A Review on Optimization Methods to Study Effect of Process Parameters in Friction Stir Welding

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***Abstract*— Friction stir welding (FSW) process is an innovative solid state joining method in which the material that is being welded does not melt and recast. FSW uses a non-consumable tool to produce frictional heat in the adjoining surfaces. It is considered to be the most significant development in metal joining in a decade. This joining technique is energy efficient, environment friendly, and versatile. It has been employed for welding various joints required for several industrial applications as in aerospace, rail, automotive and marine industries for joining similar and dissimilar alloys. To obtain the desired strength, it is essential to have a complete control over the relevant process parameters to maximize the tensile strength and other properties on which the quality of a weldment is based. Therefore, it is very important to select and control the welding process parameters for obtaining such kind of welded joints. In order to achieve this, various prediction methods can be applied to define the desired output variables through developing mathematical models to specify the relationship between the input parameters and output variables. In this work it is aimed to study the research work related to the FSW by different researchers proposed process optimization methods to predict suitable process parameters which affect the efficiency of the Friction Stir Welded joints of similar and dissimilar alloys.**

Keywords*— *Friction Stir Welding, Process Parameters, Optimization Methods, Similar and Dissimilar Materials.

I. INTRODUCTION

The respiratory effects often seen in full time welders include bronchitis, airway irritation, lung function changes, lung fibrosis, and a possible increase in the incidence of lung cancer. Traditionally, control of fumes and gases has been by enclosure and local exhaust ventilation, respiratory protective equipment may also be necessary in certain circumstances, in particular in confined spaces. In this context, an environmentally cleaner process has been invented at The Welding Institute (TWI) in 1991, UK [1], which is popularly known as Friction Stir Welding (FSW) process, especially for aluminum alloys [2,3]. The process as shown in Fig. 1, require slower energy than conventional fusion welding processes [4,5] and no consumables such as electrodes and protecting gases are needed [6,7] and have been successfully applied to the aerospace, automobile, shipbuilding industries, etc. In this process a rotating tool is inserted into the butt of the workpiece due to the action of the axial pressure it produces a highly plastically deformed zone through the associated stirring action. FSW is an environmentally cleaner process, due to the absence of a need for the various gases that normally accompany fusion welding. FSW process produces no smoke, fumes, arc glare and it is an eco-friendly welding process. This comparatively recent innovation has permitted friction technology to be used to produce continuous welded seams for plate fabrication. Compared to many of the fusion welding processes that are routinely used for joining structural alloys, similar and dissimilar alloys. Studies report that the maximum temperature in the material being welded is usually less than 80% of its melting temperature [8]. FSW is an emerging solid state joining process in which the material that is being welded does not melt and recast.

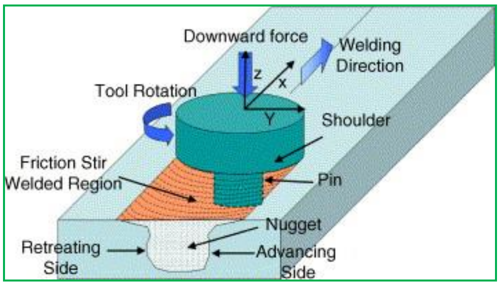

Fig. 1. Schematic drawing of Friction Stir Welding process

To obtain the desired strength, it is essential to have a complete control over the relevant process parameters to maximize the tensile strength on which the quality of a weldment is based. Therefore, it is very important to select and control the welding process parameters for obtaining the maximum strength. Various prediction methods can be applied to define the desired output variables through developing mathematical models to specify the relationship between the input parameters and output variables. In this review four methods of optimization are studied i.e. ANN, Taguchi Method, ANOVA and Response Surface Methodology.

II. OPTIMIZATION METHODS

A. Artificial Neural Networks

ANNs have been described as the model of the brains cognitive process. This is because in their operation, they try to mimic the way the human brain operates in solving complex problems.

It is possible to get good results when ANNs are used to predict the tensile strength using welding speed and rotational speed as the input parameters especially when sufficient data is used to train the ANN. Input parameter prediction is, however, not an easy task due to the several number of possible combinations of input parameters that can give that same output. Also the input values depend on the availability of the spindle speeds and feed rates provided on the machine. Further work still needs to be done in grouping the input parameters, train the network independently and then observe the outputs. Furthermore, a more desirable though complex method can be devised which allows the determination of all the possible input parameters at once without the need to group the input parameters. This is because grouping input parameters will obviously require more input data to train the ANN.

Hasan et al.[1] (2007) developed an artificial neural network (ANN) model for the analysis and simulation of the correlation between the friction stir welding (FSW) parameters of aluminium (Al) plates and mechanical properties. The input parameters of the model consist of weld speed and tool rotation speed (TRS). The outputs of the ANN model include property parameters namely: tensile strength, yield strength, elongation, hardness of weld metal and hardness of heat effected zone (HAZ). Good performance of the ANN model was achieved. The model can be used to calculate mechanical properties of welded Al plates as functions of weld speed and TRS. The combined influence of weld speed and TRS on the mechanical properties of welded Al plates was simulated. A comparison was made between measured and calculated data. The calculated results were in good agreement with measured data.

(GONNS) was developed by Ibrahim N. Tansel et al [2], the intelligent decision making capability of human beings was simulated. The use of GONNS was used for the estimation of operating conditions in FSW process. The network was trained with observations and one or more ANN(s) was used by GONNS to represent complex systems and to optimize genetic algorithms study was performed. To relate two input parameters with each welding zone characteristics it is represented by five ANNs. Among the input parameters, maintaining remaining within the range, the optimum value (either maximum or minimum) of one parameter is searched by GA and one of the optimization tool which showed good results is GONNS.

Simulated annealing technique was used to prevent the ANN model from getting stuck in local minima by K.M.Dawas et al [3] in which the ANN model was developed for the analysis and simulation of the correlation between the FSW parameters and mechanical properties in joining aluminum plates. The developed model can be applied to calculate mechanical properties as a function of weld speed and tool rotational speed and the work was extended by simulating the combined properties of the two parameters.

The objective of the research by Livan [4] is to develop a finite element simulation of FSW of AA6061 where trend line equations were developed for thermal conductivity, specific heat and density to obtain the relationship of these factors with peak temperature. Mechanical properties for the specimens are obtained for different spindle speeds and feeds and variation of temperature with input parameters is also observed. In the paper, to predict the average grain size ANN was linked to FEM. The used net was trained using the experimental data and numerical results of butt joints.

A.K. Lakshminarayanan, V. Balasubramanian [5] developed Response Surface Methodology (RSM) to predict the tensile strength of friction stir welded AA7039 and compared with the ANN model. Considering central composite face centered design full replications technique a mathematical model was developed and three factors each at three levels were considered for experimentation. Further, critical parameters were identified by sensitivity analysis.

Table 1 Experimental design matrix and results

Std	**Run**	**Coded value**			**Real value**			**Tensile strength MPa**
		N	***S***	***F***	***Rotational speed (r·min−1)***	***Welding speed (mm·min^{-1})***	***Axial force kN***	
1	15	-1	-1	-1	1200	22	4	180
2	9	+1	-1	-1	1600	22	4	238
3	8	-1	+1	-1	1200	75	4	170
4	7	+1	+1	-1	1600	75	4	211
5	10	-1	-1	+1	1200	22	8	200
6	18	+1	-1	+1	1600	22	8	224
7	5	-1	+1	+1	1200	75	8	209
8	17	+1	+1	+1	1600	75	8	214
9	1	-1	0	0	1200	45	6	255
10	16	+1	0	0	1400	45	6	292
11	11	0	-1	0	1400	22	6	258
12	12	0	+1	0	1400	75	6	243
13	3	0	0	-1	1400	45	4	296
14	20	0	0	+1	1400	45	8	298
15	2	0	0	0	1400	45	6	317
16	13	0	0	0	1400	45	6	315
17	4	0	0	0	1400	45	6	309
18	14	0	0	0	1400	45	6	311
19	6	0	0	0	1400	45	6	312
20	19	0	0	0	1400	45	6	314

They have used central composite face centered design (Table 1) which fits the second order response surfaces very accurately. Central composite face centered (CCF) design matrix with the star points being at the center of each face of factorial space was used, so $\alpha = \pm 1$. CCF designs provide relatively high quality predictions over the entire design space and do not require using points outside the original factor range. The upper limit of a factor was coded as +1, and the lower limit was coded as –1. All the coefficients were obtained applying central composite face centered design using the Design Expert statistical software package. 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:

Tensile strength(σ)={311.44+16.50(N)– 5.30(S)+5.00(F)−4.50(NS)−8.75(NF)+4.50(SF)−35.59N2−58.59S2−12.09F2 (1)

They have used the back-propagation (BP) algorithm was used with a single hidden layer improved with numerical optimization techniques called Levenberg-Marquardt (LM). The neural network described in this work, after successful training, was used to predict the tensile strength of friction stir welded joints of AA7039 aluminium alloy within the trained range. Statistical methods were used to compare the results produced by the network. Errors occurring at the learning and testing stages are called the root-mean square (RMS), absolute fraction of variance (R2), and mean error percentage values. These are defined as follows, respectively:

$$\mathrm{RMS} = \left[(1/p) \sum \left| t_j - o_j \right|^2 \right]^{1/2} \quad (2)$$

$$R^2 = 1 - \left[\frac{\sum_j (t_j - o_j)^2}{\sum_j (o_j)^2} \right]^{1/2} \quad (3)$$

TABLE 2 TRAINING PARAMETERS USED

Parameter	Value
Number of input nodes	3
Number of hidden nodes (feed forward)	11
Number of output nodes	1
Learning rule	Levenburg-Marquatt
Number of epochs	500
Error goal	1.0×10−4
Mu	0.01
Number of training sets used	1

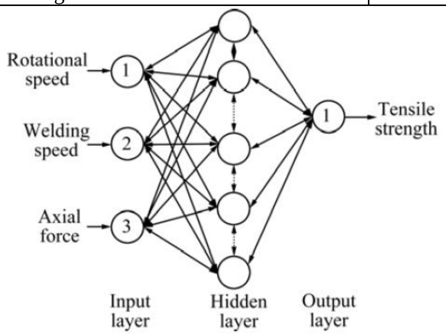

Fig 2.ANN architecture used

$$\text{Mean error} = (1/p) \sum_j \frac{t_j - o_j}{t_j} \times 100 \quad (4)$$

Where p is the number of patterns, tj is the target tensile strength; oj is the actual tensile strength.

Similar work was carried out by M. Jayaraman et al [6] on A319 where the results obtained by RSM model were compared with that obtained by ANN and found that the predicted error rate of artificial network is closer to experimental values than that predicted by the RSM.

TABLE 3.COMPARISON BETWEEN RSM AND ANN

Model summary and prediction errors	Response surface methodology(RSM)	Artificial neural network(ANN)
Root mean square (RMS)	2.784 724	1.454 125
R^2	0.969 978	0.991 814
Mean error/%	0.769 831	0.258 847
Computational time	Short	Long
Experimental domain	Regular	Irregular or regular
Model developing	With interactions	No interactions
Understanding	Easy	Moderate
Application	Frequently	Frequently

B. *Taguchi Method*

Taguchi techniques were developed by Taguchi and Konishi; these techniques have been utilized widely in engineering analysis to optimize the performance characteristics within the combination of design parameters. Taguchi technique is also powerful tool for the design of high quality systems. It introduces an integrated approach that is simple and efficient to find the best range of designs for quality, performance, and computational cost. Some researchers have been performed to optimize the optimum levels of process parameters based on orthogonal array experiment of Taguchi's.

Oktem et al. [7] investigated the application of Taguchi optimization technique to reduce warpage problem related to the shrinkage variation depended on process parameters during production of thin-shell plastic components for orthose part. They carried out a number of MoldFlow analyses by utilizing the combination of process parameters based on three-level of L_{27} and L_9 Taguchi orthogonal design. They used signal-to-noise (S/N) and the analysis of variance (ANOVA) to find the optimum levels and to indicate the impact of the process parameters on warpage and shrinkage. Their results show that warpage and shrinkage are improved by about 2.17% and 0.7%.

K.Venkata Kalyani et al [8] This paper deals with friction stir welding of AA6061-T6 Aluminium Alloy by using H13 tool at different rotational speeds and welding feeds and pin diameters. Experiments were conducted according to L9 orthogonal array which was suggested by Taguchi. Optimum parameters for optimum tensile strength, hardness and ductility were found with the help of s/n ratios. Therefore optimization of input process parameter is required to achieve good quality of welding. In this experiment the effect of process parameters on welded joint was studied and optimizes the parameter by using Taguchi method for tensile strength, hardness, ductility. Assign the rank to each factor which are having more influence on the mean tensile strength, hardness and ductility.

Koilraj et al., [9] in their work, optimization of process parameters of friction stir welding of dissimilar aluminum alloys (copper, aluminum and magnesium alloys)using Taguchi technique (Taguchi L16 orthogonal design of experiments), considered parameters rotational speed, traverse speed, tool geometry and ratio between tool and shoulder diameter and pin diameter for optimization to investigate tensile strength of the joint. The results were analyzed with the help of analysis of variance and concluded that optimum levels of tool rotational speed is 700 rpm , traverse speed is 15mm/min , ratio between tool shoulder diameter and pin diameter is 3, pin tool profile is cylindrical threaded and finally friction stir welding produces satisfactory butt welds.

Yahya Bozkurt [10] has done work on optimization of friction stir welding process parameters to achieve maximum tensile strength in the polyethylene slab. Three process parameters, tool rotational speeds, tool traverse speed, and tilt angle of the tool were identified for optimization. The material taken for study is high density polyethylene sheet which is a thermoplastic to determine welding process parameters on ultimate tensile strength of the weld for good joint efficiency. The optimization technique applied is Taguch's L9 orthogonal array, signal to noise ratio and ANOVA. The results depicted are tool rotational speed of 3000rpm contributes 73.85% to the overall welding parameters for the weld strength and the tool tilt angle has least contribution.

S.M.Bayazid et al [11] have investigated on effect of process parameters on Friction Stir Welding of dissimilar materials. They have butt welded Al6063 along with Al7075. They have investigated the tensile strength of the welded joint and considered as main parameter in order to achieve a joint with proper quality. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio and for higher the better quality characteristics the S/N ratio is calculated using the formula

$$\frac{S}{N} = -10Log\ (1/n \sum_{i=1}^{R} \frac{1}{Y_{Hi}^2}) \qquad (5)$$

Where n is the numbers of replicates of each experiment at same conditions and YHi is the tensile strength of each sample in test number i.

It has been observed that according to Table 4, 9 main values for tensile strength and 9 corresponding values of S/N (orthogonal array OA) were obtained. Optimal combination of factors and levels were obtained by analyzing each calculated main values, in order to achieve the maximum tensile strength. The main value of tensile strength in Table 4 for each experiment was calculated by averaging three values of measured tensile strengths. Also, main and average values of tensile strength and S/N ratio in all levels were calculated and listed in Table 5. As its clear, higher values of S/N ratio of an experiment, corresponds to better quality of welded joint. Therefore the optimal condition is a condition with maximum S/N ratio. Value of tensile strength is maximum when rotational speed, travel speed and plates' position were in 3, 2 and 1 levels respectively, because, values of S/N ratios in these levels are maximum. Investigation of friction stir welded A319 alloy joint also has declared that maximum values of S/N ratio were obtained when rotational speed and travel speed values are 1200 rpm and 40 mm/min respectively.

TABLE 4. STANDARD ORTHOGONAL ARRAYS OF 9 DIFFERENT GROUPS FOLLOWING TAGUCHI'S SUGGESTION.

Test number	W (rpm)	V (mm/min)	L (AS or RS)	UTS (MPa)			S/N
1	800	80	AS-7075	98	95	100	39.780
2	800	120	AS-6063	102	97	94	39.789
3	800	160	AS-7075	88	91	84	38.842
4	1000	80	AS-7075	120	118	123	41.603
5	1000	120	AS-7075	106	108	103	40.473
6	1000	160	AS-6063	98	90	95	39.477
7	1600	80	AS-6063	115	113	121	41.303
8	1600	120	AS-7075	157	147	150	43.588
9	1600	160	AS-7075	139	140	145	43.000

TABLE 5. MAIN EFFECTS OF THE PROCESS PARAMETERS.

Process Parameter	Level	Mean			S/N ratio		
		W	V	L	W	V	L
	1	94.333	111.444	117.333	39.470	40.898	41.216
Average value	2	106.777	114.888	102.777	40.518	41.084	40.186
	3	136.333	111.111	-	42.630	40.636	-
Main effects	2 – 1	12.444	3.444	-14.556	1.048	0.185	-1.031
	3 – 1	42	-0.333	n/a	3.160	-0.262	n/a
	3 – 2	29.556	-3.777	n/a	2.112	-0.449	n/a

The optimal value of tensile strength will be achieved in such a condition that effective parameters positioned in their own effective levels. According to equation 6, Value of tensile Strength for 6063 and 7075 FSW joint was estimated to be 143.59 MPa.

$$TS = RS3 + TS2 + PS1 - 2T \qquad (6)$$

RS3 is the mean value of tensile strength for rotational speed in level 3, TS2 is the mean value of tensile strength for travel speed in level, PS1 is the mean value of tensile strength for plates' position in level 1 and T is the mean value of tensile strength of all experiments.

C. ANOVA

The Analysis of Variance popularly known as the ANOVA can be used to identify the process parameters that are statistically significant which affect the tensile strength of the welded joints produced by FSW.

Furkan Sarsilmaz & Ulas Caydas et al [12] studied about the joining of FSW of AA1050/AA5083. The parameters considered for study are spindle speed, traverse speed and stirrer geometry. For obtaining response measurements full factorial experimental design was conducted. Analysis Of Variance (ANOVA) and main effect plots were used to determine the significant parameters and to optimize the levels for each parameter. For predicting output characteristics a linear regression equation was derived.

C.Devanathan et al [13] were worked on friction stir weld ability of 5% SiC particulate aluminum matrix cast composite using TiAlN coated tool and investigation of effect of process parameters such as tool rotation speed, traverse speed, and axial force on ultimate tensile strength. The result showed that there was no noticeable tool wear, only aluminum particles were deposited on the tool pin. They observed that the optimal FSW process parameter combinations were spindle speed at 1200 rpm, traverse speed at 40 mm/ min and axial load at 8 KN. It was found that the axial force had the maximum contribution of 35% followed by traverse speed and spindle speed of 25% and 12% respectively. The effect of process parameters were evaluated using ANOVA and S/N ratio of robust design. It was observed that the axial force exhibits more influence on tensile strength followed by traverse speed and tool rotation speed.

A.K. Lakshminarayanan, V. Balasubramanian [5] have tested the adequacy of the developed model by using the analysis of variance (ANOVA) technique and the results of second order response surface model fitting in the form of analysis of variance (ANOVA) are given in Table 6. The determination coefficient (R^2) indicates the goodness of fit for the model.

It has been observed from ANOVA the value of the determination coefficient (R^2=0.969 98) indicates that only less than 3% of the total variations are not explained by the model. The value of adjusted determination coefficient (adjusted R2=0.953 9) is also high, which indicates a high significance of the model. Predicted R^2 is also in a good agreement with the adjusted R^2. Adequate precision compares the range of predicted values at the design points to the average prediction error. At the same time a relatively lower value of the coefficient of variation (CV=1.52) indicates improved precision and reliability of the conducted experiments.

The value of probability >F in Table 6 for model is less than 0.05, which indicates that the model is significant. In the same way, rotational speed (N), welding speed(S) and axial force (F), interaction effect of rotational speed with welding speed, interaction effect of rotational speed with axial force (NF), interaction effect of welding speed with axial force (SF) and second order term of rotational speed (N), welding speed(S) and axial force (F) have significant effect. Lack of fit is non significant as it is desired. All the above consideration indicates an excellent adequacy of the regression model. Each observed value is compared with the predicted value calculated from the model.

D. Response Surface Methodology

Response surface methodology (RSM) is an interaction of mathematical and statistical techniques for modelling and optimizing the response variable models which several independent variables influence a dependent variable or response and the goal is to optimize the response.

RAJAKUMAR et al [14] proposed models using RSM to investigate the effect of FSW process parameters and weld parameters on the tensile strength of AA7075 aluminum alloy. In this work, an empirical relationship was developed relating FSW process parameters and tensile strength of the joints using statistical tools such as design of experiments, analysis of variance, and regression analysis. The developed empirical relationship can be effectively used to predict the tensile strength of FSW joints at the 95% confidence level.

TABLE 6. ANOVA RESULTS FOR TENSILE STRENGTH (ONLY SIGNIFICANT TERMS)

Source	Sum of squares	df	Mean square	F value	p-value probability>F
Model	44 763.17	9	5 307.02	342.33	<0.000 1
Rotational speed, N	2 722.50	1	2 722.50	175.61	<0.000 1
Welding speed, S	280.90	1	280.90	18.12	0.001 7
Axial force, F	250.00	1	250.00	16.13	0.002 5
NS	162.00	1	162.00	10.45	0.009 0
NF	612.50	1	612.50	39.51	<0.000 1
SF	162.00	1	162.00	10.45	0.009 0
N^2	3 483.46	1	3 483.46	224.70	<0.000 1
S^2	9 440.46	1	9 440.46	608.95	<0.000 1
F^2	402.02	1	402.02	25.93	0.000 5
Residual	155.03	10	15.50		
Lack of fit	113.03	5	22.61	2.69	0.150 6
Pure error	42.00	5	8.40		
Corrected total	47 918.20	19			

Standard deviation	3.94	R^2=0.969 9
Mean	258.85	Adjusted R^2=0.953 9
Coefficient of variation	1.52	Predicted R^2=0.952 2
Press	758.28	Adequate R^2=50.94 0

Elatharasan et al [15] in their research study, experimental analysis of process parameters of friction stir welding and its optimization. They identified different process parameters like tool rotational speed, welding speed and axial force that have significant role in deciding joint characteristics on an aluminum alloy. They have adopted Response Surface Methodology (RSM) and ANOVA for the optimization of process parameters. The outcomes of the experimentation are ultimate tensile strength, yield strength increased with increase in tool rotational speed, welding speed and tool axial force. The percentage of total elongation increased with increase in rotational speeds and axial force but decreased when there is increase in welding speed continuously. The results documented as maximum tensile strength is 197.50MPa, yield strength is 175.25MPa, percentage of total elongation is 6.96 was exhibited by the friction stir welding joints fabricated with optimized parameters of 1199rpm rotational speed, 30mm/min welding speed and 9 KN axial force.

III. CONCLUSION

The Taguchi optimization method is an efficient quality improvement tool that has been receiving attention in several engineering problems, owing to its simplicity and minimal optimization cost requirement based on the concept of orthogonal arrays. The use of trial and error, full factorial, and heuristic search methods such as GA for large-scale optimization problems can be prohibitive due to the high computation times associated with complex simulations/experiments.

The predictive ANN model is found to be capable of better predictions of tensile strength within the range that they had been trained. The results of the ANN model indicate it is much more robust and accurate in estimating the values of tensile strength when compared with the response surface model.

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