Establishing Empirical Relation For Microhardness During Solid State Joining of Mg Alloys

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Abstract

Friction stir welding (FSW) is an appropriate technique for fabricating flawless welds, especially for light weight alloys. The various input parameters play significant role for the resulting welds and determining the mechanical and metallurgical features of fabricated joints. In the current work, the microhardness observed for FSWed AZ31B Mg alloy is represented. The empirical relationship between the process variables and the output responses i.e. microhardness were established. The weld settings to maximize the microhardness were optimized and reported.

Keywords:

Friction stir welding, microhardness, empirical

1 Introduction:

Magnesium and its alloys are in great demand due to many advantages like lightest of all structural metal alloys available, high strength. This makes them suitable for a variety of applications especially in auto industry which will lead to higher fuel savings and emission reductions [1-3]. Apart from auto industry, magnesium alloys are also in demand in marine as well as aero industry. Due to this demand, joining of these alloys also becomes a point of significance. Traditional welding techniques like Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW) leads to certain defects like porosity and hot cracks [4-5]. Also it is difficult to use magnesium alloy wires as filling electrodes.

FSWis a solid state joining technique [6], is capable of joining magnesium alloys under solid state and thus eliminates the defects related to solidification. Good quality welds can be achieved using FSW since no filler material is required, so the metallurgical harms are eliminated [7-9]. Rose et al. [5] evaluated tension properties of FSWed joints for AZ61 magnesium at 1200 rpm and varying welding speeds. They concluded that there is a significant influence of welding speed on the development of flaws in the weld nugget and also the entire properties of the welded specimen is affected. Motalleb et al. [1] investigated the effects of changed tool pin profiles viz; simple cylindrical, screw threaded cylindrical and taper on the resulting

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characteristics of FSWed AZ31B Mg. Tapered shape was found to be best as it resulted in superior mechanical properties.

The input process parameter selection is a challenging task for the welder/manufacturer for getting the sound joints. Mostly it is trial and error selection which is a very tedious task; it also depends upon operator skill [10]. It may happen that optimized combinations of input process parameters are not chosen which can yield best output properties. For the accurate prediction of input parameters, there are several optimization techniques available such as Response Surface Methodology (RSM). Getting optimized parameters which will yield superior weld quality in addition with improved metallurgical and mechanical properties will save a lot of labor time and effort [11]. Microhardness is one of the most important properties of welded region which is required to be improved so as to improve the surface properties. In the current work, the microhardness is evaluated for the welded joints' performance. Furthermore, modeling and optimization of the microhardness is employed to yield best set of input parameters. The empirical relationship between input parameters i.e. tool rpm, travel speed and plunge and the response i.e. microhardness is developed using RSM. The target for developing the empirical relations is to maximize the microhardness and generate optimal welding conditions.

2 Experimentation

2.1 Joints fabrication and Specimen preparation

The magnesium AZ31B alloy 6mm thick plates, used as base material were cut into the required dimensions by machining process to prepare the initial butt joint configuration as shown in Fig. 1A. The chemical composition of the material is 2.87% Al, 0.94% Zn, 0.3% Mn, 0.08% Si, 0.005% Cu and balance Mg. The joints were fabricated on a computerized numerical controlled vertical milling center at varying tool rpm, travel speed and plunge depth. The tool used for FSW was made of H13 tool steel with a conical pin profile and is shown in Fig. 1B. Figure 2 represents friction stir welded specimen. The optical micrographs were captured using a LEICA optical microscope with analysis core installed software. The equivalent grain circular diameter and average length of the grains were measured and analyzed.

The results represented in the current research are the average of three different images taken at three different locations in the welded specimens. The microhardness of the welded joints were evaluated in transverse direction along the centerline both in advancing as well as retreating side.

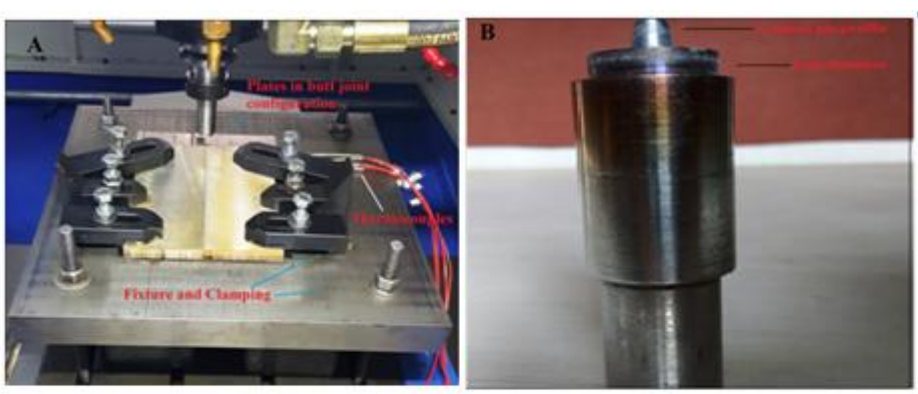

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Fig. 1: A) FSW set up with abutted and clamped magnesium alloy plates, B) Conical tool used for conducting FSW experiments.

Fig. 2: Friction stir welded specimen

2.2 Planning of Experiments: Design matrix development

There are many modeling and optimization systems available such as Factorial designs, Taguchi design, Artificial Neural networks, Response surface methodology, Genetic algorithms etc. [11-13] Response Surface Methodology (RSM) was preferred in the present work because of advantages like the less computational, optimization is done through the model, high accuracy level and the understanding and availability is easy [15]. RSM is a collection of mathematical and statistical systems used for modeling of experimental problems that checks the outcome of several input parameters on the resulting output parameters with the target of optimizing these output parameters [14]. RSM follows the following procedure:

a) Preliminary experimentation is done.

b) As per preliminary experimentation and output responses quality characteristics, input parameters are designed.

c) After setting the input parameters, experimental design is finalized

d) Regression analysis and Analysis of Variance (ANOVA) to be carried out.

e) On getting the model which is significant, optimal settings are to be evaluated.

f) Confirmation of the predicted experimental values on these optimal settings.

g) If the model is not significant, screening out the input variables and repetition of the process from step c.

Tunnel defects and voids in the welded samples can be observed during friction stir welding and are expected to occur at certain parameters. It is therefore necessary to carry out the preliminary experiment carefully in order to obtain a variety of input variables that yield free defect joints. The selected input variables were rotational speed (1400, 1500, 1600 rpm), travel speed (80, 100, 120 mm/min) and plunge depth (0.3, 0.35, 0.4mm) in the present work. The other input variable s that influence the output response such as layout of the tool, force, etc. have been maintained c onstantly.

Experimental design approaches are defined by commonly used system modeling and evaluation as total factorial design, partial design and central composite design (CCD).
CCD delivers full data as a 3level factorial design which needs fewer experiment / test numbers c ompared to full factorial analysis.

Different process parameters along with the chosen levels are represented in Table 1. As per central composite face centered design, total 20 experiments are to be performed with 3 input variables and 3 levels. All the experiments were conducted in line with the final set of experimental design.

3. Results and Discussion

As per the design of experiments, total 20 experiments were carried out. The maximum value of microhardness achieved in the weld nugget is represented in Table 1. Data analysis demands that the prepared mathematical model be tested for fitness. For evaluating the adequacy of the developed mathematical model, significance testing of regression model, model coefficients and lack of fit (LOF) are to be evaluated, for which ANOVA is performed [11].

3.1 Development of mathematical model

Microhardness of the welded joints was measured in the transverse direction along the centerline both in advancing as well as retreating side using Vicker's microhardness tester. The experimental results of maximum hardness value obtained in the weld nugget are shown in Table 1. The experimental results obtained for microhardness of the friction stir welded AZ31B magnesium alloy, as represented in table 1, are used to develop the mathematical model for predicting microhardness of stir zone of the welded specimens. Microhardness of FSW joints is a function of rpm, travel speed and plunge.

The mathematical modeling for microhardness as per the experimental results is done at 95% level of confidence and the fitted summary for microhardness with no transformation is shown in Tables 2 to 3. Table 2 represents the contribution of the terms of rising complexity in the form of sequential sum of squares. It is clearly observed from the table that linear, 2FI and cubic models do not have significant terms and therefore these cannot be employed. The sequential sum of squares results in Table 2 clearly shows only quadratic model consists of significant terms, and therefore it is suggested for modeling impact energy as a response. The linear and 2Fi models are not significant and the cubic model is aliased. Table 3 represents the summary of lack of fit results for different models. It is clear from the table that lack of fit is insignificant only for the quadratic model and for rest of the models, it is significant. Moreover, the R^2, adjusted R^2 and predicted R^2 values are in the acceptable range in case of quadratic model only.

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Table 1: Experimental design with output response

Experiment	Type	Factor1 A: Tool RPM	Factor2 B: Tool Travel speed mm/min	Factor3 C: Plunge mm	Response : Microhardness HV
1	Factorial	1400	80	0.3	76.4
2	Factorial	1600	80	0.3	81.4
3	Factorial	1400	120	0.3	70.6
4	Factorial	1600	120	0.3	80.4
5	Factorial	1400	80	0.4	77.6
6	Factorial	1600	80	0.4	74.2
7	Factorial	1400	120	0.4	79.8
8	Factorial	1600	120	0.4	82.6
9	Axial	1400	100	0.35	70.2
10	Axial	1600	100	0.35	73.8
11	Axial	1500	80	0.35	74.2
12	Axial	1500	120	0.35	70
13	Axial	1500	100	0.3	71.2
14	Axial	1500	100	0.4	74.8
15	Centre	1500	100	0.35	64.2
16	Centre	1500	100	0.35	65.8
17	Centre	1500	100	0.35	68.4
18	Centre	1500	100	0.35	68
19	Centre	1500	100	0.35	67.4
20	Centre	1500	100	0.35	64

It is concluded as per the data in tables 2-3 that the quadratic model is the best suited out of all the mentioned models for modeling of microhardness of the welded specimens for the factors and their levels under consideration. The final empirical quadratic model prepared to predict the microhardness using all the significant terms is represented in equation 1.

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Vol-22-Issue-17-September-2019

The mathematical model is prepared after backward elimination of insignificant terms at a confidence level of 95%. Equation 1 represents the mathematical model in the coded terms:

$$Microhardness = +82.70 + 2.86*A - 1.38*B + 1.62*C - 2.40*A*C + 1.05*B*C - 5.42*A^2 - 8.23*B^2 \quad (1)$$

Table 2: Sequential model SS for microhardness

Source	Sum of Squares	dof	Mean Square	F Value	p-value Prob > F	
Mean vs Total	1.15E+05	1	1.15E+05			
Linear vs Mean	127.08	3	42.36	0.82	0.5022	
2FI vs Linear	56.52	3	18.84	0.32	0.8125	
Quadratic vs 2FI	754.66	3	251.55	153.29	< 0.0001	Suggested
Cubic vs Quadratic	9.98	4	2.49	2.33	0.1702	Aliased
Residual	6.43	6	1.07			
Total	1.16E+05	20	5805.51			

Table 3: LOF for microhardness

Source	SS	dof	Mean Square	F Value	p-value Prob > F	
Linear	823.95	11	74.9	103.08	< 0.0001	
2FI	767.43	8	95.93	132.01	< 0.0001	
Quadratic	12.78	5	2.56	3.52	0.0969	Suggested
Cubic	2.8	1	2.8	3.85	0.1069	Aliased
Pure Error	3.63	5	0.73			

3.2 Analysis of mathematical model:

The output of the quadratic regression equation for microhardness as (ANOVA) Analysis of Variance are represented in Table 5. ANOVA also tests adequacy of the developed model. The terms that are nor sifnificant are not considered. The interaction between factor C (plunge depth) and factor C (plunge depth) i.e. C^2 and the interaction of A (rpm) and factor B (welding speed) i.e. AB possess non-significant "P-values". The insignificant terms C^2 and AB which are removed from the model as well as ANOVA analysis, with their p value are shown in Table 4.

Table 5 represents the F-value that is 81.96 and the corresponding p value is <0.0001, which results into a significant model. The value for (LOF) F-value is 3.13 and for 'p' is 0.1137 that is insignificant and is accepted. The determination coefficient (R^2) as shown in table 5 is 0.9795 that means the model produced could explain 97.95 percent of the variation and only 2.05 percent of the vari ation can not be clarified, which confirms the consistency of the investigational data with the mo del's predicted data.
In fair accordance with the revised R^2 value of 0.9676, the expected R^2 value is 0.9176. The acce ptable accuracy value is 30.442 (greater than 4), confirming the relevant signal. The low value of CV i.e. 1.68 is is in the favour of the generated model.

The normal probability plot developed for the proposed empirical relation for impact energy for studentized residuals is represented in Fig. 3A. The figure shows t hat all the residuals are accumulated in a straight line, indicating that the errors are normally distr ibuted.
The experimental observations are compared and represented in Fig with the predicted values fro m the method. 3B. Such considerations reflect the excellent suitability of the microhardness regr ession model.

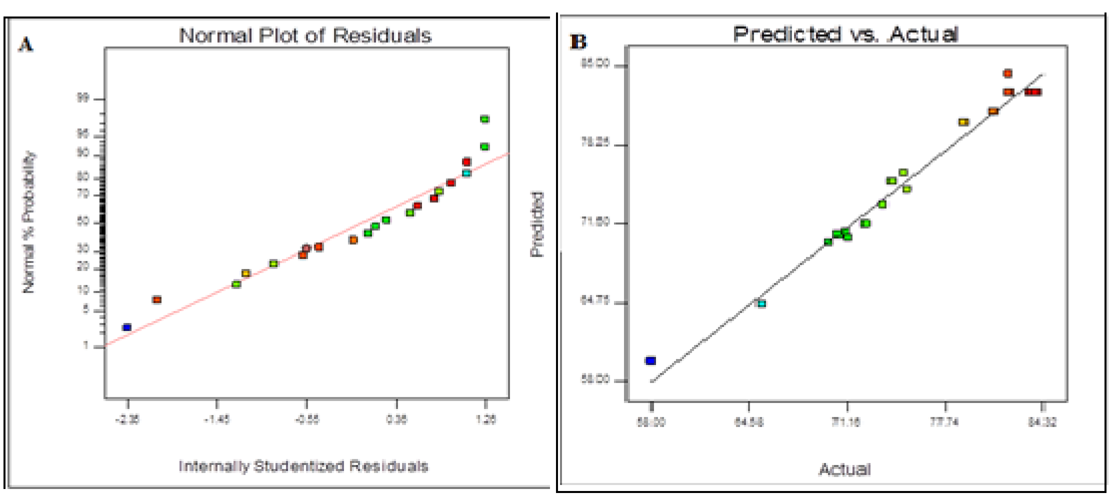

Fig. 3 **A)** Normal probability plots for microhardness, **B)** Comparison of actual and predicted values of microhardness

3.3 Effects of parameters on microhardness

The effect of each of the factors i.e. rotational speed, welding speed and plunge depth, individually, on the output response i.e microhardness can be estimated using perturbation graph as shown in Fig. 4A. The center of the design space (coded zero level of each factor) is chosen as the reference point for the plot revealed in Fig. 4A which represents a curvature for factors tool rpm (A), and tool travel speed (B). However for the third factor i.e. plunge depth (C), the plot is not a curve but a straight line. The straight line for factor C implies that microhardness is not much sensitive to plunge depth. The curvature of factor B is more than that of A which signifies more senstiveness of microhardness towards welding speed compared to rotational speed.

Table 4: Insignificant terms C^2 and AB removed from mathematical model and ANOVA table after backward elimination at 95% confidence level

Removed	**Coefficient Estimate**	**t for H0 Coeff=0**	**Prob > |t|**	**R-Squared**	**MSE**
C^2	-0.75	-0.97	0.3573	0.9812	1.63
AB	0.45	1	0.3403	0.9795	1.63

Table 5: ANOVA for response surface quadratic model for microhardness

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	935.11	7	133.59	81.96	< 0.0001	significant
A-Rotational Speed	81.8	1	81.8	50.19	< 0.0001	significant
B-Welding Speed	19.04	1	19.04	11.68	0.0051	significant
C-Plunge Depth	26.24	1	26.24	16.1	0.0017	significant
AC	46.08	1	46.08	28.27	0.0002	significant
BC	8.82	1	8.82	5.41	0.0383	significant
A^2	94.18	1	94.18	57.78	< 0.0001	significant
B^2	216.48	1	216.48	132.82	< 0.0001	significant
Residual	19.56	12	1.63			
Lack of Fit	15.92	7	2.27	3.13	0.1137	not significant
Pure Error	3.63	5	0.73			

Cor Total	954.67	19				
Std. Dev.	1.28			R-Squared	0.9795	
Mean	75.88			Adj R-Squared	0.9676	
C.V. %	1.68			Pred R-Squared	0.9176	
PRESS	78.63			Adeq Precision	30.442	

Increase in microhardness on increasing tool rpm (A) from low level of -1.0 to +0.3 could be judged from Fig. 4A. On further increase of factor A, there is a fall in the value of microhardness. However for factor B, there is a rise in the value of microhardness with increasing welding speed till center point, and then it falls steeply on further increase of welding speed. Hence, it is concluded from the pertrubation graph in Fig. 4A that the response (microhardness of the welded zone) is sensitive factors A and B but is least sensitive to the factor C.

The interaction on the response (microhardness) among variables A (tool rpm) and C (plunge de pth) is represented in Fig in the form of 3D surface graphs and contour plots. 4B, 4C. The 3D surface plot and contour plot of the interaction AC at the center level of B (welding speed = 100 mm/min) are shown in figures 4B and 4C respectively. It can be depicted from figures 4B and 4C that microhardness increases very steeply when the rotational speed is increased from lower level of 1400 rpm to about 1530 rpm. On further rise of rotational speed, there is a slight fall in the value of microhardness. The highest value achieved for response at 1530 rpm and 0.38mm plunge depth is about 83HV. On increasing the plunge depth, microhardness increases linearly. However, the increase in response is steep and much sensitive at lower rpm. At higher rpm also, there is a slight decrease in response and that too is linear but the variation in the values is not much significant

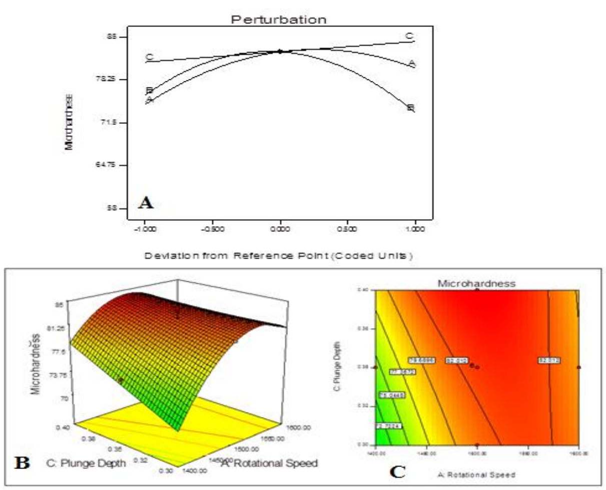

Fig. 4A: Pertrubation graph for microhardness, B) 3D surface plot of interaction AC with B at center level, C) Contour plot of AC with B at center level

Conclusion

Magnesium alloy AZ31B was friction stir welded at varying input process parameters i.e. tool rotational speed, travel speed and plunge depth. Microhardness was measured in the transverse direction from advancing side to retreating side. Mathematical model was developed for correlating output response i.e. microhardness to the input variables. Microstructure of the specimens was evaluated through optical microscopy. Following are the important conclusions:

1) Highest microhardness of 82.6 HV was observed at 1600rpm, 120mm/min and 0.4mm plunge depth.
2) The mathematical model was developed for microhardness. The output microhardness can be predicted at any value of rpm, travel speed and plunge.

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