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Shear Strength Prediction of Multi-Spot Welded Lap Shear Specimen through Experimentation and Validation by FEM

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Abstract-
The effect of design parameters and process parameters on the tensile shear strength of two similar galvanized steel sheets is investigated through experiments using Taguchi method .Design parameters are number of spots, specimen thickness and spot spacing. Process parameters are squeezing force, welding current. Similar sheets of galvanized steel sheets are made by resistance spot welding at different processing conditions and these joint populations have been tested under defined loading conditions. Specially fabricated and designed fixture is used to load the lap shear specimen in the universal testing machine Regression analysis is done to obtain relationship between tensile shear strength and selected parameters. Confirmation tests have been conducted to check accuracy of regression model. More over Monte Carlo simulation i.e probabilistic analysis under dynamic loading condition has been carried to know uncertainty in shear strength also probability for safety of structure is determined. The experimental results indicate that the failure loads of spot welds in lap shear specimens increase when number of spot, squeezing force, welding current and sheet thickness increase for the given ranges while Shear strength increases by 1.318% as loading velocity increases from 1.32m/min to 2m/min.
Keywords*-Number of spots, Spot spacing, Tensile shear strength, Spot spacing, Monte Carlo simulation*

I. INTRODUCTION.

Resistance spot welding (RSW) is a process of joining metal components through the fusion of discrete spots at the interface of the work pieces. It is one of the most useful and practical methods for the manufacture of sheet metal assemblies. This process is common for welding sheets of aluminum, stainless steel, titanium alloys etc. A typical automobile consists of more than 5000 spots [1].This study gives relationship among process parameters and strength of spot weld. Galvanized sheets are spot welded at permissible level of parameters so as to visualize interfacial mode of failure after tensile shear test [2]. Author considered processing time as parameter. It was observed that shear strength of spot weld increases with increasing processing time [3].This study consists of application of Taguchi method to study effect of process parameters on strength of spot weld [4]. This study consists of relationship between pre-straining and tensile shear of spot weld [5]. Lap shear specimen is used and its fatigue strength is obtained through experimentation .Effect of nugget diameter on fatigue strength of spot weld is studied [6]. Effect of fusion zone size on the shear strength is studied [7]. Experiments were planned on the basis of response surface methodology (RSM) [8]. Effect of process parameters on the shear strength of spot welded lap shear specimen had been obtained. Higher levels of parameters were considered [9]. Authors used software package LS-DYNA. Objective of this simulation was to find out fatigue strength of spot weld and compare it with results obtained by KS2 test. KS2 test was conducted for loading in different direction so as to find out effect of direction on the fatigue strength [10]. Objective of this FE model was to develop a mathematical model. Here, input parameters were varied according to matrix from design of experiments and strength of the spot weld was obtained [11].

Strength of spot weld defines the quality of integrated structure of automobile and improves the reliability of assembled sheets. Structural stability of multi spot welded structure depends upon number of spots, their locations and variable loads acting on it. So, investigation on the relations between the tensile shear strength of spot weld, spot spacing and number of spots is the key to solve problem in the design of multi-spot welded structure. Monte Carlo simulation of multi spot welded specimen is necessary to perform under dynamic loading conditions to know behavior of multi spot welded specimen under the influence of input parameters. At the same time, Mote Carlo simulation will give probability of failure of multi spot welded specimen. Effect of different parameters on the tensile shear strength can be seen on developed cause effect diagram

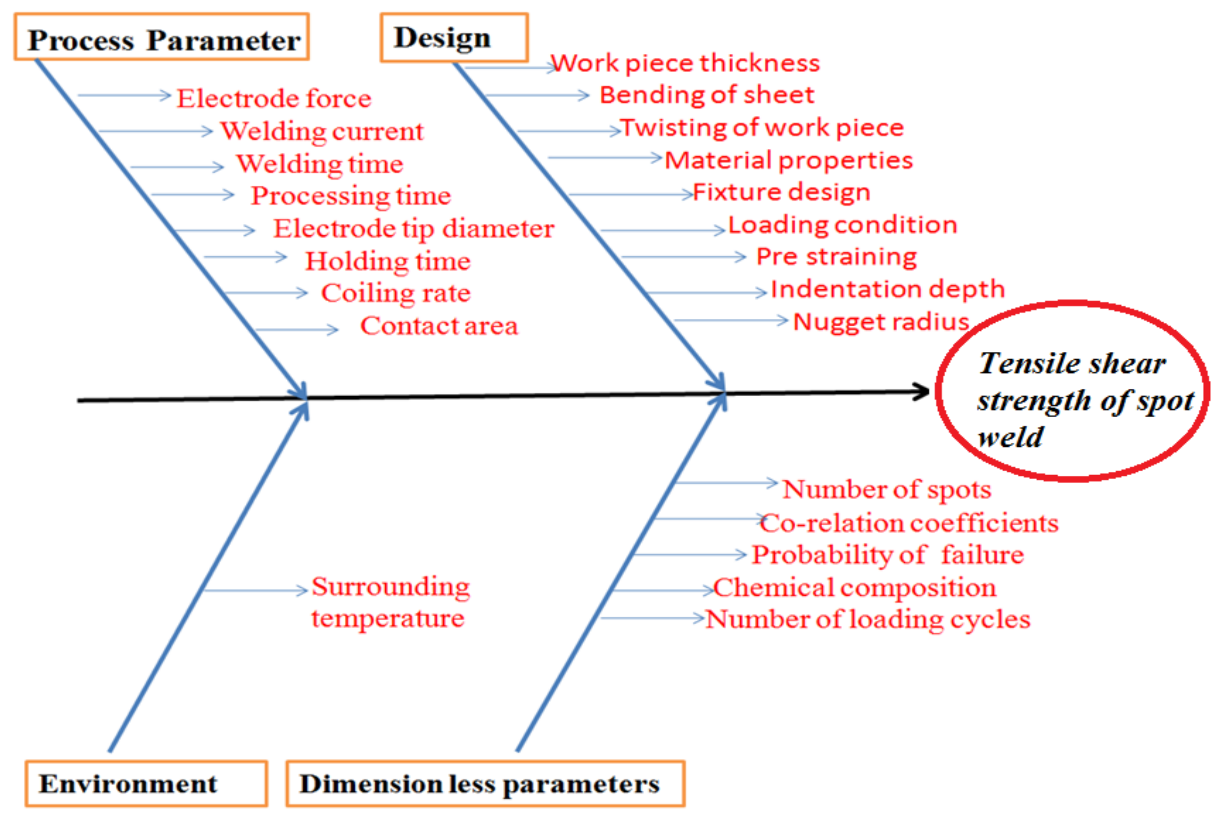

Fig.1. Cause-effect diagram

The diameter of the spot weld nugget, d, is chosen based on an empirical formula recommended by the

$$d \geq 4\sqrt{t} \quad (1)$$

Resistance spot welding (RSW) is a process of joining metal components through the fusion of discrete spots at the interface of the work pieces. However, several author claim that this equation is not safe for thickness beyond 1.5 mm.

Table I .Chemical Composition of Galvanized steel sheet

T.S	Y.S	Alloying elements (wt %)					
MPa							
350	240	c	Mn	Si	S	p	Cr
		0.16	0.3	0.25	0.030	0.03	0.004

The welds were done using a RSW electric resistance spot welding machine, with a nominal welding power of 7.5 kVA. The tensile shear strength testing was done in a servo hydraulic Universal Testing machine at a cross-head speed of 1.31 mm/min to 2 mm/min up to the final failure of the joint. Specimen failed Partially by pull out faiure mode under constant loading velocity. Selected ranges of parameters are given in table II as shown below.

Table II Ranges of Parameters.

Sr No.	Parameters and Designations	Ranges		
		Low	Middle	High
1	Force (F)	700	800	900
2	Number of spots(n)	2	4	6
3	Spot spacing(X)	12	14	16
4	Thickness(t)	0.71	0.91	1.22
5	Current(I)	7	8	9

I I EXPERIMENTAL PROCEDURE

Mechanical properties of galvanized steels are given in Table 1. Resistance spot welding lap joints were done on specimens of 200 mm× 120 mm×1.22 mm in size. Figure 2 shows the geometry and dimensions of the welded specimens. Sheet surfaces were randomly abraded with silicon carbide paper P220 grade. Specially designed and fabricated fixtures are used to load the lap shear specimen in universal testing machine. While fabricating the designed fixture, care is taken that studs of it will remain axially aligned.

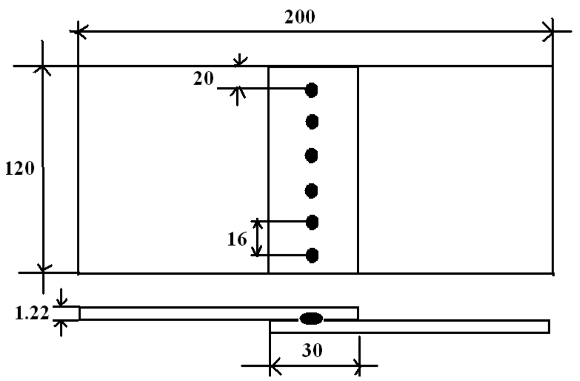

Fig.2. Dimensions of lap shear specimen (not to scale).

Fig.3 Local display of experimental set up

Regression analysis has been carried out to find relationship between tensile strength and parameters. Equation of regression is obtained as given below.

$$P = - 3707 + 147 I + 4210t + 306 X + 295n - 0.93f \quad (2)$$

Where,
P=Shear Strength in N.
I=Current in Kamp.
T=Thickness in mm
X=Distance between two spots
n= Number of spots
f=Electrode force in N

Three levels of each parameter are decided and Taguchi's L_{27} array is used to decide number of test.

Table III Resistance spot welding parameters and corresponding tensile strength (Taguchi's $L_{27)}$ Array)

F (N)	n	X (mm)	t (mm)	I (KA)	P(N)
700	2	12	0.71	7	3000.23
700	2	14	0.91	8	5002.63
700	2	16	1.22	9	7997.59
800	4	12	0.71	7	5870.96
800	4	14	0.91	8	7205.01
800	4	16	1.22	9	8201.75
900	6	12	0.71	7	4991.97
900	6	14	0.91	8	6857.89
900	6	16	1.22	9	8596.89
800	6	12	0.91	9	5089.6
800	6	14	1.22	7	7956.87
800	6	16	0.71	8	5895.5
900	2	12	0.91	9	3574.26
900	2	14	1.22	7	7958.544
900	2	16	0.71	8	6578.68
700	4	12	0.91	9	7856.56
700	4	14	1.22	7	5904.6
700	4	16	0.71	8	5917.6
900	4	12	1.22	8	6897.5
900	4	14	0.71	9	4058.56
900	4	16	0.91	7	5123.68
700	6	12	1.22	8	7158.56
700	6	14	0.71	9	5891.56
700	6	16	0.91	7	7589.51
800	2	12	1.22	8	5478.54
800	2	14	0.71	9	4789.54
800	2	16	0.91	7	5017.45

Dynamic tensile shear strength of lap shear specimen having single spot has been determined and results are validated through finite element method .Dynamic load and displacement verses time curves are obtained. According to ASTM, if strain rate is more than 5 ×10-5/s then applied load can be said as dynamic. Tensile shear testing has been carried out at dynamical loading condition i.e. loading velocities are 1.32m/min and 2 m/min. Dynamic strength has been obtained at different loading velocity .Ten number of cross tension specimens are tested. Sample load verses displacement curve is shown in Fig. 3

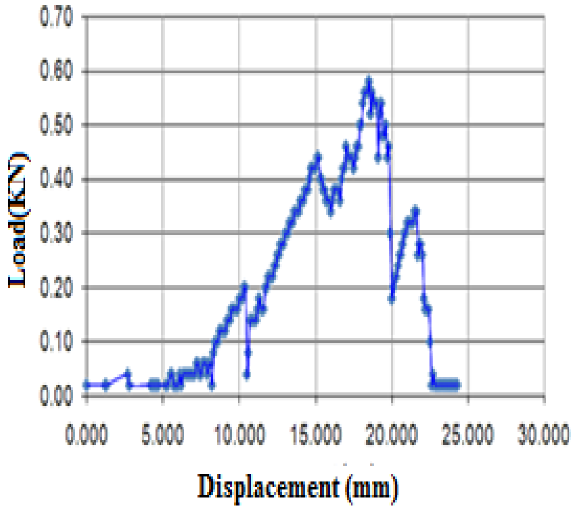

Fig. 3 Load verses displacement curve

Above graph has been obtained under dynamic loading condition .Loading velocity has been varied as mentioned above. Up to 5mm displacement, loading velocity was constant. It can be seen that load was increased with respect to time. All spot welded specimens have been made at same welding conditions but each specimen tested at different loading velocities. Specimen configuration has been kept same which is shown in Fig .2. The results of the dynamic shear strength tests for all the joints are obtained in the form of load versus displacement.

III SIMULATION

Simulation of multi spot welded lap shear specimen by using Monte carol method i.e. Latin hypercube sampling has been carried out .A three dimensional nonlinear finite element analysis of multi-spot welded lap shear specimen is carried out and uncertainty in tensile shear strength of spot weld is analyzed. Thickness, nugget radius and time of analysis are randomly varied within effective range and their effect on the tensile shear strength of multi spot welded lap specimen has been analyzed. To ensure reliability of spot welds during vehicle lifetime, probability of failure of multi spot welded lap shear specimen is determined within defined ranges of input parameters. Specimen geometry is as shown in figure 2.

FEM package ANSYS is used to perform simulation. Elements selected for meshing the geometry of the specimen are, solid 186, MPC 184, Target 170 and Contact 175.MPC184 element is used to define spot weld. Material properties of uncoated mild steels are entered. Model of same geometry has been drawn in ANSYS software. Geometry is meshed mapped type of meshing. Meshed model of specimen is as shown below in figure 4.

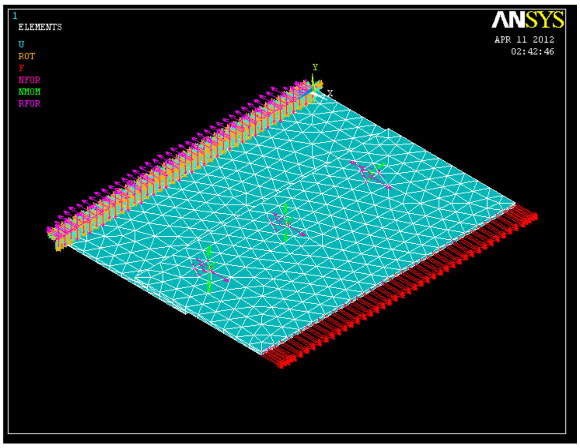

Fig.4 Finite element model of specimen

Same configuration of specimen has been modeled in FEM package ANSYS and loading has been done in different intervals of time. Time has been kept in between 1 second to 11 second. Fig. 5 shows loading conditions of spot welded specimen with respect to time.

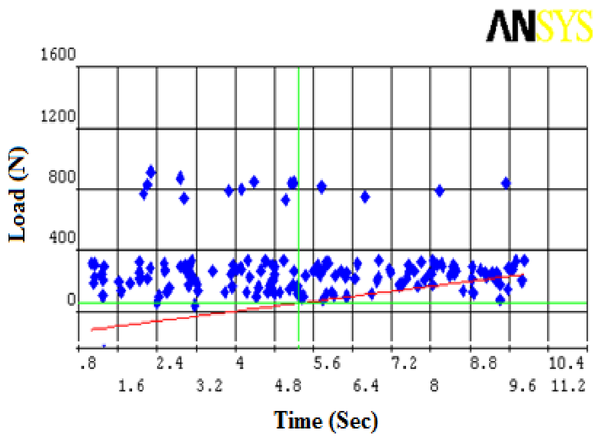

Fig.5 Load verses time

During the Monte Carlo simulation, input variables displacement; spot weld radius; thickness and time of analysis are varied.

Table IV Random Input Variable Specifications

No.	Name	Type	Par1	Par2
1	DISP	UNIF	0.10000	0.90000
2	R	UNIF	1.0000	5.0000
3	T	UNIF	0.71000	1.5000

DISP, R, T indicate displacement of one end of specimen, spot weld radius and thickness respectively. Maximum tensile shear stress at spot welding element is selected as response parameters. Non-linear properties of uncoated mild steel are entered. Degrees of freedom in Y direction are made zero for lower plate while dynamic displacement is applied on upper plate of specimen. Range of displacement is selected in such a way that excessive distortion of the elements can be avoided .Full Transient analysis is executed in 4 steps. Each step is incremented by 1.Simulation loop is defined. It is executed170 times by varying design parameters randomly within defined range. Scatter plot of maximum tensile shear stress is obtained at different combinations of selected parameters.

IV .RESULTS AND DISCUSSION

From the results of experimentations and regression analysis, effect of number of spot, spot spacing, electrode force, weld current and specimen thickness on the tensile shear strength of spot welded lap shear specimen is obtained. By using the obtained equation from regression analysis, equation (2), data is fitted on line. Effect of individual parameter on the tensile shear strength of multi spot welded lap shear specimen is obtained by keeping other parameters constant. It is discussed as below.

It is observed that there is increses in the tensile shear strength as electrode force increases.

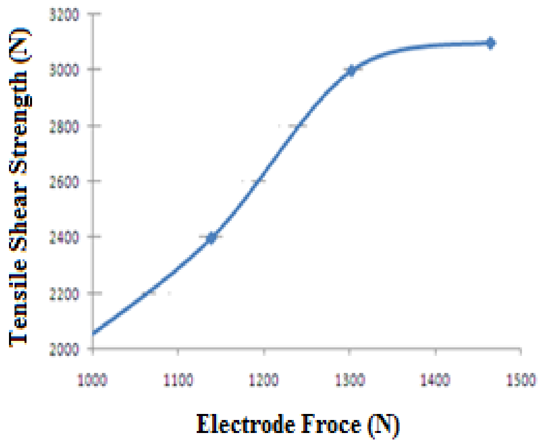

Fig.6 Electrode force Vs shear strength

Spot welds made at time range 3 -5 cycles fail in interfacial failure mode. Effect of the same is shown in Fig 5.3. At 976.44 N electrode force, 2201.31 N is shear strength and it is 3500.32 N at 1464.66 N. It happens because increase in electrode force increases contact area between workpiece and surface of sheet metal. So, there is less amount of heat transfer between heat generated in welding and surrounding temperature. This results in less amount of heat loss. It is observed that spot welds made at 700N electrode force, fail in interfacial failure mode because of the reason mentioned above. It is as shown below in Fig.7

Fig.7 Interfacial mode of failure

All spots failed at once due to axially applied load. Because applied load was equally distributed over generated spots .it is uniformly distributed over sheet surface. It is observed that there is significant increase in shear strength of spot weld when number of spot increase.

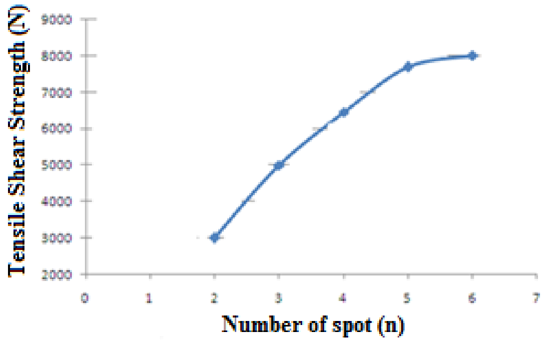

Fig.7 Relationship between number of spots and shear strength

Fig.7 shows relationship between number of spot and tensile shear strength of spot weld. Specimens having six numbers of spot got the strength 5002.63N.Specimens having two numbers of spot got the strength 3001.32N. Here, tensile shear strength is increased because all spot welds were made up to 16 mm spot spacing .above this value of spot spacing, there is overlapping of heat affected zone.

It is observed that there is significant increase in shear strength of spot weld when spot welding current increases

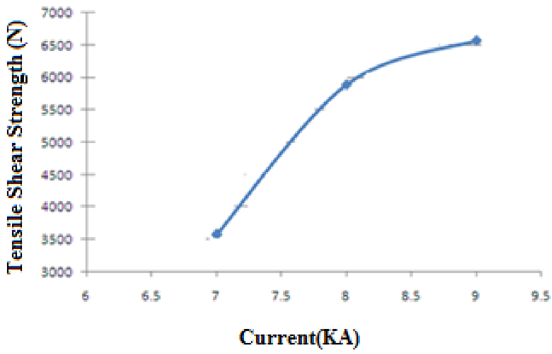

Fig.8 Relationship between current and shear strength

It happens because increases in current increases heat generation and more amount of sheet surface melts thereby increasing size of heat affected zone

and these results in decreases in grain size. Fig.8 shows relationship between spot welding current and shear strength of spot weld. Spot welds made at 9 KA current got the strength 7689.906N. Spot welds made at 7KA got the strength 3507.19 N.
It is observed that there is significant increase in shear strength of spot weld when specimen thickness increases

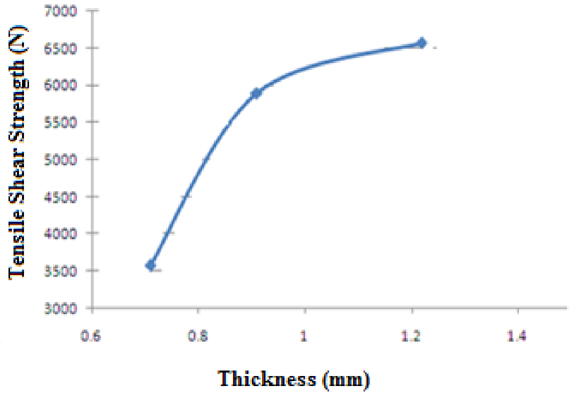

Fig.9 Relationship between specimen thickness and shear strength

Because increases in specimen thickness increases cross section area of specimen and shear force acts parallel to cross section area. Fig.9 shows relationship between specimen thickness and shear strength of spot weld. Spot welds made 1.22 mm thickness got the strength 7589.99N. It is observed that compromising with number of spots and increasing specimen thickness shear strength can be improved. Spot welds made 1.22mm thickness but having lower value of current and number of spot, got the strength 3507.99N.
It is observed that there is significant increase in shear strength of spot weld when spot spacing decreases in between range 10mm-16mm

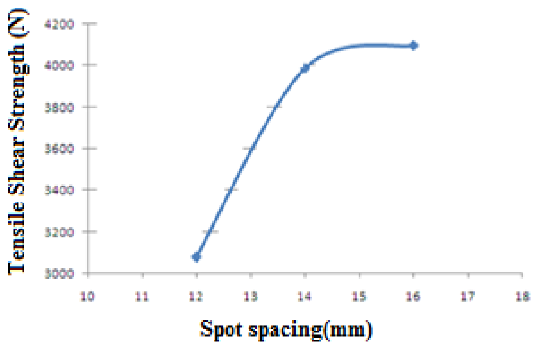

Fig.10 Spot spacing Vs shear strength

This is the least range at which there was no overlapping of heat affected zone of two adjacent spots. Fig.10 shows relationship between spacing and shear strength of spot weld. Spot welds made at 16 mm spot spacing got the strength 8531.97N. Spot weld made at 10 mm spot spacing got the strength 3776.97N.
Obtained equation of regression is validated through confirmation tests. By comparing results of regression equation and experimental result, it can be seen that there is 0.57 % maximum deviation between experimental results and results obtained by regression model. So, obtained equation is good in agreement.

Table V. Result comparison for tensile shear strength of multi spot weld

Sr. No.	Tensile shear strength(N)		Deviation % [(X1-X2)/X1]×100
	X1 Regression Modeling	X2 Experimental Results	
1	7307	7301.78	0.071438
2	6271.2	6235.345	0.571741
3	6052.1	6047.87	0.069893
4	5611.1	5610.357	0.013242

Figure 11 shows tensile shear strength N/mm^2 Vs specimen thickness in mm. It is obtained after 170 samples (tests) .Output parameter with combination of input parameters is plotted. Higher order Polynomial of 20 degree is used to plot scattering. It is observed that there is more scatter of tensile shear strength from polynomial line within the thickness range 1.12-1.22mm.

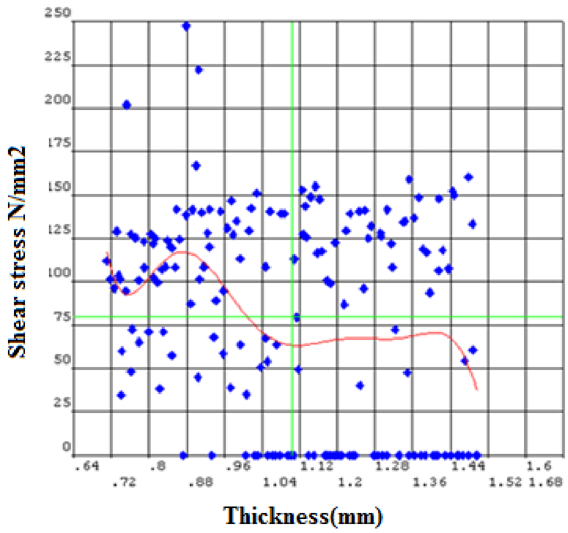

Fig.11 Scattered plot of shear stress Vs thickness distribution

Tensile shear stress = 2.59e+001 which has rank 3 out of 170 samples. The confidence bounds are evaluated with a confidence level of 95.000%. C0 to C20 indicates degree of polynomial. Linear correlation coefficient between tensile shear strength and thickness is 0.4416. Value of tensile shear stress is obtained at different values of thickness. Value of tensile shear stress at 1.22mm thickness is around 800N/mm^2.

Particularly, above graph of relationship between thickness and tensile strength is obtained for lap shear specimen having three spots. There is considerable bending when specimen having more than three spots. As analysis is done in four steps within randomly increment of step, load is applied with respect to time. It can be said that obtained strength is dynamic tensile strength. At the same time, tensile shear strength is obtained at different combinations of specimen thickness and nugget radius. At the thickness value 1.36mm, tensile shear strength is 1678.98N/mm2.

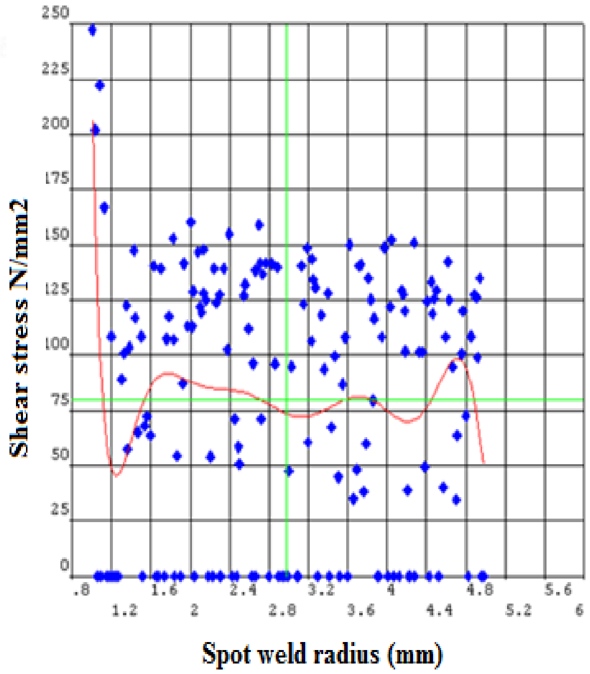

Fig.12 Scattered plot of shear stress Vs radius for single spot welded specimen

Figure 12 shows tensile shear strength N/mm2Vs radius in mm. It is observed that there is more scatter of tensile shear strength from polynomial line within the radius range 2.8- 4.8 mm. Tensile shear strength= 1.6794002e+001 which has rank 3 out of 170 samples. The confidence bounds are evaluated with a confidence level of 95.000%. Value of tensile shear stress is obtained at different values of thickness. Value of tensile shear stress at 4.8 mm spot weld radius is around 150N/mm^2.

Figure 13 shows load verses displacement curves which are obtained by experiment and finite element method. Both curves are obtained at loading velocity 1.32 m/min and 2m/min.

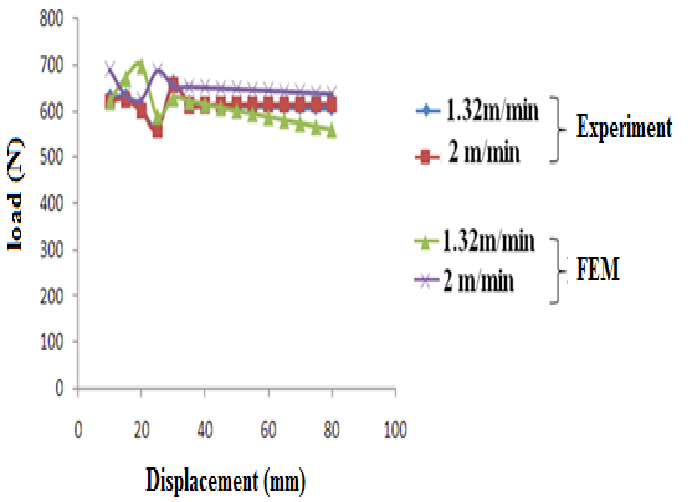

Fig.13 Validation of load verses displacement

As far experimental results are considered, shear strength increases by 1.318% as loading velocity increases from 1.32 to 2m/min. In finite element analysis, it is observed that shear strength increases by 1.597% as loading velocity varies from 1.32m/min to 2min/min. By comparing strength values obtained through experimentation with strength values obtained through FEM at loading velocity 2m/min, there is maximum deviation of 3.80%. By comparing Strength values obtained through experimentation with Strength values obtained through FEM at loading velocity 1.32 m/min, there is maximum deviation of 5.98%.

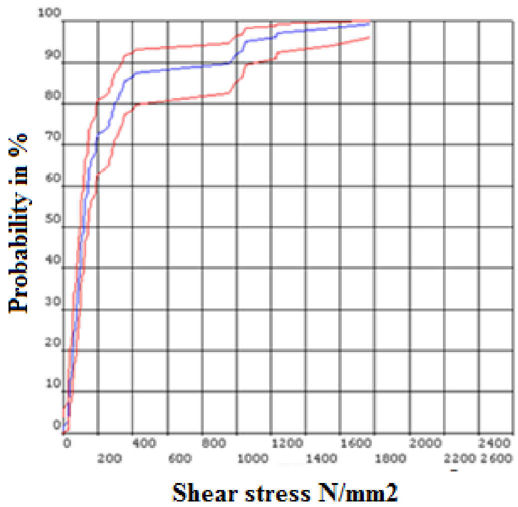

Fig.14 Shear strength Vs Probability

The curves in Fig.14 show that there is a about a 93% probability that the shear stress remains below 2000N/mm^2. As it is a maximum safe value. It indicates that multi spot welded specimen will not fail within the selected ranges of input parameters.

V .CONCLUSION

To obtain high shear strength, it is recommended to have more number of spot with spot spacing in the range 12-16 mm. It is to be noted that the minimum nugget diameter to have rated strength of spot weld joint must not be less than 4.13 mm. Size of nugget diameter decreases due to higher electrode pressure and higher value of current due to metal splash and hence welding current and electrode pressure should not exceed critical value. In order to have maximum dynamic strength, the spot spacing must be designed and providing more or closer a spot may lead to poor dynamic shear strength.

1. Simple regression equations have been proposed to predict the static tensile strength of multi spot welded lap shear specimen. They have been validated by conducting confirmation tests. Confirmation tests for suggested regression model of shear strength of lap shear multi spot welded specimen show that there is maximum 0.571741 % deviation between experimental results and results obtained by regression equation.

2. It is observed that dynamic tensile shear strength increases when loading velocity increases. It increases by 1.318% as loading velocity increases from 1.32m/min to 2m/min.

3. It is observed that there is 6.87979% maximum deviation in between results of regression model and Monte Carlo simulation for shear strength of multi spot welded lap shear specimen.

4. Monte Carlo simulation has been carried out to know the behavior of multi spot welded cross tension specimen under dynamic loading condition.

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