Optimization of Friction Stir Welding Process Parameters to Weld Cast A356 Aluminium Alloy Taguchi's Design of Experiments Approach

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ABSTRACT

This paper presents an application of Taguchi's Design of Experiments, to identify the optimum setting of process parameters to maximize the tensile strength of friction stir welded cast A356 aluminium alloy. The quality of weldments in friction stir welding (FSW) process mainly depends on the factors such as tool rotational speed, welding speed and axial force. Taguchi's orthogonal array L_{27}, signal to noise ratio (S/N) and Analysis of Variance (ANOVA) are used to find the optimum levels and the effect of process parameters on tensile strength. To correlate the process parameters and the measured tensile strength, a mathematical model has been developed by multiple linear regression analysis. The mathematical model is found to be very useful to predict the tensile strength of friction stir welded cast A356 aluminium alloy. The optimum conditions to get maximum tensile strength are tool rotation speed of 1000 rpm , welding speed of 75 mm/min and axial force of 5 kN .

Keywords: Friction stir welding, Cast aluminium alloy, Tensile strength, Taguchi design, Regression analysis

INTRODUCTION

In recent years, the technology of friction stir welding (FSW) has enormous potential in manufacturing applications [1]. High joining speed, autogenous welding, improved metallurgical properties, and reduced need for human skill, are amongst the most important advantages of FSW in comparison with conventional fusion welding methods [2, 3]. The formation of friction stir processing zone is affected by the material flow behaviour under the action of rotating tool. However, the material flow behaviour is predominantly influenced by the tool design, and FSW process parameters such as rotational speed, welding speed and axial force. The effect of some important parameters such as rotational speed, welding speed and axial force on weld properties has been major topics for researchers [3-8]. In order to study the effect of FSW process parameters most workers follow the traditional experimental techniques, i.e. varying one parameter at a time while keeping others constant. This conventional parametric design of experiment approach is time consuming and calls for enormous resources. Moreover this approach fails to capture the interaction terms of various parameters. Taguchi techniques have been used widely in engineering design and the main trust is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristic (performance measure) with minimum variation [9]. There have been plenty of recent applications of Taguchi techniques to materials processing for process optimization; some of the previous works are listed in Refs. [10-15]. Though research work applying Taguchi methods on metal cutting processes have been reported, it appears that the optimization of FSW process parameters of A356 aluminium alloy using Taguchi method has not been reported yet. Considering the above facts, the Taguchi L_{27} method is adopted to analyze the effect of each processing parameters (i.e. rotational speed, welding speed and axial force) and interaction effects among them for optimum tensile strength of friction stir welded joints of A356 alloy.

EXPERIMENTAL WORK

Identifying the important Parameters

From the literature [7, 8, 16] it is found that the primary process parameters viz., rotational speed (N) and welding speed (S), and axial Force (F), were selected as process parameters among the many independently controllable primary and secondary process parameters (as shown in Fig.1) which are directly affect the tensile strength of welded joints. These primary parameters contributing to the heat input and subsequently influencing the tensile strength variations in the friction stir welded aluminium alloy joints.

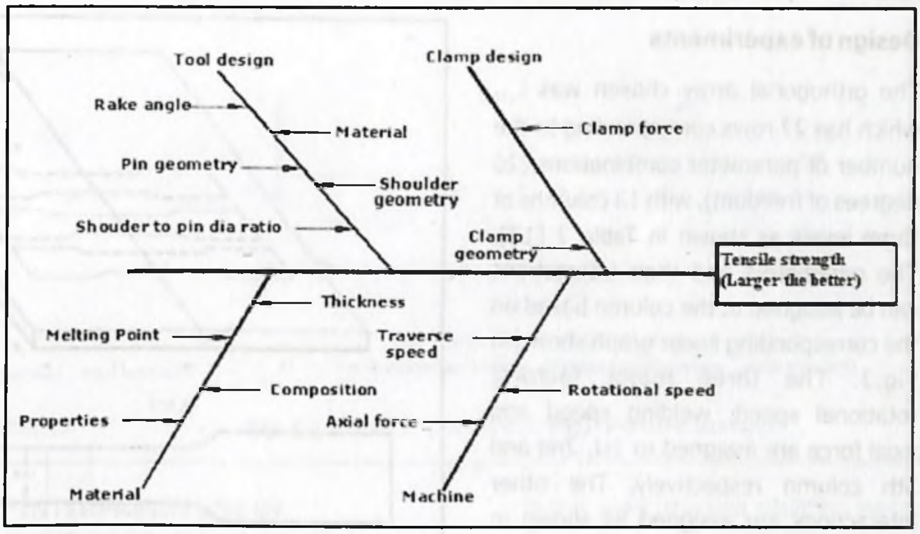

Fig. 1 : Factors influencing tensile strength

Finding the working limits of parameters

A large number of trial runs were carried out using 6 mm thick cast plates of A356 aluminium alloy to find out the feasible working limits of FSW process parameters. The chemical composition of A356 aluminium alloy is presented in Table 1. Different combinations of process parameters were used to carryout the trial runs. This was carried out by varying one of the factors while keeping the rest of them at constant values. The working range of each process parameter was decided upon by inspecting the macrostructure (cross section of weld) for a smooth appearance without any visible defects such as tunnel defect, pinhole, lazy S, segregation etc. From the above inspection, the following observations have been made:

- When the rotational speed was lower than 1000 rpm, crack like defect at the retreating side of weld nugget was observed (Fig.2a) and it may be due to insufficient heat generation and insufficient metal transportation; on the other hand, when the rotational speed was higher than 1400 rpm, tunnel defect was observed (Fig.2b) and it may be due to excess turbulence caused by higher rotational speed.
- Similarly, when the welding speed was lower than 22 mm/min, tunnel defect was observed (Fig.2c) due to excess heat input per unit length of the weld; when the welding speed was higher than 75 mm/min, tunnel at the retreating side was observed (Fig.2d) due to inadequate flow of material caused by insufficient heat input.
- When the axial force was lower than 3 kN, pin hole defect at the middle of the weld cross section in retreating side was observed (Fig.2e) due to absence of vertical flow of material caused by insufficient downward force; when the axial force was increased beyond 5 kN resulted in tunnel defect and excessive thinning (Fig.2f) due to higher heat input.

The chosen levels of the selected process parameters with their units and notations are given in Table 2.

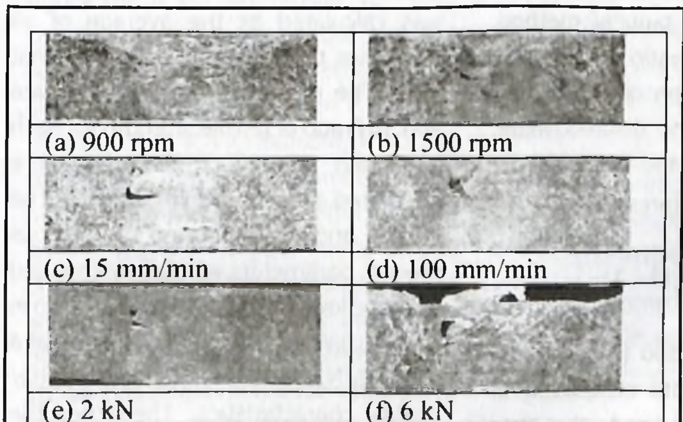

Fig. 2 : Cross sectional macrostructure of the FSW joints

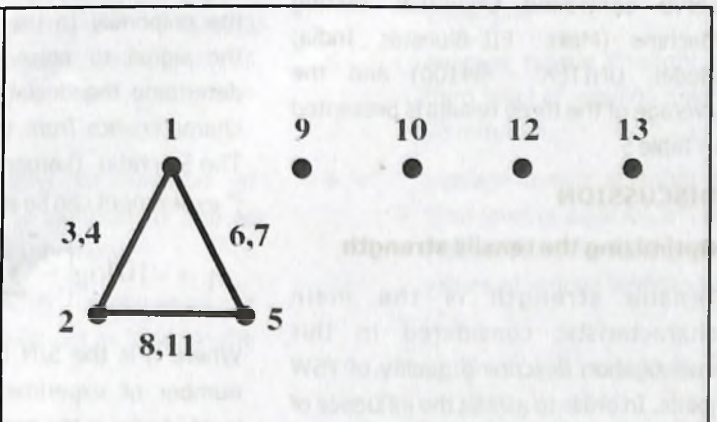

Fig. 3 : Linear graph of L_{27} (3^{13}) orthogonal array

Design of experiments

The orthogonal array chosen was L_{27}, which has 27 rows corresponding to the number of parameter combinations (26 degrees of freedom), with 13 columns at three levels as shown in Table 3 [17]. The parameters and their interactions can be assigned to the column based on the corresponding linear graph shown in Fig.3. The three major factors: rotational speed, welding speed and axial force are assigned to 1st, 2nd and 5th column respectively. The other interactions are assigned as shown in Table 4.

Conducting the experiments

Castings of commercial A356 aluminium alloy were made by sand casting method and they were machined to rectangular plates of size 175 mm X 75 mm X 6 mm. Square butt joint configuration was prepared to fabricate FSW joints. A non-consumable, rotating tool made of high carbon steel was used to fabricate FSW joints. An indigenously designed Friction Stir Welding Machine (15 hp; 3000 rpm; 25 kN) was used to fabricate the joints. The welded joints were sliced using a power hacksaw and then machined to the required dimensions as shown in Fig. 4. Three tensile specimens (ASTM E8M-04) were prepared from each joint to evaluate the transverse tensile strength. Tensile test was carried out in 100 kN, servo controlled Universal Testing Machine (Make: FIE-Bluestar, India; Model: UNITEK - 94100) and the average of the three results is presented in Table 5

DISCUSSION

Optimizing the tensile strength

Tensile strength is the main characteristic considered in this investigation describing quality of FSW joints. In order to assess the influence of factors on the response, the means and

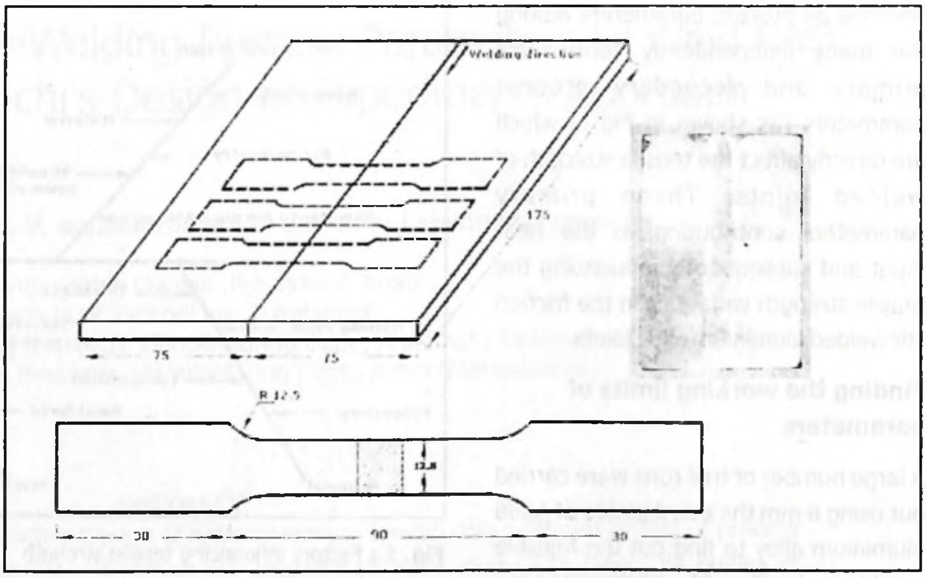

Fig. 4 : Joint configuration and tensile specimen dimensions

Signal-to-Noise ratios (S/N) for each control factor can be calculated. The signals are indicators of the effect on average responses and the noises are measures of the influence on the deviations from the sensitiveness of the experiment output to the noise factors. The appropriate S/N ratio must be chosen using previous knowledge, expertise, and understanding of the process. When the target is fixed and there is trivial or absent signal factor (static design), it is possible to choose the signal-to-noise (S/N) ratio depending on the goal of the design [18]. In this study, the S/N ratio was chosen according to the criterion the larger-the-better, in order to maximize the response. In the Taguchi method, the signal to noise ratio is used to determine the deviation of the quality characteristics from the desired value. The S/N ratio $_i$ (Larger-the-better) in the j^{th} experiment can be expressed as:

$$\eta = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n}(1/y_i^2)\right) \quad (1)$$

Where η is the S/N ratio (dB),n is the number of experiments conducted at level i and y_i is the measured value tests (here, tensile strength (TS)). In the present study, the tensile strength data was analyzed to determine the effect of FSW process parameters. The experimental results were then transformed into means and signal-to-noise (S/N) ratio. In this work, 27 means and 27 S/N ratios were calculated and the estimated tensile strength, means and signal-to-noise (S/N) ratio are given in Table.5. The analysis of mean for each of the experiments will give the better combination of parameters levels that ensures a high level of tensile strength according to the experimental set of data. The mean response refers to the average value of performance characteristics for each parameter at different levels. The mean for one level was calculated as the average of all responses that were obtained with that level. The mean response of raw data and S/N ratio of tensile strength for each parameter at level 1, 2 and 3 were calculated and are given in Table.6. The means and S/N ratio of the various process parameters when they changed from the lower to higher levels are also in are also given in Table.6. It is clear that a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the

Fig. 5 : Response graph (Means) of tensile strength

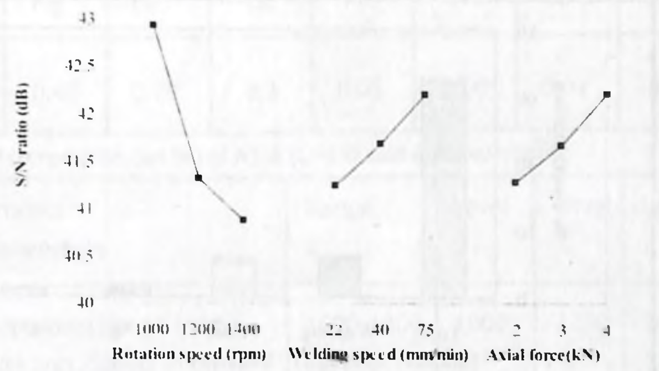

Fig. 6 : Response graph (S/N ratio) of tensile strength

level of highest S/N ratio [19]. The mean effect (Fig.5) and S/N ratio (Fig.6) for tensile strength were calculated by statistical software [20] indicates that the tensile strength was at maximum when rotational speed (level 1), welding speed and axial force (level 3) are 1000 rpm, 75 mm/min and 5 kN respectively.

Analysis of variance (ANOVA)

Analysis of variance (ANOVA) has been performed to identify the process parameters that are statistically significant. The purpose of the ANOVA is to investigate the significance of the process parameters which affects the tensile strength of FSW joints. ANOVA results for tensile strength of means and S/N ratio are given in Table.7 and Table.8 respectively. In addition, the F-test named after Fisher can also be used to determine which process has a significant effect on tensile strength. Usually, the change of the process parameter has a significant effect on the quality characteristics, when F is large. Results of ANOVA indicate that the considered process parameters are highly significant factors affecting the tensile strength of FSW joints in the order of rotational speed, welding speed and axial force and also the interaction between rotational speed and welding speed has more influence comparing with other interactions on tensile strength of welded joints.

INTERPRETATION OF EXPERIMENTAL RESULTS

Percentage of contribution

The percentage contribution is the portion of the total variation observed in the experiment attributed to each significant factors and / or interaction which is reflected. The percentage contribution is a function of the some of squares for each significant item; it indicates the relative power of a factor to reduce the variation. If the factor levels were controlled precisely, then the total variation could be reduced by the amount indicated by the percent contribution. The percentage of contribution of the rotational speed, welding speed and axial force is shown in Fig.7

Estimation of optimum performance characteristics

Once the experiments are conducted and the optimum condition is determined, one of two possibilities exists:

1. The prescribed combination of factor level is identical to one of those in the experiment.
2. The prescribed combination of factor level was not included in the experiment.

In this work, the first situation exists. The optimum value of tensile strength was predicted at the selected levels of significant levels of significant parameters. The significant process parameters and their optimum levels have already been selected as N1, S3 and F3 (Table. 6).The estimated mean of the response characteristics (tensile strength) can be computed [21, 22] as

$$TS = N_1 + S_3 + F_3 + N_3 S_3 + N_3 F_3 - S_1 F_1 - 5T \quad (2)$$

Where,

TS = Tensile Strength

T = overall mean of tensile strength

N = average tensile strength at first level of rotational speed 1000 rpm,

S = average tensile strength at third level of welding speed 75 mm/min,

F = average tensile strength at third level of axial force 5 kN (Table 6). Substituting the values of various terms in Eq. (2),

TS = 140.66 + 130 + 130.22 + 125.11+ 123.77 + 126.22 5 x 122.814 = 161.91 MPa

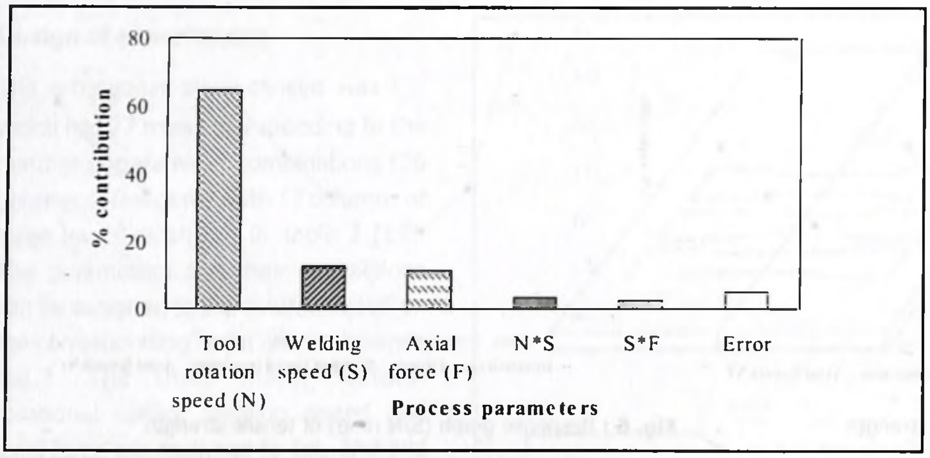

Fig. 7: Percentage contribution of factors (Means) and their interactions

Confirmation test

The final step is verifying the improvement in tensile strength by conducting experiments using optimal conditions. Three confirmation experiments were conducted at the optimum setting of process parameters. The rotational speed at first level, welding speed at third level and axial force at third level were set and average tensile strength of friction stir welded A356 alloy was found to be 166 MPa, which was within the confidence interval of the predicted optimal of tensile strength. The improvement of tensile strength at optimum parameters is attributed to the defect free macrostructure of the FSW joint due to the sufficient heat generation. More over, the coarse interdentritic eutectic Si (dark region) in base metal is getting refined and uniformly distributed in the Al matrix (white region) due to optimum stirring during FSW (Fig.8).

Correlation

In this work, to correlate the process parameters and the tensile strength of welded joints, a multiple regression model is developed to predict tensile strength of friction stir welded A356 alloy based on experimentally measured tensile strength. The regression coefficients were calculated with the help of statistical software, MINITAB 15.0. After determining the significant coefficients (at 95% confidence level), the final model was developed using only these coefficients and the final mathematical model to estimate tensile strength is given below:

Tensile strength (TS) = $\{116.47\ 15.30\ (N) + 8.10\ (S) + 7.10\ (F) - 4.25\ (NS) - 1.50(NF) + 4.50(SF) + 9.32\ N^2 + 2.32\ S^2 + 0.32F^2\}$

The adequacy of the model was tested by using the analysis of variance technique (ANOVA). All terms including N, S, F, NS, NF, SF, N^2, S^2 and F^2 were found to be significant at 95% confidence interval. The determination coefficient (R^2) indicates the goodness of fit for the model. In this case, the value of the determination coefficient (R^2 =0.978398) indicates that only less than 1% of the total variations are not explained by the model. The value of adjusted determination coefficient (adjusted R^2 = 0.958955) is also high, which indicates a high significance of the model. Predicted R^2 is also made a good agreement with the adjusted R^2.

Conclusions

The tensile strength of friction stir welded aluminium alloy A356 has been evaluated under different processing conditions using taguchi orthogonal array. Based on the experimental and analytical results, the following conclusions are drawn

1. The rotational speed is the dominant parameter for tensile strength followed by the welding speed. Axial force shows minimal effect on tensile strength compared to other parameters. The interaction between rotational speed and welding speed has more influence comparing with other interactions on tensile strength of welded joints.
2. A maximum tensile strength of 162 MPa is exhibited by the FSW joints with the optimal process parameters of 1000 rpm rotational speed, 75 mm/min welding speed

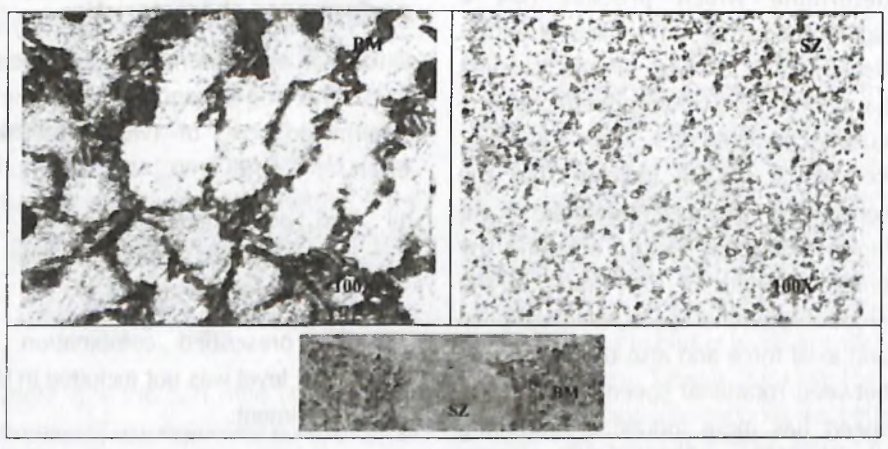

Fig. 8 : Macrostructure and microstructures of different regions of FSW joint at optimum parameters [BM - Base Metal , SZ-Stir Zone]

and 5 kN axial force shows a reasonable agreement with the experimental value of 166 MPa

3. Further, to correlate the tensile strength a mathematical multiple regression model has been developed and it is found to be useful in predicting the tensile strength.

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Alloy	Si	Mg	Fe	Cu	Mn	Zn	Ni	Al
A356	6.87	0.49	0.28	0.1	0.05	0.09	0.01	Bal

Table 1 : Chemical composition (wt %) of A356 (LM25) cast aluminium alloy

Parametric designation	Process parameters	Range	Level 1	Level 2	Level 3
N	Rotational Speed (rpm)	1000-1400	1000	1200	1400
S	Welding Speed (mm/min)	22-75	22	40	75
F	Axial Force (kN)	3-5	3	4	5

Table 2 : Process parameters with their range and values at three levels

Run	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	3	1	1	3	2	3	2	1	2	1	3
26	3	3	3	1	2	1	3	1	3	2	3	2	1
27	3	3	3	1	3	2	1	2	1	3	1	3	2

Table 3: Orthogonal array L_{27} (3^{13}) of taguchi [17]

Sl.	Factors	Column No.
1	Rotational speed (N)	1
2	Welding speed (S)	2
3	Axial force (F)	5
4	Interaction (N x S)	3, 4
5	Interaction (S x F)	8, 11
6	Interaction (N x F)	6, 7

Table 4: Parameters assignments in L_{27} Orthogonal array

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Test	Rotational Speed (rpm) N	Welding speed (mm/min) S	Axial Force (kN) F	Average Tensile Strength (MPa)	S/N Ratio (dB)
1	1000	22	3	128	42.144
2	1000	22	4	130	42.278
3	1000	22	5	134	42.542
4	1000	40	3	132	42.411
5	1000	40	4	139	42.86
6	1000	40	5	142	43.045
7	1000	75	3	144	43.167
8	1000	75	4	146	43.287
9	1000	75	5	171	44.649
10	1200	22	3	107	40.587
11	1200	22	4	109	40.748
12	1200	22	5	113	41.061
13	1200	40	3	109	40.748
14	1200	40	4	115	41.213
15	1200	40	5	126	42.007
16	1200	75	3	118	41.437
17	1200	75	4	124	41.868
18	1200	75	5	130	42.278
19	1400	22	3	106	40.506
20	1400	22	4	108	40.668
21	1400	22	5	110	40.827
22	1400	40	3	104	40.34
23	1400	40	4	114	41.138
24	1400	40	5	118	41.437
25	1400	75	3	102	40.172
26	1400	75	4	111	40.906
27	1400	75	5	126	42.007

Table 5: Experimental values of tensile strength (mean) and S/N ratio

Source	Mean				S/N ratio			
	Level-1	Level-2	Level3	Delta (L2-L1)	Level-1	Level-2	Level3	Delta (L2-L1)
N	140.66	116.77	111.0	-23.89	42.932	41.328	40.889	-1.604
S	116.11	122.11	130.22	6.0	41.262	41.689	42.198	0.426
F	116.66	121.77	130.0	5.11	41.279	41.663	42.207	0.383
NS	120.11	123.22	125.11	3.11	41.557	41.767	41.825	0.210
NF	122.88	121.77	123.77	-1.11	41.758	41.643	41.748	-0.116
SF	126.22	121.88	120.33	-4.33	41.932	41.662	41.554	-0.271

Table 6: Main effects of tensile strength (Means and S/N ratio)

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Source	DF	SS	V	F	SS'	P
N	2	20.834	10.417	184.49	20.721	66.65
S	2	3.95	1.975	34.97	3.83	12.34
F	2	3.916	1.958	34.681	3.803	12.23
N*S	4	0.961	0.48	8.518	0.735	2.36
N*F	4	0.104	0.052	0.929	0.00	0.00
S*F	4	0.869	0.434	7.702	0.643	2.07
Error	8	0.451	0.056			4.35
Total	26	31.09				100.00

Table 7 : ANOVA for tensile strength (S/N ratio)

Source	DF	SS	V	F	SS'	P
N	2	4452.53	2226.26	152.36	4423.30	64.79
S	2	902.77	451.38	30.89	873.54	12.84
F	2	814.51	407.25	27.87	785.29	11.55
N*S	4	281.50	140.74	9.63	223.06	3.29
N*F	4	19.02	9.51	0.65	0.0	0.0
S*F	4	218.82	109.41	7.48	160.37	2.35
Error	8	116.89	14.611			5.18
Total	26	6806.07				100.00

DF= Degree of freedom, SS=Sum of squares, V=Variance, SS'=Pure sum of squares
P = Percentage of contribution

Table 8 : ANOVA for tensile strength (means)

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Materials submitted to conferences may be accepted, particularly if it is expanded or modified and provided that the Editor considers that the paper would be of interest to the wider readership of the Indian Welding Journal. The authors are responsible for obtaining the consent of the editor / sponsor of the conference proceedings to publish the materials in the IWJ.

Critical assessment / Reviews

Dealing with welding of joining subject in a critical, comprehensive and well referenced manner typically around 3500-4000 words plus figures and table. The reference of the conclusions of the research work review to industrial practice should be emphasized.

SUBMISSION OF THE PAPERS

All the papers should be sent to the Editor at the Head Quarter of the Indian Institute of Welding. Normally an acknowledgement of receipt will be sent within one week by E-mail. Papers should be printed in 3 columns (please refer January / April 2005 issue of the IWJ) and sent in a CD over and above the hard print. Figures, Diagrams & sketches should be neat and clear and the papers after preliminary screening by the Editor will be sent to one or more of Review Panel Members (see list below).

Based on the feedback, the Editor will decide about publication subject to space availability in a particular issue. A final communication about acceptance / modification / non-acceptance of the papers would then be sent to the authors in due course. Normally, the authors expecting their papers to be published in a particular issue should send the manuscript at least 2 months before the issue date.

REVIEW PANEL MEMBERS

Prof. G. L. Datta, Prof. T. K. Pal, Prof. P. K. Ghosh, Mr. R. Banerjee, Mr. R. Ravi & Dr. A. K. Bhaduri.