MULTI-OBJECTIVE OPTIMIZATION OF FSW PROCESS PARAMETER USING MOORA METHOD

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Abstract
Friction Stir Welding [FSW] is a solid state joining process which uses a third body non-consumable tool for joining of two flaying surfaces. There are various parameters such as welding speed, rotational speed, shoulder diameter, axial load and many more which affects the quality of welded joint. The aim of present study is to optimize the process parameter for FSW of aluminum alloy AA 2014-T6. L18 orthogonal array with 3 levels of process parameter i.e. rotational speed, welding speed and shoulder diameter are adopted. Based on various combinations of process parameters experiments are performed. Three rotational speed of tool are 710 rpm, 1000 rpm and 1400 rpm while welding speed are taken as 80mm/min, 100 mm/min and 125 mm/min. Shoulder diameter of tool are taken as 15mm, 17mm and 19mm. These process parameters are optimized such that maximum tensile strength and hardness in nugget zone with minimum power consumption is obtained. For optimization purpose, Multi-Objective Optimization on the basis of Ratio Analysis [MOORA] is implemented. For obtaining weightage of various responses Principal Component Analysis (PCA) is used. Optimization results for present study obtained from MOORA method showed that experiments preformed with rotational speed of 1000 rpm, welding speed of 100 mm/min and shoulder diameter of 17 mm will result in higher tensile strength and hardness with lower power consumption.

Keywords:Friction Stir Welding [FSW], decision making, MOORA Method, Multi-Objective Optimization

I. Introduction

Friction Stir Welding (FSW) is a solid state joining process invented in 1991 [1] at The Welding Institute, Cambridge, UK. It uses a non-consumable rotating tool for joining of two flaying surfaces. FSW involves basically four steps, plunge in period, dwell period, welding period, and plunge out period. During plunge in period non consumable rotating tool is inserted at the weld line until the top surface of plate is in contact with bottom surface of shoulder. Once the tool is inserted, a dwell period of predetermined period is provided which enables the plastic deformation of material to be welded. After dwell period, tool is provided movement in transverse direction along the joint line which results in joining of two plates without melting.

The movement of tool along transverse direction depends on the length of joint line. After completion of welding the tool is retracted from the joint line leaving behind the hole. In the whole process tool serves as major heat source which generates heat due to friction between tool shoulder and plates. There are various process parameters such as welding speed, rotational speed, shoulder diameter, axial load, tool profile and pin profile which affect the quality of welded joint. Also the mechanical properties such as tensile strength, hardness, percentage elongation etc depends upon the process parameters. Thus a common problem faced by various manufacturers is the control of input process parameter for obtaining good mechanical properties such as higher tensile strength, higher hardness, good wear resistance etc. Thus for every new welded products it is necessary to determine the major weld input parameter with their working range.

Decision making plays an important role in selecting optimum combination of process parameter form wide range of alternatives. There are various criteria for selection of optimum parameter which the decision maker has to consider. Thus there is a need of simple, systematic and logical method for obtaining selection criteria and their interrelations [2]. The aim of various decision making technique is to identify appropriate selection criteria and came out with most appropriate criteria as per the constraints. From various Multi-Objective Decision Making (MODM) methods, the Multi-Objective Optimization on the basis of Ratio Analysis (MOORA) was found to be appropriate method for present study. MODM is found to be simple and computationally easy which eliminates the unsuitable alternatives and selects the most suitable alternatives with provided constrains. Several literatures shows implementation of MOORA method for obtaining optimum alternatives in different applications. For evaluation of stakeholder's society design Brauers [3] had implemented these method for the first time. MOORA method has also been implemented for evaluating road design [4, 5], transition economy [6], evaluating contractor ranking [7], evaluating inner climate [8] and evaluating project management in transition economy [9]. Chakraborty [10, 11] has solved six different problems such as a flexible manufacturing system, industrial robot, the most suitable non-traditional machining process, computerized numerical control machine, rapid prototype and automated inspection system using MOORA method.

In the present study MOORA method has been implemented for multi-objective optimization of FSW process parameter. The desired input process parameters were rotational speed, welding speed and shoulder diameter. These process parameters were optimized for obtaining maximum tensile strength and hardness with minimum power consumption. The weightage of each response were obtained by performing Principal Component Analysis (PCA).

II. Experimental Procedure

The experiments described in present work were performed using vertical milling machine. The experiments consist of two plates heat treatable AA 2014-T6 having dimension of 300×50×5 mm each. Experiments were performed under immersed water condition. The orthogonal array used to determined optimal process parameter which results in best multiple-performance characteristic. To select an appropriate orthogonal array, total degrees of freedom need to be computed. The degrees of freedom are the number of comparisons to be made between design parameters. Total degree of freedom in present work is 9, i.e. 8 owing to three parameters with three levels [9]. In present work 18 experiments were carried out based on L18 orthogonal array with 3 levels of process parameter such as rotational speed, welding speed and shoulder diameter. Three rotational speed of tool were 710 rpm, 1000 rpm and 1400 rpm while welding speed were taken as 80 mm/min, 100 mm/min and 125 mm/min. Shoulder diameter of tool were taken as 15mm, 17mm and 19mm.

III. Principal Component Analysis

Principal component analysis basically describes structure of variance and covariance by linear combination of characteristic. Procedure involved for PCA is described as follows:

1. Original multiple quality characteristic array

X_i (j), i = 1, 2…m; j = 1, 2….n

$$X=\begin{bmatrix} X_1(1) & X_1(2)\ldots & X_1(n) \\ X_2(1) & X_2(2)\ldots & X_2(n) \\ X_n(1) & X_n(2)\ldots & X_n(n) \end{bmatrix} \quad (1)$$

Where m is the number of experiments and n is the number of characteristic. Here m=9 and n=3.

2. Correlational coefficient array

Correlational array can be defined as follows:

$$R_{jl} = \left(\frac{cov(x_i(j), x_i(l))}{\sigma_{x_i}(j) \times \sigma_{x_i}(l)}\right) \quad (2)$$

Where $cov(x_i(j), x_i(l))$ is the covariance of the sequences x_i (j) and x_i (l) and $\sigma_{x_i}(j), \sigma_{x_i}(l)$ is the standard deviation of the respective sequence.

3. Next step is to determine the Eigen value and Eigen vector from the below mention correlation coefficient array.

$$(R - \lambda_k I_m) V_{ik} = 0 \qquad (3)$$

Where λ_k is Eigen value, $\sum_{k=1}^{n} \lambda_k = n$, k=1, 2,……,n $V_{ik}=[a_{k1}, a_{k2},\ldots a_{kn}]^T$

4. Principal component

The uncorrelated principal component can be found out by using following formula:

$$Y_{mk} = \sum_{i=1}^{n} x_{im}(i) . V_{ik} \qquad (4)$$

Where Y_{m1} is called the first principal component, Y_{m2} is called the second principal component and so on.

The principal component should be aligned in decreasing order with respect to variance, and thus the first principal component Y_{m1} accounts for variance in the data.

IV. The MOORA Method

The process of simultaneous optimizing two or more conflicting attributes (objectives) subjected to certain constraints is known as Multi-objective optimization or Multi-Criteria or Multi-Attribute optimization [12]. MOORA method begins with decision matrix showing the performance of different alternatives w.r.t. various objectives.

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} & \cdots & X_{1n} \\ \vdots & & \ddots & & \vdots \\ X_{m1} & X_{m2} & X_{m3} & \cdots & X_{mn} \end{bmatrix} \qquad (5)$$

Where X_{ij} is the performance measure of i^{th} alternative on j^{th} attribute, m is the number of alternatives and n is the number of attributes. The next step involves development of ratio system in which each performance of an alternative on an attribute is compared to a denominator which is representative for all alternatives concerning that attributes. From the previous literature various ratio system such as total ratio, Scharlig ratio, Weitendorf ratio, Juttler ratio, Stopp ratio, Korth ratio etc has been reported. From various available it was concluded that the best choice is the square root of the sum of square of each alternative per attributes. The ratio will be expresses as:

$$X_{ij}^{*} = X_{ij} \Big/ \sqrt{\sum_{i=1}^{m} X_{ij}^{2}} \qquad (6)$$

Where j= 1, 2, 3,……n, X_{ij} will be dimensionless number belonging to the interval [0, 1]. It represents the normalized performance of i^{th} alternative on j^{th} attribute. The next step involve addition of these normalized performance in case of higher the better or subtraction of these normalized performance in case of lower the better. Thus the optimization problem became:

$$Y_i = \sum_{j=1}^{g} X_{ij}^{*} - \sum_{j=g+1}^{n} X_{ij}^{*} \qquad (7)$$

Where g is the number of attributes to be maximized and (n-g) is the number of attributes to be minimized. Y_i is the normalized assessment values of i^{th} alternative w.r.t all the attributes. Often it is observed that some attributes are given more weight age compare to other attributes. In such cases equation 7 can be written as:

$$Y_i = \sum_{j=1}^{g} W_j \times X_{ij}^{*} - \sum_{j=g+1}^{n} W_j \times X_{ij}^{*} \qquad (8)$$

Where W_j is the weight age of j^{th} attribute which can be determined by applying various methods. The obtained Y_i can have positive value or negative value depending upon the total of its maxima and minima in the decision matrix. These Y_i shows the final preferences. Thus the best alternative will have higher value of Y_i while the worst alternative will have lowest Y_i value.

V. Optimization of Process Parameters

Experiments were carried out based on various combination of rotational speed, welding speed and shoulder diameter. Tensile strength, power consumption and hardness of NZ were taken as response from various experiments. Base on L18 orthogonal matrix various combination of process parameter was obtained.

First step involves decision of the weight age of various responses. Weight age was calculated by using Principal Component Analysis (PCA). PCA was performed for responses and obtained Eigen values, Eigen vector and contribution are shown in below table I to table III. Table IV shows the combination of various process parameters along with their respective responses.

TABLE I. EIGEN VALUE AND VARIATION FROM PCA

	F1	F2	F3
Eigenvalue	2.08	0.87	0.04
Variability (%)	69.33	29.31	1.35
Cumulative %	69.33	98.64	100.00

TABLE II. EIGEN VECTOR FOR VARIOUS VECTORS

	F1	F2	F3
Tensile Strength	0.66	0.24	-0.70
Power Consumption	-0.31	0.94	0.03
Hardness	0.67	0.20	0.71

TABLE III. EIGEN VECTOR FOR VARIOUS VECTORS

	F1	F2	F3
Tensile Strength	44.51	31.66	34.58
Power Consumption	10.11	66.84	8.53
Hardness	45.36	1.48	56.89

TABLE IV. VARIOUS COMBINATION OF PROCESS PARAMTER AND THEIR CORRESPONDING RESPONSES

	Process Parameter			**Responses**		
Trial No.	**Rotational Speed (rpm)**	**Welding Speed (mm/min)**	**Shoulder Diameter (mm)**	**Tensile Strength (MPa)**	**Power Consumption (Watt)**	**Hardness in NZ (HV)**
1	710	80	15	217	1225	126
2	710	100	17	298	1260	136
3	710	125	19	254	1430	132
4	1000	80	15	245	1248	131
5	**1000**	**100**	**17**	**332**	**1632**	**139**
6	1000	125	19	232	1536	130
7	1400	80	17	283	1584	134
8	1400	100	19	303	1632	136
9	1400	125	15	235	1490	130
10	710	80	19	254	1340	131
11	710	100	15	229	1152	128
12	710	125	17	240	1296	129
13	1000	80	17	283	1590	136
14	1000	100	19	224	1525	127
15	1000	125	15	264	1296	134
16	1400	80	19	261	1545	131
17	1400	100	15	274	1440	130
18	1400	125	17	297	1488	135
$\sum_{i=1}^{m} x_{ij}^2$				1257529	37116359	313583
$\sqrt{\sum_{i=1}^{m} x_{ij}^2}$				1121.39	6092.32	559.58

Table V also shows the normalized performance score of each attributes which were obtained using equation 6. Based on the normalized performance score and obtained weight age of each response, normalized assessment value of each attributes were calculated using equations 8. Table V also shows the outcome of the MOORA method which provides ranking of each attributes based on the normalized assessment value.

TABLE V. NORMALIZED DECISION-MAKING MATRIX AND RESULTS OF MULTI-OBJECTIVE ANALYSIS

Trial No.	**Tensile Strength (MPa)**	**Power Consumption (Watt)**	**Hardness in NZ (HV)**	$\bar{Y}$	**Rank**
1	0.1935	0.2011	0.2250	0.1680	17
2	0.2657	0.2068	0.2429	0.2076	2
3	0.2265	0.2347	0.2357	0.1841	11
4	0.2185	0.2048	0.2339	0.1827	12
5	**0.2961**	**0.2679**	**0.2482**	**0.2174**	**1**

6	0.2069	0.2521	0.2321	0.1720	16
7	0.2524	0.2600	0.2393	0.1947	6
8	0.2702	0.2679	0.2429	0.2034	3
9	0.2096	0.2446	0.2321	0.1739	15
10	0.2265	0.2199	0.2339	0.1848	9
11	0.2042	0.1891	0.2286	0.1755	14
12	0.2140	0.2127	0.2304	0.1783	13
13	0.2524	0.2610	0.2429	0.1962	5
14	0.1998	0.2503	0.2268	0.1666	18
15	0.2354	0.2127	0.2393	0.1919	7
16	0.2327	0.2536	0.2339	0.1842	10
17	0.2443	0.2364	0.2321	0.1903	8
18	0.2648	0.2442	0.2411	0.2026	4

VI. Result and Discussion

From table V it can be seen that the trial 05 has higher normalized assessment value compared to other attributes. Thus it can be said that for rotational speed of 1000 rpm, welding speed of 100 mm/min and shoulder diameter of 17mm will result in tensile strength of 332 MPa, hardness of 139 HV and power consumption of 1632 Watt. Lower rotational speed will result in lower heat generation and thus at lower rotational speed defects such as void, tunnel defect will occur which ultimately reduces the mechanical properties of welded joint. Also at the higher rotational speed, heat generation will be higher which will result in dissolution of strengthening precipitates in various zones. Also at higher rotational speed power consolidation of material will result in formation of defects. Thus due to these reasons higher rotational speed will result in reduction of mechanical properties. Lower welding speed will result in higher heat generation and thus will cause dissolution of strengthening precipitation and reduction of mechanical properties. For higher welding speed insufficient heat will be generated which causes poor consolidation of material, leading to formation of defects in weld zone and reduction of mechanical properties. Lower shoulder diameter will result in insufficient heat generation which causes defect in weld joint and thus reduces mechanical properties of welded joint. On the other hand higher shoulder diameter will causes excessive heat generation which will result in dissolution of strengthening precipitates and thus will cause reduction in mechanical properties of welded joint. Due to these reasons rotational speed of 1000 rpm, welding speed of 100 mm/min and shoulder diameter of 17 mm will result in optimum value of tensile strength, hardness in NZ and power consumption.

VII. Conclusion

For optimizing process parameters of Friction Stir Welding process (FSW), experiments were performed in immersed water condition. Various combination of process parameter were obtained using L18 orthogonal array. By using Principal Component Analysis (PCA) it was observed that hardness was having maximum weightage of 45.36 % which was close to the weight of tensile strength which was 44.51%. Power consumption was found to have lowest weightage of 10.11%. By using Multi-Objective Optimization based on Ratio Analysis (MOORA) optimum process parameter were obtained which results in maximization of tensile strength and hardness with lower power consumption. Obtained optimum process parameter were rotational speed of 1000 rpm, welding speed of 100 mm/min and shoulder diameter of 17 mm. For these combinations of process parameter obtained tensile strength, hardness and power consumption was 332 MPa, 139 HV and 1632 Watt respectively.

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