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Process Parameter Selection for Resistance Spot Welding Through Thermal Analysis of 2mm CRCA Sheets

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Abstract

An attempt is made to arrive at suitable process parameters for resistance spot welding through thermal analysis. 2mm Closed Rolled Closed Anealing (CRCA) sheet metal is selected as work piece. Nugget and electrode diameter are evaluated from emperical relations. Full factorial Design Of Experiment (DOE) is applied for weld current and time. Thermal analysis is carried out for selected DOE values using SYSweld. Temperature distribution, nugget and Heat Affected Zone dimensions are obtained from the analysis. Weld strenght is analysed through experimental trails. Optimum process parameter for spot welding of 2mm CRCA sheet is arrived by comparing simulation and experimental results.

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Keywords: Resistance Spot Welding; Nugget formation; Thermal analysis; Weld Strenght; SYSweld®

1. Introduction

Resistance spot welding is a unique welding process, where weld nugget is not visible outside. Fig.1 shows the schematic of spot welding. During spot welding process, the electrical resistance between two faying surfaces of sheet metal is utilized by passing higher magnitude electrical current under force for set time, which heats up the interface spot of sheet metals to melting temperature there by creating the coalescence between two sheet metals. In

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automotive industry CRCA material plays an important role among various other materials. Thickness of sheets varies from 0.3-3mm (JSW, website).

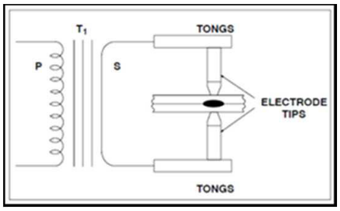

Fig. 1. Schematics of resistance spot welding (Millers handbook, 2010)

Nomenclature

CRCA Cold Rolled Closed Annealed
DOE Design of Experiments
HAZ Heat Affected Zone
RSW Resistance spot Welding
OEM Original Equipment Manufacturer
RWMA Resistance Welders Manufacturer Association

In automotive industries RSW plays an important role in joing the sheet metals. There is a great demand for obtaining good quality weld joint in order to have defect free product. Car body is made up of different sheet metal thickness, which requires process parameter to be varied (Al-Jader et al., 2010). Process parameters like welding current, time and pressure are closely controlled to obtain superior weld quality. A study is carried out by varying electrode force, welding current, welding time and electrode diameter to achieve good quality weld. An optimum welding parameter is determined using Taguchi experimental design method (UgurEsme, 2009). On similar guide lines an experimental investigation for optimizing tensile shear (T-S) strength of RSW for galvanized steel is carried out. Taguchi quality design concepts of L27 (Thakur et al., 2010) orthogonal array is used to determine Strength to Noise (S/N) ratio for optimum process parameters.

In automotive industries sustenance of spot welding is important. Sustainability factors like voltage, current, force, water cooling rate, material thickness are evaluated by using software package SORPAS. And electrode current and its effect on electrode tip life is investigated (Al-Jader et al., 2010). During spot welding, expulsion is a major factor; study of the effect of time on expulsion is carried out (Hwanga et al., 2011). And to reduce expulsion through electrode force and current is studied.

Simulation techniques are used along with experimental trials to arrive at suitable process parameters. In literature axis-symmetric, finite element model is developed to carry out thermo-mechanical analysis behaviour of RSW process using ANSYS software. In this, stress distribution (Hou et al., 2007), temperature and phase transformation (Hamedi and Pashazadeh, 2008) in the weldment and their changes in RSW process are observed. Similarly finite element model is developed to study the effect of welding time and current intensity on nugget size in AISI type 304L austenitic stainless steel (Moshayedi and Sattari, 2012). And a parametric model is developed to predict the transient thermal behaviour (Yeung et al., 1999).

Major studies are carried out on different materials and thickness like, refractory alloy 50Mo–50Re (wt %) sheet with a 0.127 mm gauge (Xu et al., 2007), aluminium alloy sheet of 1.2 mm (Zedan and Talib, 2008) and aluminium alloy sheet 5J32 of 1mm (Kim et al., 2009). The effect of the welding time on tensile test of 1mm mild steel (Md. Ibrahim, 2008) and chromate micro-alloyed steel sheets of 1.2 mm thicknesses are investigated using related period diagram(Aslanlar et al., 2008).

From above literature, it can be observed that weld time, current and electrode force plays a vital role in obtaining good quality weld. But a minimal work is reported on CRCA sheets involving 2mm sheet thickness. Therefore, the present study aims at implementing full factorial DOE technique for process variable such as weld time and current to carry out thermal analysis. Experimental trails for same DOE values are also carried out for analyzing weld strength.

2. Numerical calculation

Numerical calculations are carried out for evaluating nugget diameter, area, volume and mass. The calculations are for 2mm sheet only. The material properties of the selected CRCA sheet are obtained from Cambridge Engineering Software, which is provided in Table 1.

Table 1 - Material Properties

Sl. No.	Property	Description
1	Material	Mild steel (0.04 - 0.06% carbon, equivalent to IS 513D)
2	Specific heat of material	468 kJ/ kg ^{0}C
3	Density of material	7850 kg/ m^3
4	Melting temperature	1480^{0}C
5	Each sheet thickness	2mm

Using the values from Table 1, numerical calculations are carried out to evaluate heat required to melt the mass of the nugget at the interface of two sheet metals. Electrode diameter is evaluated to arrive at heat required. Then nugget diameter is calculated using electrode diameter.
The empirical relations from literature for evaluating electrode, 'D' (Yeung and Thorton, 1990) and nugget diameter, 'd' (Weman, 1993) are given in Eq. (1) and (2) respectively

$$D = \sqrt{T} * 5 \tag{1}$$
$$d = \sqrt{T} * 4 \tag{2}$$

From Eq. (1) and (2), electrode diameter and nugget diameter are found to be 8mm and 5.65mm respectively. Area and volume of the nugget are evaluated by using Eqs. (3) and (4).

$$Area\ of\ the\ circle = 0.7853 * d^2 \tag{3}$$
$$Volume\ of\ the\ nugget = Area\ of\ the\ cirlce * sheet\ thickness \tag{4}$$

The area and volume of nugget are found to be 2.463e-5 m^2 and 5e-8 m^3 respectively by substituting the value from Eq. (2). The mass of the nugget which is to be melted is provided in Eq. (5)

$$Mass\ of\ the\ nugget = Volume\ of\ the\ nugget * Density \tag{5}$$

Mass of the nugget to be melted is found to be 3.95e-4 kg, which is obtained by multiplying density from Table 1 and value from the Eq. (4).
The Eq. (6) provides the value of heat required to melt the mass of nugget, which is obtained by multiplying mass of the nugget obtained from Eq. (5), specific heat value from the Table 1, along with change in temperature.

$$Heat\ required\ to\ melt\ nugget\ = mass\ of\ nugget * specific\ heat * \Delta T \tag{6}$$

To form the nugget between sheet metals, the materials at the interface have to undergo complete melting. In order to achieve complete melting, the rise in temperature (ΔT) has to be 1480^{0}C from Table 1**.** Thus to melt 3.95e-4 kg of mild steel (nugget material) 273.5 kJ of heat is required.
When an electric current is passed through contact spots, the temperature rise is observed. The contact resistance is depends upon surface roughness, hardness of the material, impurities, oxide layer, load and temperature. Among these the temperature and material hardness are depend upon on electricity (Wei and Wu, 2012). The transformer in RSW machine steps down the supply voltage and increase the secondary current. The secondary currents are in the order of the several thousands of ampere and it is practically difficult to measure these current levels. The secondary currents are analytically obtained using the transformer ratio (UgurEsme, 2009). In the present study the primary current values are collected from OEM and secondary currents are calculated from the Eq. (7)

$$\frac{V_s}{V_p} = \frac{I_p}{I_s} = \frac{N_s}{N_p} \quad (7)$$

$$I_s = \frac{V_p}{V_s} * I_p \quad (8)$$

Where:

V_p = Primary voltage, Volts
V_s = Secondary voltage, Volts
I_p = Primary current, Amps
I_s = Secondary current, Amps
N_p = Primary turns
N_s = Secondary turns

The spot welding equipment is used for the study consists of 5 tapings. The secondary voltages are calculated from the Eq. (7) and are tabulated in the Table 2.

Table 2 - Voltage and current values in secondary current

TAPPING	1	2	3	4	5
Primary voltage (V_p)	440	440	440	440	440
Primary current (I_p)	10	12	15	18	25
Secondary voltage (V_s)	1.6	1.8	2	2.4	2.8
Secondary current (I_s)	2750	2933	3300	3300	3928

Heat generated is calculated from Eq. (9). It is done for all 5 taping by considering secondary current obtained from Eq. (8) and total resistance of the setup and time duration of current supply. The total resistance of setup includes bulk resistance of electrode, sheet metal, and interface resistance between work piece-electrode and between work piece-work pieces (Aslanlar et al., 2008).

$$Q_{calc} = I^2 * R * T \quad (9)$$

$$Q_{act} = 40\% * I^2 * R * T \quad (10)$$

Where:

Q_{calc} = Heat generated due to current
I = Current Supplied
R = Total resistance
T = Time duration of current supply

Actual heat transfer is given by Eq. (10) and is only 40% of the calculated heat generated. This is due to the heat loss to the surrounding. During welding process both bulk resistance as well as contact resistance will vary according to temperature and weld force (Wei and Wu, 2012).

It is observed from the literature and simulations, is that shorter weld time and current will not have sufficient time to heat up the interface region between the sheets to achieve the melting temperature, thereby reducing the weld strength at the joints. And when welding current is too high due to overheating at weld joints it will results in expulsion (Hwanga et al., 2011). Considering these two limitation, a full factorial DOE is designed for conducting the numerical analysis. DOE techniques enable to determine simultaneously the individual and interactive effects of many factors that could affect the output results. DOE also provides a complete insight of interaction between variables. DOE helps to pin point the sensitive parameters which causes problems in experiment. The number of variable selected for the DOE are current and weld cycle. To have a wider range, weld cycle of 3 set i.e. 0.3, 0.4 and 0.5 seconds are selected; along with 3 set of secondary current i.e. 2750A, 2933A, 3300A, 3928A.

A full factorial method of DOE covers all combination of input variable which affect the output process. In this study 3 sets of full factorial DOE are constructed. It can be notice from Table 2 that among 5 taping only four tapings are selected. As taping 3 and 4 both have same secondary current of 3300A. Thus 4th taping from the Table 2 is not considered for generating DOE table.

Table 3 - Full factorial DOE for RSW

Sl. No	Current(A)	Time(sec)
1.1	2750	0.3
1.2	2933	0.3
1.3	3300	0.3
1.4	3928	0.3
2.1	2750	0.4
2.2	2933	0.4
2.3	3300	0.4
2.4	3928	0.4
3.1	2750	0.5
3.2	2933	0.5
3.3	3300	0.5
3.4	3928	0.5

Using DOE values generated in Table 3 and substituting these values of current and time in Eq. (10) results in heat generation at the interface of two sheet metals, as shown in Table 4.
By comparing the values in Table 4 with the value obtained for heat generated from Eq. (6), it is observed that $Q_{2.3}$, $Q_{3.3}$ in DOE-3 and $Q_{1.4}$, $Q_{2.4}$, $Q_{3.4}$ in DOE-4 has heat transfer value equal to or greater than the value obtained from equation (6) i.e. 273.5 kJ, which is required to melt the mass of the nugget. Thus it is evident that parameters from DOE-3 and DOE-4 are used to carry out simulation.

Table 4 - Full factorial DOE values

DOE No.	Identification no.	Heat transfer Values
DOE-1	$Q_{1.1} = 0.4 * (2750)^2 * 0.13 * 0.3$	117.9 kJ
	$Q_{2.1} = 0.4 * (2750)^2 * 0.13 * 0.4$	157.3 kJ
	$Q_{3.1} = 0.4 * (2750)^2 * 0.13 * 0.5$	196.6 kJ
DOE-2	$Q_{1.2} = 0.4 * (2933)^2 * 0.13 * 0.3$	134.1 kJ
	$Q_{2.2} = 0.4 * (2933)^2 * 0.13 * 0.4$	178.9 kJ
	$Q_{3.2} = 0.4 * (2933)^2 * 0.13 * 0.5$	223.6 kJ
DOE-3	$Q_{1.3} = 0.4 * (3300)^2 * 0.13 * 0.3$	169.8 kJ
	$Q_{2.3} = 0.4 * (3300)^2 * 0.13 * 0.4$	226.5 kJ
	$Q_{3.3} = 0.4 * (3300)^2 * 0.13 * 0.5$	283.1 kJ
DOE-4	$Q_{1.4} = 0.4 * (3928)^2 * 0.13 * 0.3$	240.6 kJ
	$Q_{2.4} = 0.4 * (3928)^2 * 0.13 * 0.4$	320.9 kJ
	$Q_{3.4} = 0.4 * (3928)^2 * 0.13 * 0.5$	401.1 kJ

Thermal analysis simulations are carried out for selected parameters from Table 4. Totally six simulations are carried out for different input conditions. Conditions for each simulation are given in Table 5.

3. Simulation

Spot welding module of SYSweld® is used for simulating the spot welding. These simulations help in analyzing the effect of input variable on output results. In particular, the effects of input variable such as current, electrode force, holding time are studied through thermal analysis. In this analysis, the following outputs are available

- Temperature distribution
- Heat Affected Zone
- Phase transformation
- Nugget dimensions

Table 5- Selected parameters of DOE for simulation

Description	PSet01	PSet02	PSet03	PSet04	PSet05	PSet06
Current (A)	3300	3300	3300	3928	3928	3928
Frequency (Hz)	50	50	50	50	50	50
Force (N)	2000	2000	2000	2000	2000	2000
Application Cycle (Seconds)	0.3	0.4	0.5	0.3	0.4	0.5
Each Sheet Thickness (mm)	2	2	2	2	2	2

For the simulation, the sheet metal of 2mm is considered, the material data of the sheet metal used are provided in the Table 1.These outputs are used to analyze and compare results with numerically obtained values. Six simulations are carried out and the inputs for simulations are provided in Table 5.

For all six simulations constant force of 2000N is applied on the sheet metals, which is generated due to electrode force. These six simulations are carried out for current varying from 3300-3928A, along with varying application time of 0.3-0.5 seconds. These are classified under the name of PSet01-06 as referred in Table 5. Among all six simulations, result of simulation PSet01 is explained in detail.

3.1. Simulation of PSet01:

For the simulation PSet01, variable parameter current of 3300A is considered for a period of 0.3 seconds. A uni-direction electrode force of 2000N is applied on to the sheet metal. The edges of the sheet metal are fixed in all degree of freedom which represents the clamping force (Moshayedi and Sattari, 2012).

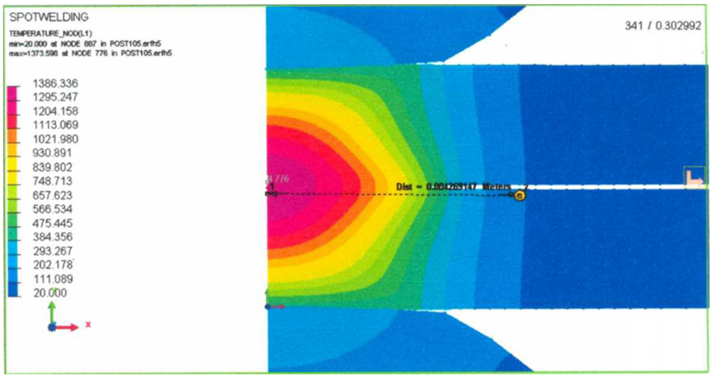

Fig. 2. Temperature distribution of PSet01

Temperature distribution at the sheet metal interface during spot welding is provided in the Fig. 2. A maximum temperature of 1386.34^{0}C is achieved in and around the region of node number 776 which is at the interface of two sheet metals. A minimum temperature of 20^{0}C is recorded at node number 887 which demarks itself as HAZ. The HAZ is 4.27 mm from the centre.

Fig. 3 shows the formation of nugget at the sheet metal interface. The dimensions of the nugget are obtained from the simulation. The length and height of the nugget are measured and found to be 1.5mm and 1.4mm respectively. Output results provide information about the phase transformation.

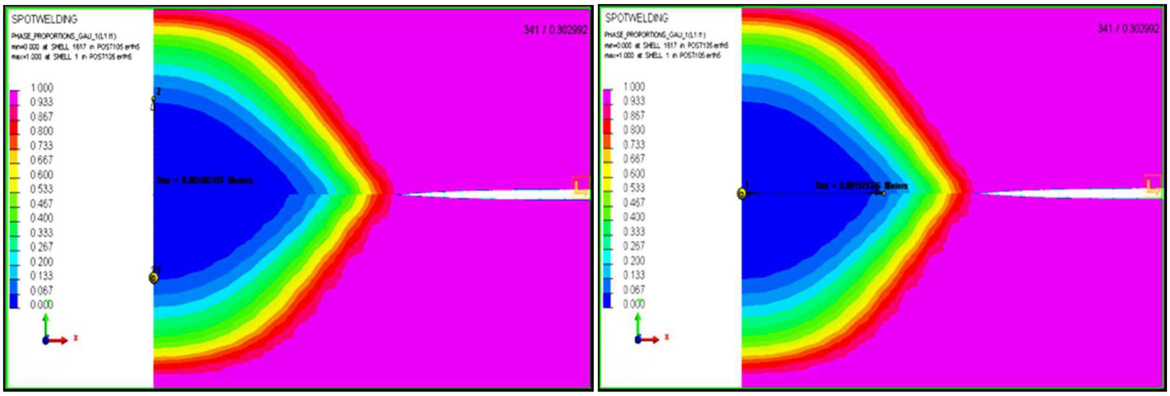

Fig. 3. Dimensions of the nugget weld of PSet01

By adopting similar procedure, remaining five simulations are carried out for inputs provided in the Table 5. The maximum temperature rise at the interface of two sheet metals is obtained and shown in Fig. 4.

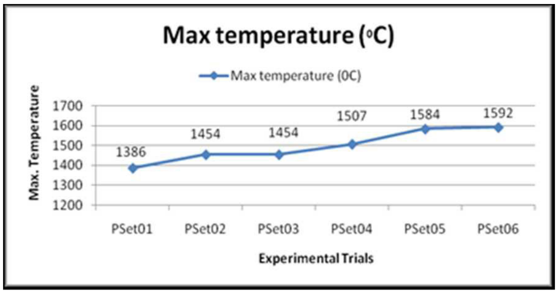

Fig. 4. Maximum temperature at the interface for all six trails

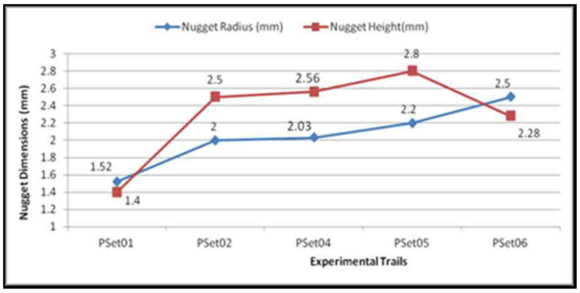

Fig. 5. Nugget formation at the sheet interface for all six simulations

The rise in temperature achieved at the interface of the two sheet metals is due to electrical resistance offered by the sheet metal. The heat developed causes the temperature to rise and there by fusing the two metals sheet which causes the nugget. Since the maximum temperature of PSet02 and PSet03 are identical i.e. 1454^{0}C, the results of PSet03 are not considered for further discussion. Results of all the six simulations are tabulated in the Table 6.

Table 6: Simulation results of PSet01, PSet02, PSet04, PSet05 and PSet06

Description	PSet01	PSet02	PSet04	PSet05	PSet06
Current (A)	3300	3300	3928	3928	3928
Force (N)	2000	2000	2000	2000	2000
Time period (Seconds)	0.3	0.4	0.3	0.4	0.5
Maximum temperature (^{0}C)	1386.34	1454.14	1507.25	1584.68	1592.94
HAZ distance from center(mm)	4.2	5.06	4.5	5.06	5.5
Nugget radius (mm)	1.52	2.0	2.03	2.2	2.5
Nugget Height (mm)	1.4	1.25	1.28	1.43	1.143

Variation of nugget radius and height is shown in the Fig. 5. The nugget radius varies from 1.5-2.55mm as the current is increased from 3300A-3928A. But for the simulation PSet06 the nugget dimension is reduced from 2.8mm to 2.28mm as there is metal expulsion due to overheating induced due to high current (Hwanga et al., 2011). 401.1 kJ of heat is generated when compared to 270 kJ required to melt the mass of the nugget.

4. Experimental Trials

In section 3, simulation results shows maximum temperature rise at the interface of the sheet metal but provided very little insight about the strength of the weld joint. To evaluate weld strength, experimental trials are carried out for the same input provided in Table 5.

Experimental trails are conducted on 2mm CRCA sheet metal. The work piece considered here is as per welding standards of RWMA (UgurEsme, 2009); the dimensions of the standard specimen are shown in Fig. 6.

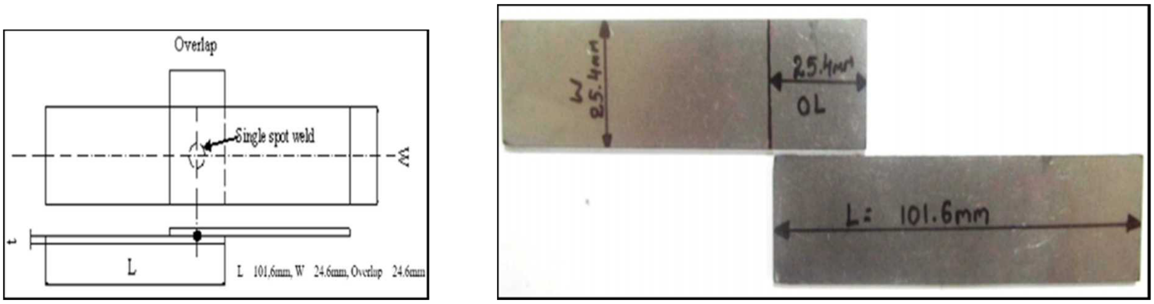

Fig. 6. Dimensional details and standards of RSW specimen

To determine the strength of the spot welded joint, two sets of specimen are prepared for each input from DOE Table 5. First set of specimens are used for pull load test and second set of specimens are used for peel-off test. Fig.7 shows a set of specimen prepared according to Table 5.

In pull load test, the test specimen is loaded on to the universal testing machine. The load is applied on the work piece till it breaks apart (Chao, 2003).The load where it breaks is recorded as the strength of the weld joint.

Fig. 8 shows the load vs. displacement curve for PSet01 experiment trail. In the graph it can be observed that when the displacement is around 2.6mm, the weld joint break away when the load is reached 4500N. There by indicating the maximum load which can be withstood by PSet01 is 4500N. The reason for breaking at lower load is due to the insufficient melting temperature at sheet metal interface. From Fig. 2, where it can be observed that maximum temperature reached at interface is 1386^{0}C when compared to the required melting temperature of 1480^{0}C. All six specimens are subjected to pull load test. The test results of the six experiments are tabulated in Table 7. Fig. 9 shows the variation of the breaking load with respect to six specimens when subjected to pull load test. It can be observed that experiment number PSet06 has highest strength of 8.39kN with displacement of 4.8mm, when subjected to pull-load test.

Table 7: Results of the pull load test

Description	PSet01	PSet02	PSet03	PSet04	PSet05	PSet06
Breaking Load (kN)	4.5	6.89	6.47	7.34	8.12	8.93
Displacement (mm)	2.6	3.2	3	3.3	4.2	4.8

The maximum load which the specimen i.e. PSet06 withstands is found to be 8390N. The increased strength of the joint is mainly due to overheating which causes metal expulsion (Hwanga et al., 2011). The Fig. 10 shows metal expulsion in PSet05 and PSet06. However, the metal expulsion not only rise the temperature but also leads to high consumption of electricity which is not recommended.

Fig. 7. Test specimen after RSW processes

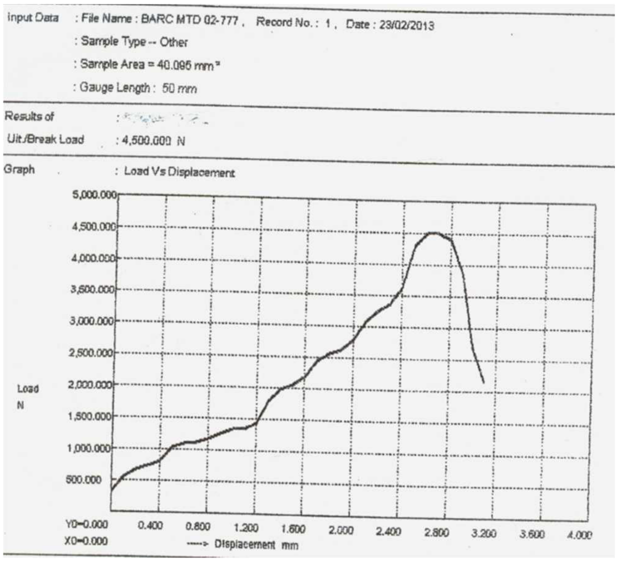

Fig. 8. Load vs. displacement graph of PSet01

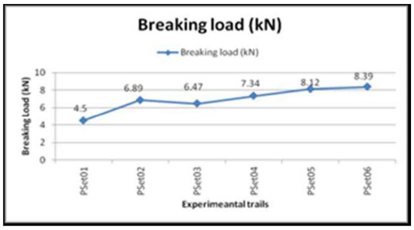

Fig. 9. Breaking load for six experimental trails

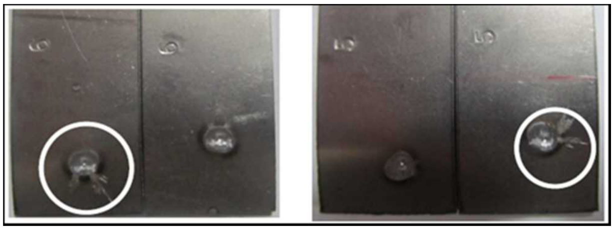

Fig.10. Metal sputtering in PSet06 and PSet05 (L to R)

Peel-off test is a qualitative test conducted by pulling by fixing one end of the specimen to a vice and pulling the other end. There is no quantitative data to determine the weld quality. Generally these tests analyse the failure mode of the nugget. In general there are two modes of failure namely, interface failure and nugget pull-out failure. Second set of specimen are tested for nugget failure mode. Among the six specimens only PSet06 has complete nugget pull-out failure mode as compared to other, as shown the Fig. 11.

Fig. 11. Nugget Pull in specimen PSet06

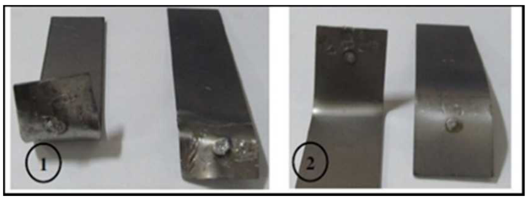

Fig. 12. Interface failure mode in specimen PSet05 and PSet01 (L to R)

Fig. 12 shows the interface failure. It is observed from experimental and simulation results that to obtain better weld strength for 2mm CRCA sheet metals through resistance spot welding, current of 3928A with 0.3 seconds cycle time is considered satisfactory.

5. Conclusion

Process parameter selection of resistance spot welding through thermal analysis for 2mm CRCA sheets is carried out using SYSweld. The effect of current and time is studied on the strength of weld joints. It is observed that the optimum quality of weld strength for 2mm CRCA sheet is observed for 3928A and 0.3 seconds. Nugget diameter value from simulation and experiment trails are in acceptable range. From simulation it can be observed that HAZ remains around 5mm from the centre of the axis. Metal sputtering is observed in experimental trial of PSet05 and PSet06 due to overheating of the joint.

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