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Procedia Engineering 38 (2012) 49 – 55

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Modeling, Optimization and Computing (ICMOC 2012)

Optimizations of friction stir welding process parameters for the welding of Al-B_4C composite plates using generalized reduced gradient method

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Abstract

Now a days Friction stir Welding (FSW) has become very popular for joining of aluminium alloys and aluminium based composites. FSW produced the effective joints on the Metal matrix composites (MMCs) without defects like porosity, interfacial chemical reactions, reinforcement segregation etc., The desired mechanical properties of the weld can be achieved, depends on the FSW parameters such as rotational speed (N), welding speed (S), axial force (F) and the reinforcement content (%R) in the MMCs. In this study, a mathematical model was developed to predict the tensile strength friction stir welded Al/B_4C joints using SYSTAT software. The central composite design of four factors and five levels has been used to conduct the experiments. The optimal process parameters were estimated from the developed regression equation using Generalized Reduced Gradient (GRG) method.

Key words: FSW process; Al/B_4C Composites; Methematical model.

1. Introduction

In nuclear industries, Al-B_4C composites possess a special capability to absorb thermal neutrons. Boron and metalmic are currently used as neutron shielding material in nuclear power plants [1, 2]. The fabrication of durable joint on MMCs by fusion welding process evidenced the limitation on the

Nomenclature

N	rotational speed	S	welding speed
F	axial force	R	% of reinforcement

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doi:10.1016/j.proeng.2012.06.008

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mechanical properties. Hence a solid state welding is needed for joining of MMCs. Friction Stir welding is a solid state welding technique invented by TWI [3]. During the process a nonconsumable rotating tool moves along the weld line, generating the frictional heat and plasticized material to weld. The FSW parameters such as tool rotational speed (N), Welding speed (S) and axial force (F) are influencing the mechanical properties of the composite joints. In order to produce an effective tensile strength on MMC joints, the optimization of welding parameters is highly important.

It has been reported that the tensile strength of friction stir welded AA 6061 plates were influenced by welding parameters such as tool rotational speed, welding speed, axial force and tool pin profile [4]. S.J. Vijay et.al[5] reported that the effect of various pin profiles on mechanical properties of AL-10 wt.% TiB_2 composite joint and it is found that joints welded with straight square pin profile produced better tensile strength compared to the other pin profiles. In this study, a mathematical model for predicting the tensile strength of Al-B_4C composites joint were developed by incorporating the process parameters such as tool rotational speed (N), welding speed (S), axial force (F) and % of reinforcement(R) using SYSTAT software and it is optimized to maximize the tensile strength.

2. Experimental Procedure

The material used in this study is AA (6061)-B_4C composites. The chemical composition of base metal is shown in Table 1. MMCs having different weight percentage of B_4C reinforcements (4 to 12 at a step of 2) were fabricated by modified stir casting route. The details of fabrication are available in our earlier publication [6]. The typical produced stir cast composite is shown in Fig. 1. The plates of size 100 mm x 50 mm x 6 mm were obtained from the fabricated composite and used for welding. The tool made of High Carbon High Chromium (HCHCr) steel tool having square pin profile was used. The dimension of fabricated tool is shown in Fig. 2. A specially designed and fabricated FSW machine has been used to fabricate the joints. The working ranges were set by conducting the trail run and are shown in Table 2. Four factors (N, S, F and R) and five levels (-2 to +2) central composite design have been selected. The upper limit of a parameter was coded as +2 and its lower limit was coded as -2. The intermediate coded values can be calculated from the relationship [7]

$$X_i = 2[2X-(X_{max}+X_{min})]/(X_{max}-X_{min}). \qquad \text{(Eq 1)}$$

Where X_i be the required coded value of a variable X; X be the any value of the variable from X_{min} to X_{max}; X_{min} be the lower level of the variable; X_{max} be the upper level of the variable. The developed design matrix is shown in Table 3. As per the design matrix, 31 butt joints were fabricated using FSW machine. The tensile specimens were prepared from each of the welded plates obtained as per ASTM E-08 standards and evaluated using a computerized Universal Tensile Testing Machine (TUE-C-1000).

Table 1. Chemical composition of Aluminum alloy (6061-T6)

Elements	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	Al
% by weight	0.95	0.54	0.22	0.17	0.13	0.09	0.08	0.01	Balance

Fig. 1. A typical stir casted AA6061-B_4C Composite

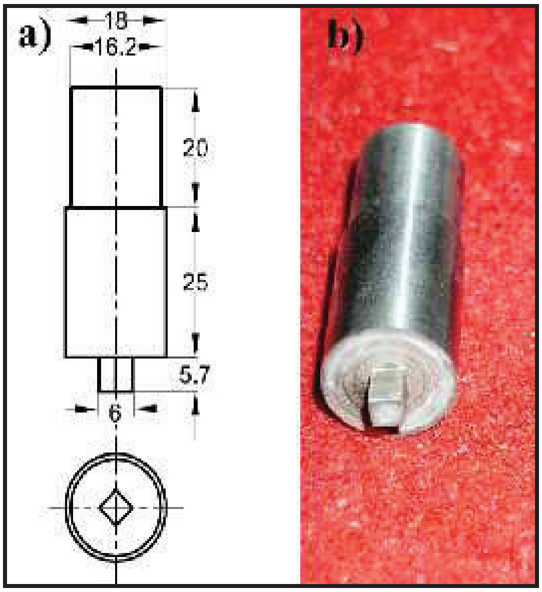

Fig. 2. The dimension of fabricated tool

Table 2. FSW process parameters range and levels

Process parameter	Notation	Unit	Levels				
			-2	-1	0	1	2
Rotational speed	N	rpm	800	900	1000	1100	1200
Welding speed	S	mm/s	0.3	0.8	1.3	1.8	2.3
Axial force	F	kN	6	8	10	12	14
Reinforcement	R	wt.%	4	6	8	10	12

3. Development of a mathematical model

A procedure based on regression was used to develop a mathematical model. The response surface function representing ultimate tensile strength (UTS) of friction stir welded Al-B_4C joints can be expressed as

$$UTS = f(N, S, F, R) \qquad \text{(Eq 2)}$$

The second order polynomial (regression) equation used to represent the response surface (Y) can be expressed as

$$\mathbf{Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{\substack{i=1 \\ i \neq j}}^{k} b_{ij} X_i X_j} \qquad \text{(Eq 3)}$$

Table 3. Design matrix with experimental results

Trial Run	Design matrix Process parameters				Estimated UTS (MPa)
	N	S	F	R	
1	-1	-1	-1	-1	146.2
2	1	-1	-1	-1	137.1
3	-1	1	-1	-1	131.5
4	1	1	-1	-1	139.3
5	-1	-1	1	-1	148.8
6	1	-1	1	-1	142.2
7	-1	1	1	-1	150.5
8	1	1	1	-1	141.3
9	-1	-1	-1	1	163.9
10	1	-1	-1	1	154.2
11	-1	1	-1	1	165.7
12	1	1	-1	1	159.3
13	-1	-1	1	1	142.9
14	1	-1	1	1	151.4
15	-1	1	1	1	158.2
16	1	1	1	1	149.3
17	-2	0	0	0	124.7
18	2	0	0	0	131.5
19	0	-2	0	0	121.1
20	0	2	0	0	136.2
21	0	0	-2	0	128.8
22	0	0	2	0	138.3
23	0	0	0	-2	175.5
24	0	0	0	2	203.1
25	0	0	0	0	188.5
26	0	0	0	0	181.7
27	0	0	0	0	179.8
28	0	0	0	0	185.4
29	0	0	0	0	183.2
30	0	0	0	0	186.5
31	0	0	0	0	185.1

For four factors, the selected polynomial could be expressed as

$$UTS = b_0 + b_1 N + b_2 S + b_3 F + b_4 R + b_{11} N^2 + b_{22} S^2 + b_{33} F^2 + b_{44} R^2 + b_{12} NS + b_{13} NF + b_{14} NR + b_{23} SF + b_{24} SR + b_{34} FR \quad \text{(Eq 4)}$$

Where b_0 is the average of responses and $b_1, b_2, \ldots b_{34}$ are the response coefficients that depend on the main and interaction effects of the parameters. All the coefficients were evaluated and initial model was developed using a Statistical software package (SYSTAT 12). After determining the significant coefficients, the final model was developed by eliminating least and insignificant terms. The developed mathematical model for predicting the tensile strength of FSW joints is given below.

$$UTS = 186.262 - 0.833N + 1.608S + 0.267F + 6.800R - 13.596N^2 - 13.459S^2 - 12.234F^2 - 4.375FR \quad \text{(Eq 5)}$$

The developed model was checked for the adequacy by analysis of variance (ANOVA) and the results are shown in Tables 4 and 5. The value of R^2 is 0.951 and adjusted R^2 is 0.933. Higher value of R^2 indicates that the regression model is quite adequate [8].

Table 4. Statistical result for the developed model

Response	Multiple R	Squared Multiple R	Adjusted squared Multiple R	Standard Error of Estimate
UTS	0.975	0.951	0.933	5.744

Table 5. Analysis of Variance

Response	Source	Sum of square	Degree of freedom	Mean square	Calculated F-ratio	Tabulated F-ratio
UTS	Regression	14,013.65	8	1,751.71	53.084	2.4
	Residual	725.968	22	32.999		

4. FSW Parameters optimization

The developed model was used for optimizing the friction stir welding parameters to obtain maximum tensile strength using GRG method. The optimization is a nonlinear constrained maximization problem and is solved using GRG which is embedded in MS Excel solver module. The results of optimized FSW parameters are as follows.

Rotational speed = 996.936 rpm;

Welding speed = 1.329 mm/s;

Axial force = 9.306 kN; the reinforcement = 12 % and

The predicted tensile strength = 201.39 MPa.

The FSW process parameters were set near to the predicted optimum process parameter values and a conformity test was conducted. The value of UTS is 208.2 MPa. The percentage of error is 3.381.It confirm the predicted results with the observed optimum UTS with high accuracy.

5. Summary

B_4C reinforced aluminum matrix composites are widely used in the fabrication of high strength structures and neutron absorbing materials in the nuclear industry. The joining of MMCs by conventional welding process brings certain limits on the mechanical properties and creates some weld defects like porosity, solidification shrinkages and deleterious reactions with reinforcement etc. Hence solid state welding (ie FSW) is preferred to joint those MMCs. But the mechanical properties of friction stir welded Al- B_4C composite joints are highly depends on the process parameters. Hence a mathematical model was developed by incorporating all parameters (tool rotational speed (N), welding speed (S), axial force (F) and percentage of reinforcement (R) to predict the UTS of composite joint. Using GRG method available in the MS Excel solver module, the optimum process parameters were estimated and it is reported.

Acknowledgement

The authors gratefully thank the Management and Welding Research Cell, Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore, India for providing the welding equipment and wear testing equipment facilities to carry out this research work. The authors wish to express thanks to Naval Research Board, DRDO, Govt. of INDIA, vide funded project; Ref. no. DNRD/05/4003/NRB/85 dt 30.10.2006 for sponsoring FSW machine. The authors are grateful to Mr. I.Dinaharan for the technical support offered to execute the research work.

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