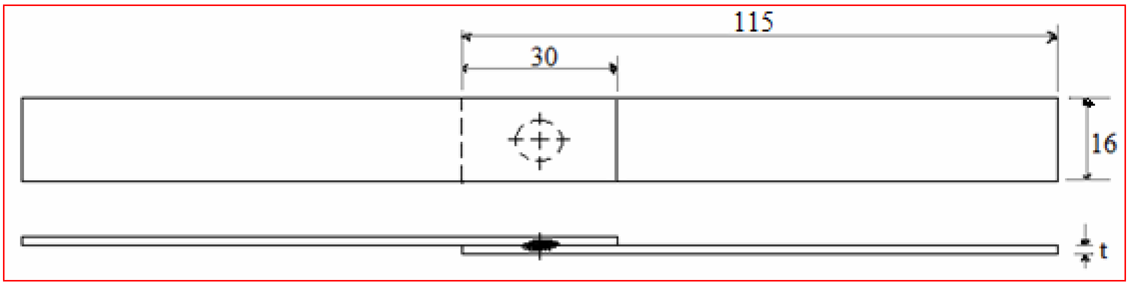

Fig. 1 Schematic illustration of tensile test specimen

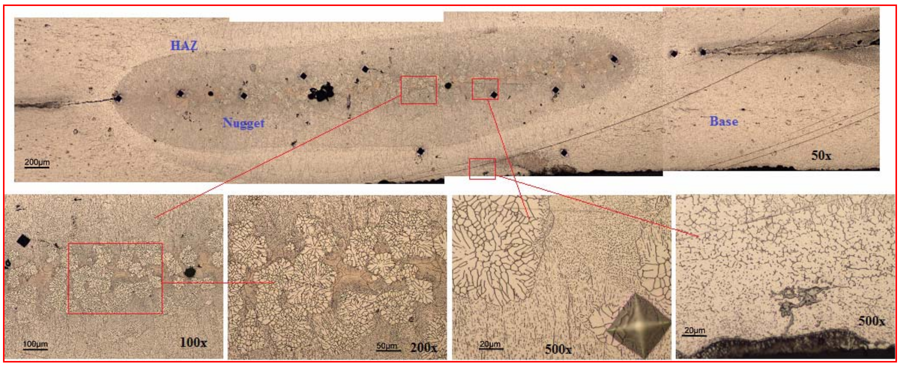

Fig. 2 Micrographs of RSW of 1.0 mm sheet, welding parameters (29 kA, 5 cycles)

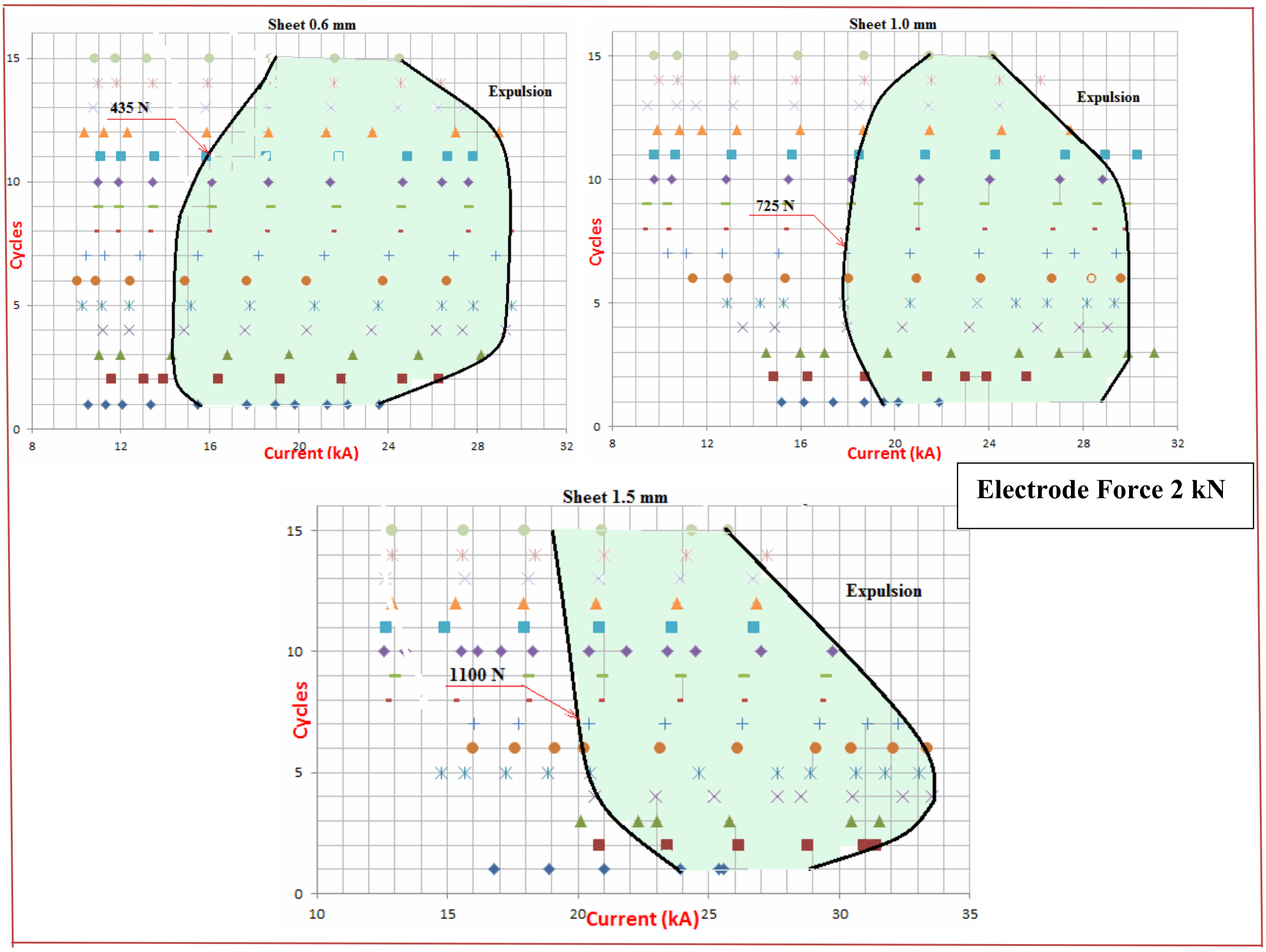

Fig. 3 Weld current-Weld time lobe diagram

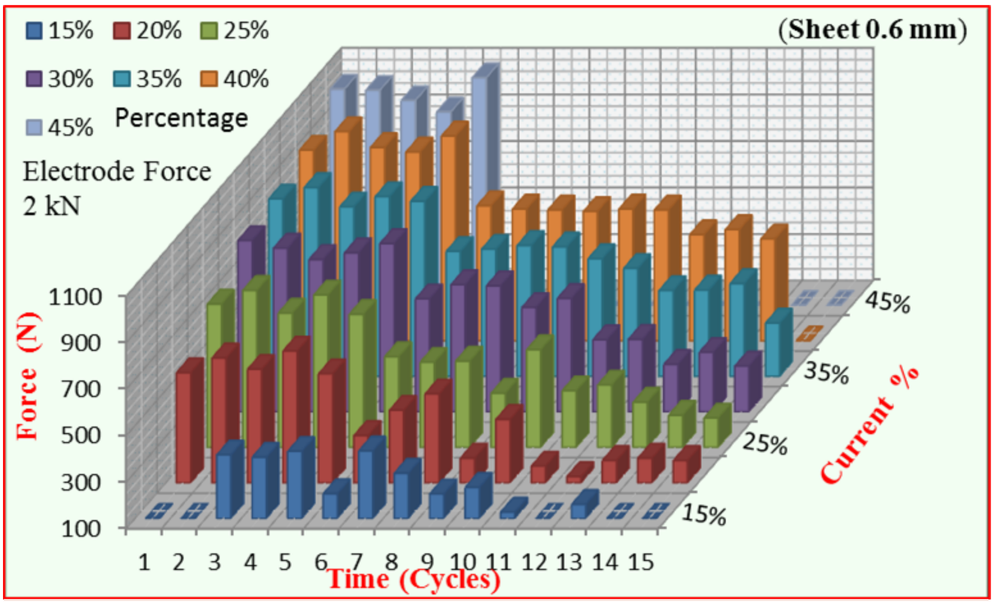

Fig. 4 The relationship between the shear tensile strength and the RSW parameters (0.6 mm)

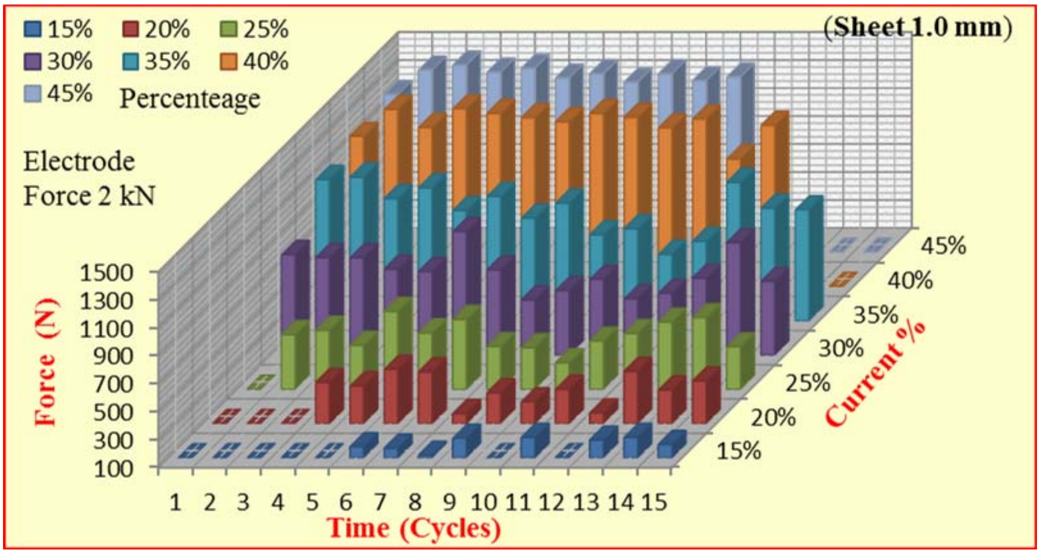

Fig. 5 The relationship between the shear tensile strength and the RSW parameters (1.0 mm)

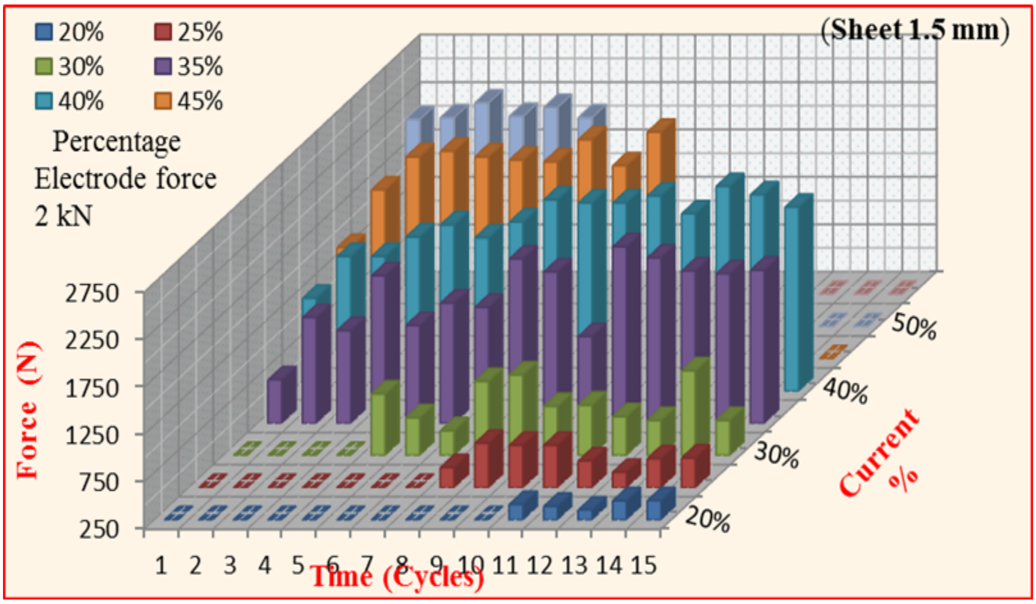

Fig. 6 The relationship between the shear tensile strength and the RSW parameters (1.5 mm)

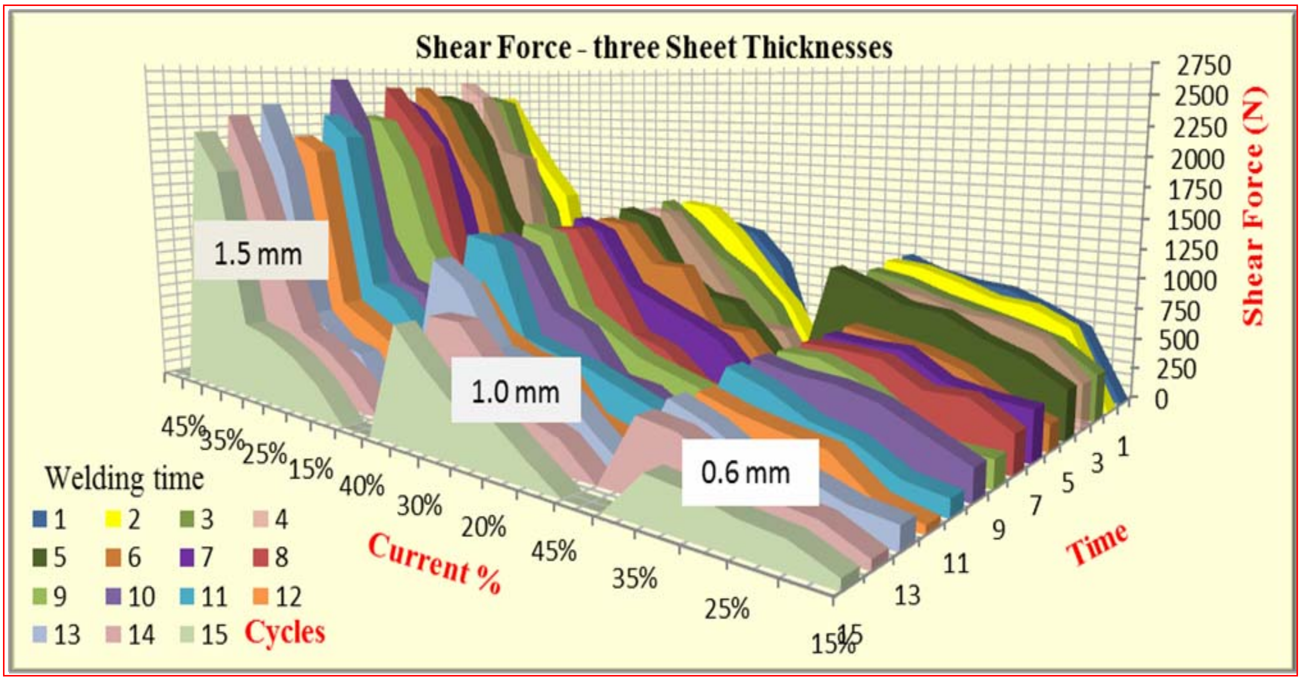

Fig. 7 The relationship between the shear tensile strength and the RSW parameters (three sheets)

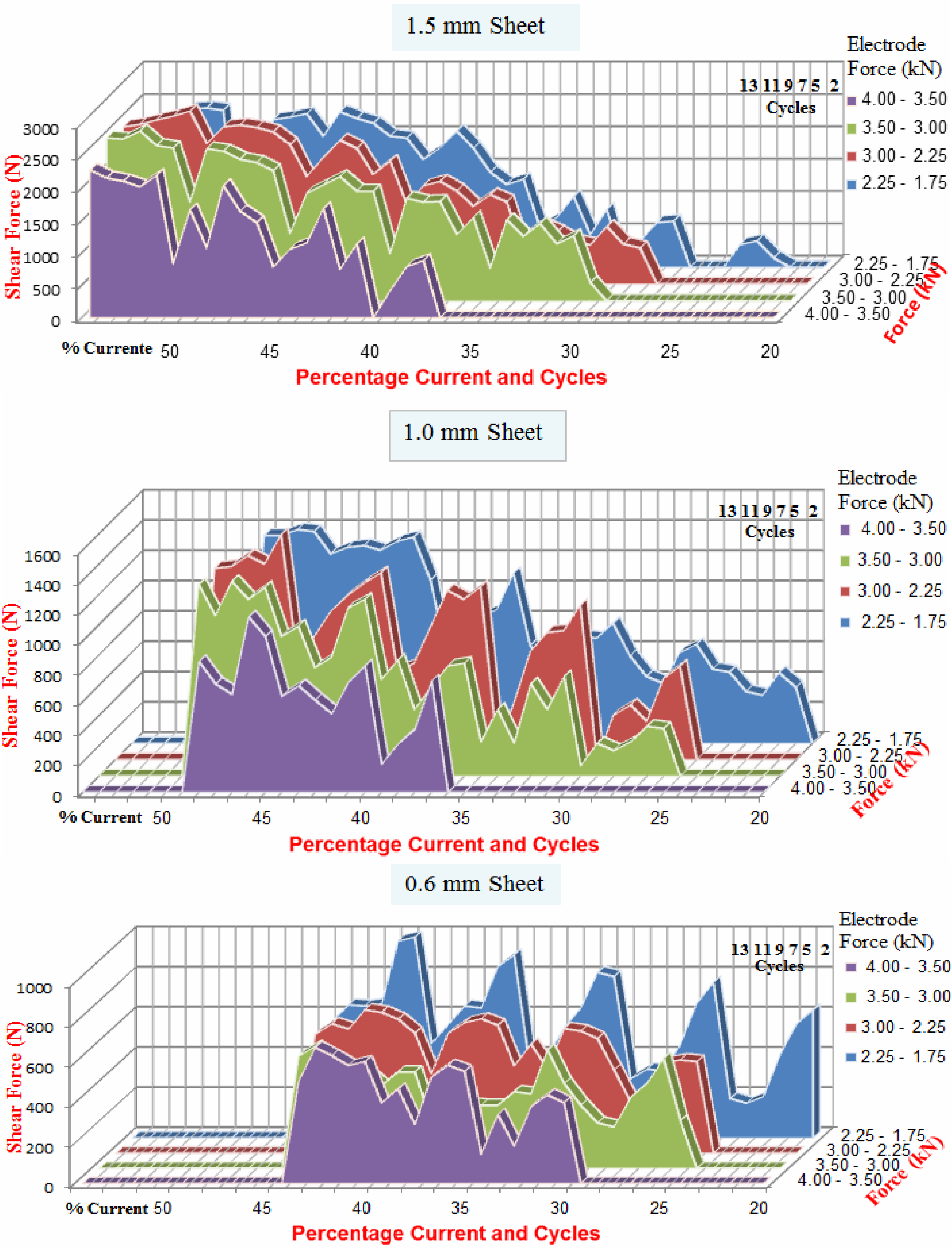

Fig. 8 The influence of the electrode forces on the shear tensile strength (three sheets).