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Optimization of Process Parameter And Failure Analysis For Resistance Spot Welding Of IS 513 Low Carbon Steels Using Minitab

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ABSTRACT: *The present work is an investigation towards making the spot welding joint reliable by improving the quality of a welded joint for a commercially available low carbon steel of BIS 513:2008 standard. The focus is to optimize process parameters electrode force, squeeze time, weld time and hold time. Tensile shear strength was used response to these parameters. Analysis of variation was used to determine the most and least contribution of different parameters. The verification was done through the experimentation using optimized combination of levels for parameters. Tensile tests were performed using instron type UTM machines to give accurate results. Finally, an attempt was made to outline modes of failure for different sets of experiment and preventing them to strength the welded joint making them reliable. The investigation proved the effectiveness of taguchi method to enhance the quality of spot welded joint. Minitab being a powerful software package, has been implemented to carry out the entire optimization analysis.*

KEYWORDS: *Resistance spot welding, UTM, Anova, mechanical characterization, steel, taguchi*

I. INTRODUCTION

The techniques for manufacturing. Whether it may be advanced materials or welding techniques the area of research has widen in the recent scenario. The automobile or aerospace industries have broadened their area of interest especially in joining or fabrication techniques to achieve properties such as higher strength to weight ratio, enhance safety and crashworthiness keeping the cost factor in mind. [1-2]. Welding is the most crucial fabrication technique of joining in the automobile industry, and its condition plays a vital role in end result i.e. the mechanical properties of the joint. The heat input from welding heat source creating a large temperature gradient on workpiece could certainly affect the microstructure in turn the mechanical properties of steel. It is therefore of prime importance to characterize the microstructure and its influence on final mechanical properties during welding. [3]

With rising popularity of resistance spot welding (RSW) due to high production rate, low skilled worker with added advantage of being an economic process, its area of application has increased with passage of time.
The strength of the joint is commonly characterized by the modes of failure it undergoes, may it be plug pullout type, partial pullout type or interfacial type.

The minimum size of the spot weld was formulated as

$$D = K\sqrt{t}$$

Where D denoted as the nugget diameter of weld in mm and t is minimum sheet thickness in mm whereas K is process dependent constant and value ranges from 3 – 6 [4]. Zhang et al. [5] inferred that strength of joint is mostly concern with fusion zone, especially pullout mode of failure is due to increase in size of fusion zone.
Resistance spot welding utilized the copper electrode to impinge upon the workpiece material to which the resistance to flow of current through the interface leads to local heating of the overlapped surface. Bouyousfi et al. [6] studied the effect of spot welding process parameters (welding current, welding duration, and applied load) on the mechanical properties and characteristics of spot welded join between two stainless steel sheet (304ASS) having same thickness. This investigation revealed micro hardness and tensile test results have revealed weld resistance is depends upon the process parameters especially load. Applied load being a major factor compared to welding time and current.
Similarly, Esme et al. [7] studied the optimization of process parameters involved in welding of SAE 1010 using Taguchi method. This investigation is related to welding current and electrode force as prime factor in determination of welding strength. He concluded that Taguchi method is quite reliable optimization technique.

He also focused on the use of ANOVA to emphasize on the level of contribution of each factor, concluding welding current and electrode force being highly effective parameter on tensile shear strength compared other factors. Khan et al. [8] considered the amount of carbon at joints which is related to fusion zone (FZ) hardness. Upon increase in carbon content, hardness of FZ increases. Similar studies were conducted related to welding parameters on RSW of DP600 automobile steel sheets [9]. Pouranvari and Marashi [10] investigated upon mechanical performance of dual – phase DP600, DP780, DP980 grade sheets. Their research was mostly related to microstructure of welded portion, focusing upon heat affected zone which plays a crucial role in mechanical strength of DP steels with high fraction of martensite. Eshraghi et al. [11] studies regarding the finite element analysis indicating current density as the major factor on the sizes of fusion and heat affected zone. Basically, current density is indirectly related to pressure of contact. The microscopic study reveals there is only contact between peaks at lower pressure as a result lesser area comes in contact increasing the current density to compensate for the decrease in flow of electric current. Marashi et al. [12] found the strength and size of fusion zone was directly related to type of failure whether pull out or interfacial. The other aspect of the RSWed portion is the development of residual stresses, Anastassiou et al. [13] found the residual stresses are responsible for decrease in fatigue and fracture strength of structure. So, priority was given to selection of appropriate process parameters. This could only be achieved through optimization techniques as discussed by various authors. Khanna and Long [14] added that it was the electrical resistance that electrode force imposes upon during heating and cooling that affects the residual forces. Lindh and Tocher [15] for the first time studied the residual stresses through 2D finite element model to predict these stresses in 5mm thick titanium alloys. Studies were extended to low carbon steel sheets by Popkovskii and Berezienko [16]. The research was conducted for non – ferrous material e.g. aluminium which has high electrical and thermal conductivity, thermal expansion and forming oxide making it less suitable for RSW compared to steel which is highly conducive due to its robustness, reliability and cost effectiveness. These factors were studied by Partick et al. [17]. Similarly, Zhang and Taylor [18] have optimized the position of two spot welds in tensile specimen. Chae et al. [19] focused upon the two-spot weld location and its optimization under static and impact loading condition. Their research was concentrated on maximizing safety factors of spot weld joints. Besides, with increase in spots, the strength also increases but abiding to the appropriate location of these spot welds. Rui et al. [20] used an optimization algorithm to minimize the stress intensity factor of spot welds, these were solely for the purpose of fatigue life of the structure. A.G. Thakur and V.M. Nandedkar [21] studied the optimization of galvanized steel sheet using taguchi method to using L18 orthogonal array to improve quality of weld. Vignesh, K., A. Elaya Perumal, and P. Velmurugan [22] studied the effect of various control parameters like electrode tip diameter, welding current, and heating cycle on the nugget size and tensile shear strength of dissimilar metal spot welding of 2-mm-thick AISI 316L austenitic stainless steel and 2205 Duplex Stainless Steel sheets.

Although this was a rare study but to the best of my knowledge neither of them have studied the importance of squeeze time, weld time and hold time in relation to electrode force. The purpose of the present research is to emphasize upon the contributions of electrode force in relation to squeeze time, weld time and hold time without considering current as a major factor in RSW.
Taguchi method was used to optimize process parameters using orthogonal array and Anova to determine the percent contribution of each factor towards Tensile shear strength in terms of peak load. Failure analysis was also carried out to investigate the nature of stresses responsible for failure.

II. OPTIMIZATION OF PROCESS PARAMETERS THROUGH TAGUCHI METHOD.

Taguchi method is considered as a powerful, systematic tool for design of high quality system. Being a simple and efficient tool to optimize designs for quality, cost and performance. It not only optimizes the parameters but also increases the productivity during research.

The major force behind optimization of process parameters through Taguchi lies in its low cost and high productivity principle. It does vary with environmental conditions and noise factors. An inherent advantages of Taguchi method is the closeness of its result to the target value rather that within a specified limit while increasing quality of productivity and ease of adopting and applying with limited knowledge of statistics. Taguchi design developed by Dr. Genichi Taguchi is a set of methodologies by which sensitivity of material and manufacturing processes can be considered at the design stage. Compared to other methods like Fractional Factorial Design, it only conducts the orthogonal (balanced) experimentation, making it more effective. Taguchi uses an orthogonal array to design the experiment assisting the designer in studying the effect of various factors that can be controlled while using Signal to noise ratio (S/N) ratio to analyze the experimental data and to determine the optimal parameters during design or manufacturing.

In short, Taguchi parameter design involves following steps namely, selection of proper orthogonal array (OA) depending on controllable factors or parameters; running the experiment in accordance with OA; identifying the optimum conditions and conducting confirmation test using optimal levels to decide the nature of the control.
Signal to noise ratio is used to calculate optimum characteristics. Generally, three categories of quality characteristics could be used namely Lower- the – better, the larger the better and nominal the better. Regardless of categorization, a higher S/N ratio corresponds to better quality. So, optimal level of the process parameters is level with highest signal to noise ratio.

Furthermore, Analysis of variance (ANOVA) is applied to result to determine the percentage contribution of each parameter towards the response using a stated level of confidence.
Finally, a confirmation experiment is conducted to verify the optimum process parameters.

III. EXPERIMENTAL DETAILS

3.1 Material selection

Cold rolled sheets were cut to the dimension of 100mm length and 25 mm width for three thickness 0.8mm, 1.2mm and 1.5mm. Prior to resistance spot welding, it was cleaned with ethanol to make it free of oil and dust. The samples were spot welded to 25mm x 25mm. The standard spot-welded samples are shown in the figure 1.
The chemical composition and mechanical properties of the specimen are summarized in Table 1 and 2 respectively.

Table 1 Chemical composition of CR3 mild steel (IS 513: 2008)

Element	**Content %**	**Content (%)**
Fe	Bal.	99.18-9.62 %
C	0.10	
Mn	0.45	0.30-0.60 %
S	0.030	≤0.050 %
P	0.025	≤0.040 %

Table 2 Mechanical properties of CR 3 mild steel (IS 513: 2008)

Sample	UTS (MPa)	YS (MPa)	EI %	Hardness (HRB)
Base Metal	350	220	34	57

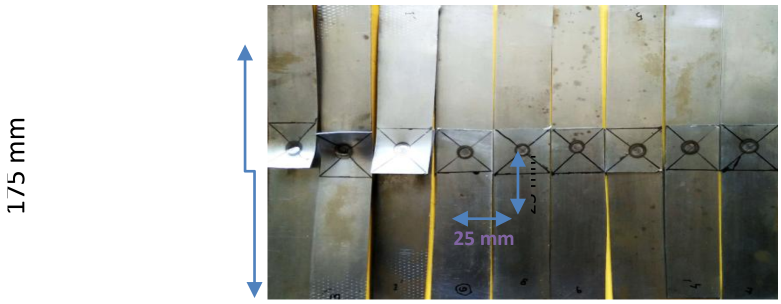

Fig. 1 Standard spot welded sample

The experiment was performed on a mechlonic-made SS-35-450 model 35kVA pedestal type spot welding machine and throat depth of 450mm using pointed type copper-chromium electrode of cap 16mm and tip diameter 6.5mm controlled by microprocessor based resistance control system shown in figure 2. The experiment was conducted for each different thickness of 0.8mm, 1.2mm and 1.5mm. The welding current was kept constant throughout the operation at 75 % duty cycle. Tensile shear strength was considered as response characteristics to determine the strength of RSWed joint. Tensile testing was carried out on an Instron – built 3382 floor type universal testing machine at a constant strain rate of 0.5mm/min. The peak loads were recorded through blue-hill lite software package inbuilt to the system. The UTM machine is shown in the figure 3.

3.2 Selection of process parameters

The process parameters were selected considering the independent controllable parameters such as electrode pressure, squeezing time, welding time and holding time. The levels were chosen from the available range for each parameter from the machine.

Process parameters and level of operation are presented in the Table 3.

Table 3 Process parameters at different levels

Parameters	Low (1)	Medium (2)	High (3)
Pressure (kg/cm^2) (A)	2	4	6
Squeeze time (ms)(B)	400	500	600
Weld time (ms)(C)	400	500	600
Hold time (ms)(D)	400	500	600

3.3 Selection of Orthogonal array (OA)

Four factors with three levels for each were selected for the experiment. Accordingly, L9 OA was chosen from the available design [23]. The orthogonal arrays are shown in the Table 4, 5 and 6 for thickness of 0.8 mm,.2 mm and 1.5 mm respectively.

Table 4 Orthogonal array for sheet thickness of 0.8mm

Sl. No.	(A)	(B)	(C)	(D)	TSS (kN)	S/N ratio	Failure
1	1	1	1	1	2.68	8.5627	PF
2	1	2	2	2	2.79	8.9120	PF
3	1	3	3	3	2.98	9.4843	PF
4	2	1	2	3	2.76	8.8181	PF
5	2	2	3	1	2.06	6.2773	IF
6	2	3	1	2	2.09	6.4029	PF
7	3	1	3	2	1.55	3.8066	IF
8	3	2	1	3	2.11	6.4856	IF
9	3	3	2	1	2.05	6.2350	IF

Table 5 Orthogonal array for sheet thickness of 1.2mm

Sl. No.	(A)	(B)	(C)	(D)	TSS (kN)	S/N ratio	Failure
1	1	1	1	1	4.09	12.2345	PF
2	1	2	2	2	4.76	13.4235	PF
3	1	3	3	3	4.69	12.3819	PF
4	2	1	2	3	4.16	10.0485	IF
5	2	2	3	1	3.18	9.1576	PF
6	2	3	1	2	2.87	10.0758	IF
7	3	1	3	2	3.19	8.0280	IF
8	3	2	1	3	2.52	6.4856	IF
9	3	3	2	1	2.11	13.5521	IF

Table 6 Orthogonal array for sheet thickness of 1.5mm

Sl. No.	(A)	(B)	(C)	(D)	TSS (kN)	S/N ratio	Failure
1	1	1	1	1	6.63	16.4303	PF
2	1	2	2	2	7.13	17.0618	PF
3	1	3	3	3	7.74	17.7748	PF
4	2	1	2	3	6.15	15.7775	PF
5	2	2	3	1	6.81	16.6629	PF
6	2	3	1	2	5.37	14.5995	IF
7	3	1	3	2	4.57	13.1983	IF
8	3	2	1	3	4.60	13.2552	IF
9	3	3	2	1	4.14	12.3400	IF

3.4 Experimentation using OA

In L9 orthogonal array, 9 experimental runs were carried in order get the response through various combinations of parameters at different levels. The selected parameters and levels are depicted in the Table 3.

Two responses were taken into consideration which are tensile shear strength and S/N ratio, with an additional information regarding the mode of failure it undergoes during tensile testing. The orthogonal array with response function are shown in Table 4,5 and 6.

S/N ratio 'η' (dB) was calculated as follows

$$\eta = -10\log\frac{1}{n}\sum_{i=1}^{n} y^2 \qquad (1)$$

Lower the best performance

$$\eta = -10\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2} \qquad (2)$$

Larger the best performance , y is denoted as the response (TS Strength) ,n is the no of iterations / experimental runs.

Fig. 2 Spot welder **model SS-35-450**

Fig. 3 3382 floor type UTM

IV. RESULTS AND DISCUSSION

4.1 Analysis of S/N ratio

According to Taguchi method, S/N ratio were calculated. Larger the best performance was used and parameters with a large difference having high influence to response as its level changes were selected.
The S/N ratio for different process parameters at different levels are summarized in the Tables 7, 8 and 9 for three thicknesses 0.8mm, 1.2mm and 1.5 mm respectively.

Table 7 Response table for S/N ratio (larger the best)

Level	(A)	(B)	(C)	(D)
1	**8.986***	7.063	7.150	7.025
2	7.166	7.225	**7.988***	6.374
3	5.509	**7.374***	6.523	**8.263***
Delta	3.477	0.312	1.466	1.889
Rank	1	4	3	2

* indicates Optimum level

Table 8 Response table for S/N ratio (larger the better)

Level	(A)	(B)	(C)	(D)
1	**13.070***	**11.564***	9.807	9.590
2	10.529	10.543	10.807	10.929
3	8.196	9.689	**11.183***	**11.278***
Delta	4.874	1.875	1.376	1.688
Rank	1	2	4	3

* indicates Optimum level.

Table 9 Response table for S/N ratio (larger the better)

Level	(A)	(B)	(C)	(D)
1	**17.09***	15.14	14.76	15.14
2	15.68	**15.66***	15.06	14.95
3	12.93	14.90	**15.88***	**15.60***
Delta	4.16	0.76	1.12	0.65
Rank	1	3	2	4

* indicates Optimum level

In the present work, it was clear that difference in S/N ratio is most prominent in all case with regards to pressure and least for squeeze time for 0.8mm sheet, weld time for 1.2mm thick sheet and hold time for 1.5mm sheet. It depicts that pressure plays a vital role for resistance spot welding. Current density decreases with increase in pressure to larger area of contact and vice versa. Keeping other parameters constant, increasing the pressure, nugget diameter also increases but upto a certain point after which it becomes ineffective. As nugget diameter increases strength of weld also increases.
According to signal to noise, with 'larger the best' principle new optimized levels are derived from ratio plot with highest value as shown in the figure 6, 7, and 8 for thicknesses 8.0mm, 1.2mm and 1.5mm respectively.

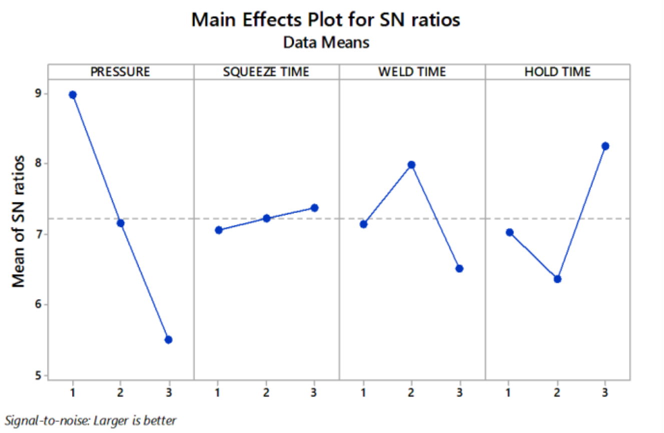

Fig. 4 S/N graph for tensile shear strength for 0.8mm sheet

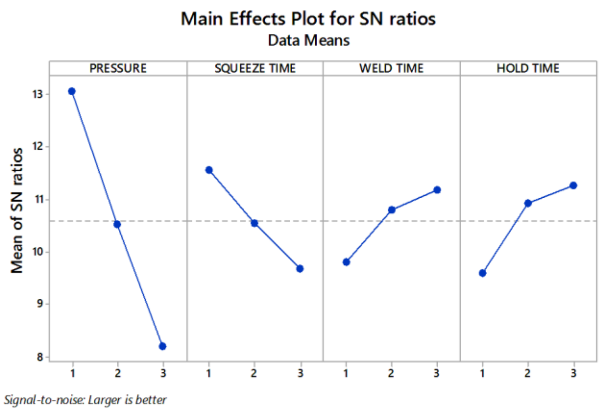

Fig. 5 S/N graph for tensile shear strength for 1.2 mm sheet.

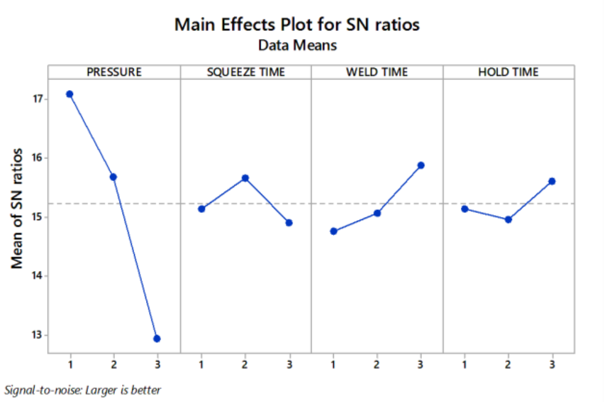

Fig. 6 S/N graph for tensile shear strength for 1.2 mm sheet

The S/N graph provides the best possible optimized level for different parameters:

1. For 0.8 mm thick sheet pressure 1, squeeze time 3, weld time 2 and hold time 3.
2. For 1.2 mm thick sheet pressure 1, squeeze time 1, weld time 3 and hold time 3.
3. For 1.5 mm thick sheet pressure 1, squeeze time 2, weld time 3 and hold time 3.

Applying the above levels in the parameters for respective sheet optimum tensile shear strength could be achieved.

4.2 Analysis of variance

Anova is a statistically based decision-making tool for detection of any difference in performance of groups of tested items. In this experiment, it gives the contribution factors for each parameter that affects the response or the output.

Table 10,11 and 12 provides all essential factors at 95 % confidence level. Percent contribution of a parameter is responsible for any minute variation on performance.

Table 10, 11 and 12 gives percentage contribution of various parameters in response to tensile shear strength for three sheets.

Table 10 Anova for TSS of 0.8 mm sheet

Source	DOF	SS	MS	%C
Pressure	2	1.2577	0.6289	69.64
Squeeze time	2	0.0048	0.0024	0.27
Weld time	2	0.1803	0.0901	9.98
Hold time	2	0.3633	0.1816	20.11
Error	0	*	*	
Total	8	1.8061		100

Table 11 Anova for TSS of 1.2 mm sheet

Source	DOF	SS	MS	%C
Pressure	2	5.5022	2.7511	75.63
Squeeze time	2	0.5242	0.2621	7.21
Weld time	2	0.5444	0.2722	7.48
Hold time	2	0.7040	0.3520	9.68
Error	0	*	*	
Total	8	7.2748		100

Table 12 Anova for TSS of 1.5 mm sheet

Source	DOF	SS	MS	%C
Pressure	2	11.3695	5.6847	86.40
Squeeze time	2	0.3434	0.1717	2.61
Weld time	2	1.1014	0.5507	8.37
Hold time	2	0.3450	0.1725	2.62
Error	0	*	*	
Total	8	13.1592		100.00

Pressure has highest contribution for all sheets with maximum percent at 69.64% for 0.8mm, 75.63% for 1.2mm and 86.40% for 1.5 mm sheet. This influence rises with increase in thickness of the sheet.
Holding time has contribution of about 20.11% and 9.68% compared to 9.98% and 7.48% of pressure for 0.8 mm and 1.2 mm. For 1.5 mm sheet, pressure leads at 8.37 % compared to 2.62 % of hold time. It is due the fact, thin sheets with increase in weld time, high heat is generated at the interface as
a result of which weld nugget size increases so it requires more time for heating and cooling cycle to take place at lighter loading conditions. Similarly, for 1.2 mm sheet, squeeze time and weld time has nearly same influence on tensile shear strength as squeeze time and hold time for 1.5 mm sheet. Squeeze time that has least contribution towards tensile shear stress irrespective of sheet thickness.
Tensile strength reduces as pressure increases in relation to different parameters at different levels.
The contribution factor of different parameters for TSS are shown in the figure 7, 8 and 9.

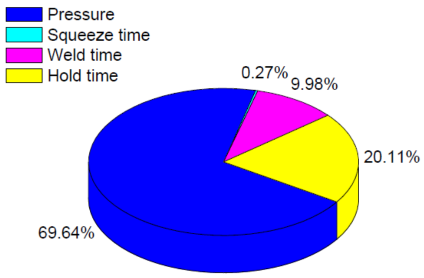

Fig. 7 Percentage contribution of parameters for TSS in 0.8 mm sheet

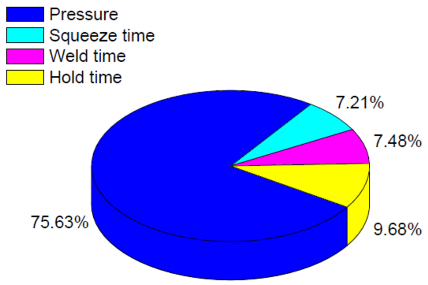

Fig. 8 Percentage contribution of parameters for TSS in 1.2 mm sheet

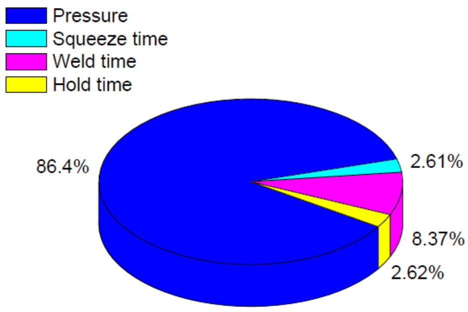

Fig. 9 Percentage contribution of parameters for TSS in 1.5 mm sheet

4.3 Confirmation test

The confirmation step is the final step in the design of experiment process. It is a method to validate the analysis. The experiments were conducted as per the combination of factors in accordance with previously evaluated levels. After optimization using taguchi method, new experiments were designed and performed with optimum levels.
The results of these experiments are summarized in the Table 13.

Table 13 Optimized levels of parameters and TSS

Sl. No.	Thickness of Sheet	Parameter	Level	TSS (kN)	Failure
1	0.8 mm	Pressure	1	3.38	PF
		Squeeze time	3		
		Weld time	2		
		Hold time	3		
2	1.2 mm	Pressure	1	5.33	PF
		Squeeze time	1		
		Weld time	3		
		Hold time	3		
3	1.5 mm	Pressure	1	8.21	PF
		Squeeze time	2		
		Weld time	3		
		Hold time	3		

Table 14 confirmation test result

Thickness of sheet		Optimal process parameters		% error
		Predicted	Experimental	
0.8 mm	Level	$A_1B_3C_2D_3$		
	TSS (kN)	3.32	3.38	1.8
	S/N ratio	10.42	10.59	
	Level	$A_1B_1C_3D_3$		
1.2mm	TSS (kN)	5.28	5.33	0.94
	S/N ratio	14.45	14.53	
	Level	$A_1B_2C_3D_3$		
1.5mm	TSS (kN)	8.17	8.21	0.49
	S/N ratio	18.24	18.28	

It is evident from the results that the developed model with a higher accuracy and maximum error below 2% is capable of predicting the tensile shear strength and utilizing the optimum levels for parameters it is noteworthy that improvement in tensile shear stress of about 1.5 to 2 kN for each of sheet metal could be achieved. The mode of failure is preferably pullout in nature. The credit to above results are due to reduction in loss function and improvement in S/N ratio utilizing to the Taguchi methodology.

V. FAILURE ANALYSIS

During static load testing, tension shear testing is most common criteria used in determining weld strength. During the loading, the weldment tends to rotate to align the gripped ends with the welded joint. With increase in loading, sheet separation increases and heat affected zone is clearly visible. [23]

Failure is spot welding occurs in two modes:

1. Pull out failure (PF)
2. Interfacial failure (IF)

Pullout failure is tensile in nature and driving force for pullout failure mode is tensile stress. Due to certain amount of rotation, the tensile stresses formed around the nugget causes plastic deformation in sheet thickness direction. These are visible at heat affected zones in the base metal where necking occurs. This necking is more severe in one of the sheets than other. Likewise driving force for interfacial failure mode is shear stress. High shear stress is created at the interface which exceeds nugget shear strength and prior to tensile stresses that causes necking around nugget, failure occurs at the interface. Interfacial failure mode occurs certainly with a shear mechanism in the shear tensile test.

Different modes of failures are summarized in the table 4, 5 and 6 in relation to parameters at various levels of operation. It is concluded that with increase in tensile shear stress, pullout type failure is dominant with few minor exceptions.

The tendency of pullout type failure occurs at lower pressure and decreases with increase in pressure. Studies reveal that as pressure increases, the area of contact between overlapping surface increases as a result current density decreases which in turn reduces the nugget diameter. Interfacial failure which is due to shear failure acts prior to necking causing shear failure This is quite clear from the specimens depicted in figure 10.

Fig. 10 (a) Pull out failure (b) Interfacial failure

VI. CONCLUSION

The present study on the experimental research of Optimization of process parameters of RSW joint and its effects on the strength of spot welded joint of CR3 low carbon steel can be concluded with following results.

1. Taguchi method of optimization is well suited and most powerful indeed for better result. There is certainly increase in tensile shear strength. With a constant duty cycle of 75%, it is concluded from ANOVA, that pressure is the major factor that has the highest contribution of about 67%, 73% and 88% for three sheets ranging from 0.8mm to 1.5 mm. coming to various time factors such as squeeze time, weld time and hold time. Weld time is second to pressure regarding the contribution towards tensile shear stress. With an exception for 0.8mm sheet (<1mm) hold time has upper hand compared to weld time. It is due to the fact that high heat generation leads melting of greater area in contact and solidification requires more time than usual.
2. Regarding modes of failure, joint is considered reliable if it fails due to tensile stress i.e. pull out type.
   It can also be concluded that interfacial failure occurs when joint is subjected to lesser tensile stresses. The aim should be to achieve pull out type of failure shown in table 13 with each experimentation done for optimized combination of levels show Pullout failure. (PF)
3. With increasing in thickness, pressure and welding time, the tensile stresses also increase.
4. Higher welding time upto a certain limit, shows pullout type of failure whereas interfacial failure occurs at low welding time but subjected to the pressure conditions whether low or high.
5. Increasing holding time increases the enhances the hardness of fusion zone thereby turning the failure mode from IF to PF.

As the pressure increases, contact resistance at interface decreases with lesser heat generation. In order to increase this heat, weld time must be increased to compensate for the reduced resistance. At microscopic level, surface of metal are series of peaks and valleys, when pressure is low, contact is only at these peaks. Due to lesser area of contact, contact resistance increase and the joint becomes stronger.

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