Regression Modeling and Process Analysis of Resistance Spot Welded Joints

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***Abstract*: In this study, the effects of weld current, weld time, electrode force and combination of these on the nugget diameter, heat affected zone and tensile-strength of welding joint in electrical resistance spot welding of AISI 304 sheets of 1mm thickness are investigated. A timer and current controlled pneumatically operated rocker arm type spot welding machine of 10 kVA capacity with pneumatic application mechanism and foot switch, with controls for weld current periods, weld time periods and electrode force is used. Squeeze time is kept constant throughout the process at 40 cycles. The obtained welded joints are subjected to tensile-shear strength. Nugget diameter and heat affected zone (HAZ) are observed and computed. The effect of weld current, weld time and electrode force on nugget diameter, HAZ and tensile-shear are then researched by regression modeling and by related diagrams. Optimum weld current, weld time and electrode force for various configurations are thus arrived at.**

***Keywords: Tensile*–shear strength, heat affected zone (HAZ), AISI-304 Sheet, Regression modeling.**

1. INTRODUCTION

Spot welding is a resistance welding process in which overlapping sheets are joined by local fusion at one or more spots by the heat generated by resistance to the flow of electric current through work pieces that are held together under force by two electrodes, one above and the other below the two overlapping sheets. Spot welding came into use in the period 1900-1905. Spot welding is employed for joining sheet to sheet, sheets to rolled sections or extrusions, wire to wire, etc. It is used for relatively light gauge parts (up to about 3 mm thick) super imposed on one another and is widely used in automobile industry. Resistance spot welding (RSW) has high speed and adaptability for automation in high rate production and is used for fabrication of sheet metal assemblies. Resistance spot welding is one of the major welding technologies used in the manufacturing industry, especially in automobile manufacturing [1]. For example there are 3000-8000 spot welds in automobile body which one can find out. One of the major advantages of spot welding is that there is no filler rod required, no spatter generated during the welding process, and can join dissimilar metals. The tensile-strength of spot weld, which is often associated with effective area of nugget to load, is an important index to weld quality [2]. The weldability of steels is better compared to galvanized steels because in galvanized steels we need to give more heat input as compared to ordinary steels [3]. So the investigations on the tensile-strength of spot weld, heat affected zone, nugget geometry and process parameters are the key to solve the RSW problem mainly for stainless steel sheet of 304 grade.

2. THE PRINCIPLE OF ELECTRICAL RESISTANCE SPOT WELDING

In spot welding two or three stacked or stamped and overlapped sheets are welded as a result of heat created in between sheets to form a joint. Similar shape and size spot welds having the same property can be obtained at high production speeds by controlling weld current, weld time, and electrode force. The required high current and low voltage is obtained trough transformer and pressure is obtained from pneumatic, hydraulic or mechanical compressor and the coolant is supplied by pumping with 3-phase induction motor. In resistance spot welding the heat generation depends on three parameters: weld current, weld time and resistance of the sheets to be welded. The formula for heat generation is

$$Q = C.I2\ R\ t \quad (1)$$

Where Q is the heat generated (J), I is the current (A), R is the resistance of the work (Ω) and t is the duration of current (s).
C accounts for losses.

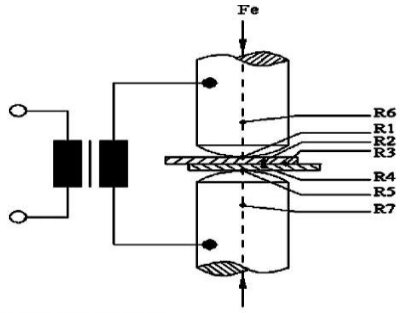

Figure.1 Weld circuit with resistance s [3 4]

The secondary circuit of the resistance welding machine and the work being welded constitute a series of resistances. The total resistance of the current path decides the heating. There are seven resistances connected in series in a spot weld setup as shown in figure 1 that account for the temperature distribution and the sum of these is expressed as:

$$R = R1 + R2 + R3 + R4 + R5 + R6 + R7 \quad (2)$$

Out of the seven resistances the resistance considered for spot weld is R3. The higher this value, the higher is the heating obtained. The magnitude of this resistance depends upon the surface condition of the base metals and the electrode force F with welding current I at welding time t. This is a region of high heat generation, but the surfaces of the base metals do not reach the fusion temperature during the current passage, due to high thermal conductivity of t he electrodes and the fact that they are usually water cooled [3 4].

3. EXPERIMENTAL PROCEDURES

3.1. Material

In this study commercially available stainless steel sheet 304 grade of 1 mm thick is used for the experimentation and the specimens are cut into 80mm length, 25mm width pieces with 20 mm over lapping provided during the experimentation. The chemical composition of steel sheet and mechanical and physical properties of material are as shown in tables 1 and 2 below.

Table1 Chemical Composition of Material (WT %)

C	Mn	P	S	Si	Cr	Ni	N
0.08	2.00	0.045	0.03	0.75	18 .00-20 .00	8-10.5	.10

Table 2 Mechanical and Physical Properties

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Tensile strength, ultimate	505 MPa
Tensile strength, yield	215 MPa
Modulus of elasticity	190 – 200 GPa
Poisson's ratio	0.29
Density	8 g/cc
Electrical resistivity	7.2 e-.005 ohm-cm
Thermal conductivity	16.2 W/m-k
Melting point	1400 - 1455 0C
Hardness Rockwell B	70

3.2. Welding machine and electrode

A timer and current controlled electrical resistance spot welding machine having 10 kVA capacity and pneumatically operated rocker arm set up with foot switch for the initiation of weld is used. The copper electrodes used are one pair Morse taper II straight type. Adjustment of electrode force is by means of air pressure. The force is adjustable and can be varied between 100 to 200 Kgf by pneumatic cylinder adjusted by a regulating valve. For current control, 6 tap change links between 50 % and 100 % switch is used. For adjusting the current, two timers are provided- one squeeze timer and other weld timer - and the timings are for short range 5 – 50 cycles and long range 1 – 10 seconds. The electrodes are water cooled. The setup is as shown in figure 2

Figure 2 RSW set up

3.3. Resistance spot welding process parameters

Experiments were conducted using design of experiment (DOE) approach. The general full factorial design tables were combined together which resulted in 27 different welding tests. To determine the feasible working limit s of welding conditions, several trial tests were carried out. Different combinations of RSW parameters were used in the trail runs. The weld penetrations and nugget appearances were inspected to identify the appropriate ranges of the welding parameters. It was observed that when welding times are less than 10 cycles, there would be lack of fusion and incomplete penetration. Actually such cycles showed very small nugget sizes and less tensile – shear strength when tested. On the other hand, welding times greater than 20 cycle s resulted in weld splash and spatter as well as penetration of electrodes into work piece surfaces and work piece crushing. The weld currents less than 3 kA resulted in incomplete penetration and lack o f fusion. For currents greater than 5 kA, weld splash and spatter occurred. Squeeze time was kept at a low constant value throughout tests because it is not seen as squeezing the plates below its melting state. [3 4]
The considered process parameters and their levels are as shown in Table 3.

Table 3

Variable	Unit		Levels		
			1	2	3
Weld current A	KA	X1	3	4	5
Electrode force B	Kgf/cm2	X2	2	2.5	3
Weld time C	Cycle	X3	10	15	20

3.4. Weld cycle

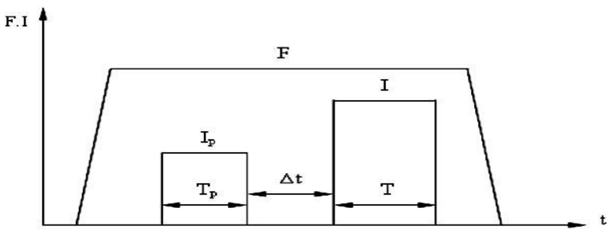

Figure 3. Typical weld cycle.

Figure 3 is a double pulse circulation designed for welding process in view of the existence of zinc coat with a higher electrical conductivity. Welding cycle is shown with F as electrode force. I is welding current, T is welding current duration, Ip is preheat current, Tp is preheat current duration and t is pulse interval.

The first current pulse is preheating pulse (Ip) with duration of Tp. It is used to preheat work pieces, break zinc coat to a certain extent and prepare for the following welding process. The second current pulse is welding pulse (I) with duration of T. It realizes the effect of welding. (1)

3.5. Tensile – shear test setup

Figure 4. Shear test setup.

Tensile- shear strength is an important measure of welding quality in RSW and describes the mechanical properties,. Therefore in this work, tensile – shear strength has been selected to describe the mechanical properties of spot weld. The tensile stress and shear stress are both playing a role during tension test to spot weld because of the eccentricity.

A tensile shear test specimen was s pot welded for each of the 27 welding conditions. The specimens were prepared according to ASTM standards. In order to increase the accuracy and the confidence level, the experiment - related to each of the parameter combinations - was carried out three times and the average value is reported here as the strength related to this parameter combination. The tensile – shear tests were carried out with a Tinius Olsen pneumatically operated compression and tension test universal testing machine with a capacity of 10kN. During the tests, three types of failures [3 7] were observed: (1) separation; (2) knotting; (3) tearing. Samples of these are as shown in figure 5

Figure 5. Samples of Three failure modes

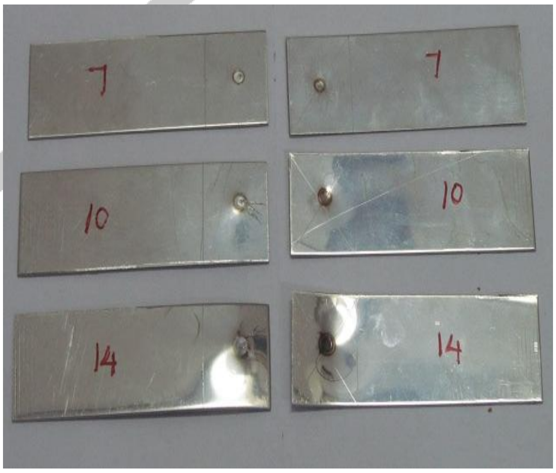

Figure 6. Failed samples

In sample 12 knotting and pull out button failure occurred and in sample 20 and 3 tearing took place. By use of process parameters heat generation in between the two pieces was calculated based on the equation (1) and setting the corresponding heat input to each run. As in the above figures for sample 12 the heat generated is 50%; for sample 3 it is 75% and for sample 20 it is 100% heat input. Based on these heat inputs the failures too varied.

From the above figure one can observe that in sample 7 & 10 separation took place and in 14 somewhat similar to knotting and pull out button failures were occurred. [3 7]

4. RESULTS AND DISCUSSIONS

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S.No	X1	X2	X3	D mm	H mm	Ft Mpa
1	4	2.5	10	2.82	4.27	174.4
2	3	2.5	10	2.38	4.2	103.8
3	5	3	15	3.71	7.38	348.4
4	5	2	20	3.09	7.5	382.8
5	5	2	15	3.36	7.11	356.8
6	4	2.5	20	4.33	6.58	323.6
7	3	3	10	2.72	3.59	124.5
8	5	2	10	3.88	5.76	291
9	5	2.5	20	4.95	7.78	375.2
10	3	3	15	3.24	4.43	170
11	4	2	10	2.88	4.57	206.1
12	5	3	10	4.18	5.94	285
13	3	2	15	3.19	4.65	170
14	3	3	20	3.99	5.54	252.9
15	4	3	20	4.79	7.24	334.8
16	5	2.5	10	5.20	5.35	288.6
17	3	2.2	20	3.79	5.54	244.8
18	3	2.5	15	3.23	4.41	166.8
19	3	2	10	2.72	3.88	121.6
20	5	3	20	3.65	8.17	383.2
21	4	3	10	3.72	5.25	223.2
22	5	2.5	15	5.02	7.26	356
23	3	2	20	3.94	5.66	242.7
24	4	2.5	15	4.17	6.12	276.9
25	4	2	20	5.00	7.59	346.4
26	4	3	15	4.42	6.03	298.5
27	4	2	15	4.19	6	268.5

4.1. Development of mathematical models

Mathematical relations between experimental indexes and process parameters can be described by the equation of Y = f (X1, X2, X3). The full quadratic regression equation can be expressed as [1]

$$Y=a+b1X1+b2X2+b3X3+b12X1X2+b13X1X3+b23X2X3+b11X12+b22X22+b33X32 \quad (3)$$

The final equations in terms of actual factors A, B and C are

Nugget Diameter:

-17.09981+4.18500A + 5.54889B +0.57311C + 0.18500AB - 0.091167AC - 0.024667BC - 0.35556A2-1.13556B2-2.28889E-003C2

Tensile Strength:

- 459.18778 + 233.66778A - 164.32222B + 28.19844C - 4.51667AB - 1.89833 AC - 0.50000 BC - 14.03000A2 + 38.74667B2 - 0.25173C2

Heat Affected Zone:

+ 2.37861 + 1.46889A - 4.52056 B + 0.30894C + 0.29167AB + 0.022167AC -0.012333 BC - 0.17500 A2 + 0.72667B2 - 5.26667E-003C2

4.2. ANOVA RESULTS

ANOVA results for tensile – shear strength of the spot welds

Source	SS	df	F	P> F	significance
Model	1.859e5	9	119.25	0.0001	Significant
A	1.2e5	1	692.88	0.0001	Significant
C	62691.04	1	361.87	0.0001	Significant
AC	1081.10	1	6.24	0.0230	Significant

Where SS – sum of squares, df – degree of freedom, p – p-value probability.

Std.dev	13.16	**R– squared**	0.9844
Mean	263.79	**Adj R- squared**	0.9762
C.V %	4.99	**Pred R- squared**	0.9618
PRESS	7218.18	**Adj precision**	36.532

ANOVA results for nugget diameter of the spot welds

Source	SS	df	F	P> F	significance
Model	8.65	9	8.73	0.0005	Significant
A	3.41	1	10.33	0.0038	Significant
C	2.75	1	8.31	0.0084	Significant
AC	2.49	1	7.55	0.0115	Significant

Std.dev	0.57	**R– squared**	0.5324
Mean	3.80	**Adj R- squared**	0.4715
C.V %	15.13	**Pred R- squared**	0.3364
PRESS	10.78	**Adj precision**	8.058

ANOVA results for heat affected zone of the spot welds

Source	SS	df	F	P> F	Significance
Model	43.56	9	40.44	0.0001	Significant
A	23.01	1	192.21	0.0001	Significant
C	19.61	1	63.87	0.0001	Significant
AC	2.49	1	7.55	0.0115	Significant

Std.dev	0.35	R– squared	0.9554
Mean	5.84	Adj R- squared	0.9317
C.V %	5.92	Pred R- squared	0.8923
PRESS	4.91	Adj precision	22.288

The significance of the factors was tested by the analysis of variance (ANOVA) technique with F ratio calculation to ensure the reliability of models. The technique of ANOVA was used to test the significance of models again with desired confidence level of 95%. For nugget diameter the parameters weld current (A), weld time (C) and interaction of these two factors (AC) are significant and for tensile – shear strength weld current (A), weld time (C) and interaction of these two parameters (AC) and also square of the weld current (A2) are the significant factors. For heat affected zone only weld current (A) and weld time (C) are the significant factors.

4.2.1 Effect of weld current on nugget diameter at different levels of electrode force

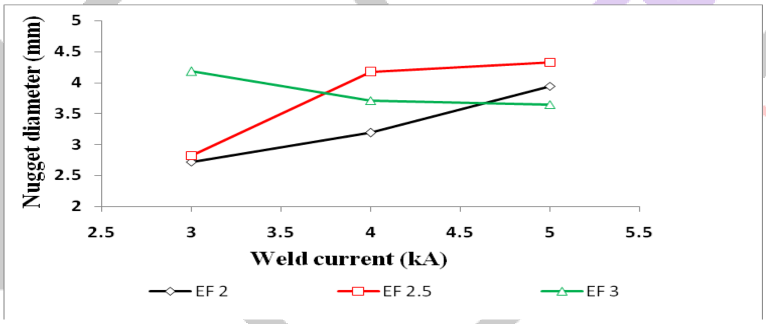

Fig .7 Effect of weld current on nugget diameter at different levels of electrode force

4.2.2 Effect of weld current on nugget diameter at different levels of weld time

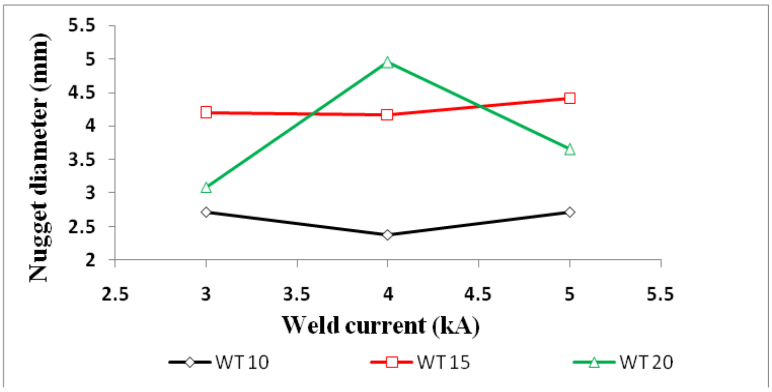

Fig.8 Effect of weld current on nugget diameter at different levels of weld time

4.2.3 Effect of weld current on tensile – shear strength of spot weld at different levels of electrode force.

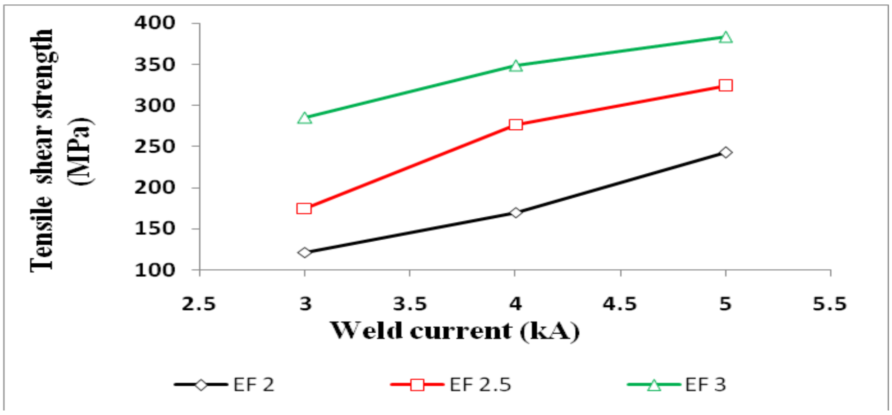

Fig.9 Effect of weld current on tensile – shear strength of spot weld at different levels of electrode force

4.2.4 Effect of weld current on tensile – shear strength of spot weld at different levels of weld time.

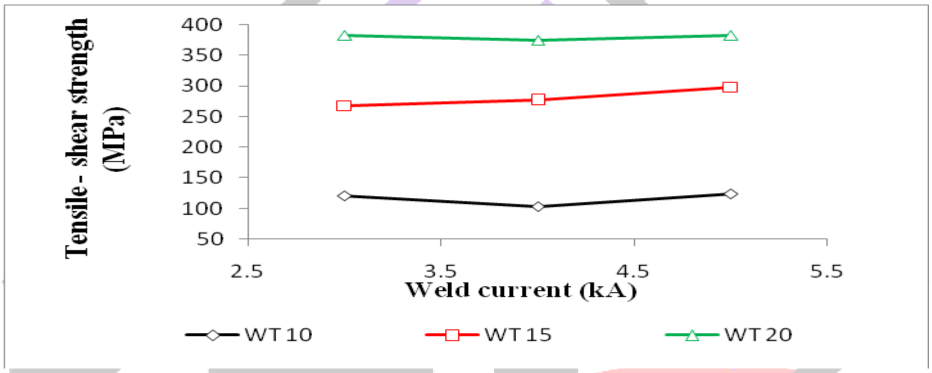

Fig.10 Effect of weld current on tensile – shear strength of spot weld at different levels of weld time

4.2.5 Effect of weld current on heat affected zone at different levels of electrode force.

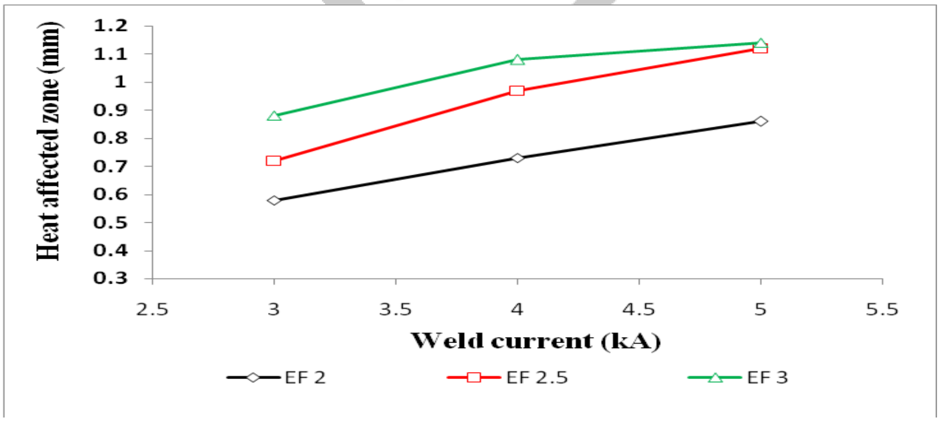

Fig.11 Effect of weld current on HAZ at different levels of electrode force

5. CONCLUSION

1. By increasing weld current from 3 kA to 5 kA, the modes of failure of the spot weld changed from separation to tearing and pull out button failure modes.

2 .While increasing weld current from 3 kA to 5 kA, the tensile – shear strength of the spot weld increased with increase of weld time; but at high weld currents and large electrode force, sparks occurred because the sheets reaching its melting point temperature. In this case the strength of the joint is good but the surface of the work piece is seen as with poor quality.

3. An increase in weld current, weld time and electrode force resulted in increase in weld nugget diameter and thus thickness.

4. With an increase in weld current, weld time and electrode force, the heat affected zone increased and maximum HAZ is found to occur at 5 kA, 3 Kgf/cm2 and 20 cycles. At this stage the nugget diameter and the strength were more. So always to get optimum nugget diameter and maximum tensile – shear strength, the selection of the parameters is important.

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