Optimization of Friction Stir welding process parameters for joining ZM 21 to AZ 31 of dissimilar Magnesium alloys using Taguchi technique

S.Prasath, S.Vijayan, S.R.K. Rao

Joining of dissimilar Mg alloy plates, ZM21 to AZ31,was carried out using friction stir welding (FSW) process and the process parameters were optimized using Taguchi L9 orthogonal design of experiments. The rotational speed, tool geometry and axial load were the parameters taken into consideration. The optimum process parameters were determined with reference to tensile strength of the joint. The predicted optimal value of tensile strength was confirmed by conducting the confirmation run using optimum parameters. This study shows that defect free, high efficiency welded joints can be produced using a wide range of process parameters and recommends the levels of the process parameters for producing best joint tensile properties.

KEYWORDS: FSW - DISSIMILAR WELDING - MAGNESIUM ALLOYS AND OPTIMIZATION

INTRODUCTION

The application of light materials has gained its importance in automotive and aerospace industries in recent years. Magnesium and its alloys are considered to be super light weight construction materials [1]. Magnesium is approximately 30 % lighter than aluminium and four times lighter than steel with a density of 1.8 g/cm^3 [2]. The weldability of magnesium alloys is generally considered poor due to their thermal, electrical and oxidation characteristics. Magnesium oxide forms at elevated temperatures and Mg alloys are susceptible to weld cracks due to higher thermal conductivity and higher thermal expansion coefficient than ferrous metals [3]. The traditional welding methods will induce stress, pores, slag, splash and other defects [4]. Compared to fusion welding processes the solid state Friction Stir Welding (FSW) process offers many advantages such as no splash, no smoke, and no oxidation, and no shielding gas. Thus FSW is a suitable process for welding magnesium alloys [5]. In this investigation joining of dissimilar Mg alloys, ZM21to AZ31 plates was carried out using friction stir welding (FSW) process and the process parameters were optimized using Taguchi L9 orthogonal design of experiments.

S.Prasath
Mohamed Sathak A.J. College of Engineering, Chennai, Tamilnadu, India
sprasathme74@yahoo.com

S.Vijayan, S.R.Koteswara Rao
SSN College of Engineering, Chennai, Tamilnadu, India
vijayans@ssn.edu.in
sajjarkr@yahoo.com

FRICTION STIR WELDING (FSW)

FSW was invented at The Welding Institute (TWI) of United Kingdom in 1991 as a solid-state joining technique, and it was initially applied to aluminium alloys [6, 7]. Now it has been extended to magnesium and ferrous alloys also as FSW offers many advantages over the conventional fusion welding processes. The tool geometry, welding parameters, joint designs are the significant parameters which affect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution [8 -11].

The detailed FSW process parameters are listed below:

1. Rotational speed of the tool (rpm);
2. Welding speed or transverse speed (mm/s);
3. Axial load (kN);
4. Tool geometry:

(I) Tool shoulder diameter, D (mm);
(II) Pin diameter, d (mm);
(III) D/d ratio of tool;
(IV) Pin length (mm);
(V) Tool inclined angle.
(VI) Pin Profile

The FSW process parameters play a vital role in affecting the mechanical as well as the metallurgical properties of the weldment. The Rotational speed is one of the significant process parameters which tends to influence the translational velocity [12]. The temperature increases with increase in the rotational speed of the tool. At high tool rotational speed, high temperature is generated and slower cooling rate is experienced on the Friction Stir Processing (FSP) zone after welding [13].At lower speeds the heat input will be low which results in lack of stirring. At high welding speed the softened area becomes narrower, than that of low welding speed. When the welding speed is high, the heat input is low, which in turn results in faster cooling rate of the welded joints [14]. The defect free FSW joints are produced when the welding speed is slower than the critical value. The frictional heat generated on the surface of the work piece is directly proportionate to the applied axial load. The shoulder force is directly responsible for the plunge depth of the tool pin to the work piece. Two effects are responsible for the creation of material flow in the weld zone. First is the extrusion process, where the applied forces and the motion of the tool pin propel the material after it has undergone the plastic deformation. The second is due to the rotation of the pin that serves as the driving force for the flow [15].

Generally Friction stir welding of Magnesium alloys with good mechanical properties and uniform microstructure is quite difficult, as it has the closed packed hexagonal structure which results in the lack of slip plane during plastic processing. The sound FSW joint is achieved under optimized FSW process parameters [1] .The material flow during friction stir spot welding of AZ31 magnesium alloy is significantly influenced by tool rotation rate [16].

Lechosław Tuz et al concluded that the there is the strong relationship exists between the process parameters on the properties of the joints. Defect free FSW welded joints AZ 91 and AM Lite were produced when the welding speed is at 220 mm /min with 450 rpm as the spindle speed [5].The tool materials also found to one of the factors which affects the properties. The SS tool produces better mechanical properties and micro structure when compared to HSS in FSW of AZ 31.The rotational speed of 1200 rpm and the welding speed of 40 mm/min produces a sound joint. At lower rotational speed at 900 rpm defect welds were formed [17]. The effect of weld pitch i.e. ratio of welding speed to tool rotational speed (0.0020 mm/rev to 0.05 mm/rev) was examined on the mechanical and micro structural properties of friction stir welded joints of AZ31B-O Mg alloy and found a linear relationship exists between tensile strength and weld pitch was observed by Inderjeet Singh et al [18].

Friction Stir Weld quality of AZ 31 was found to be improved with increase in load applied, weld speed and rotation rate. The stress levels are higher on the retreating side. The grain growth is increasing in the processing parameters that promote heat generation. The temperature distribution is uniform along the weld length, whereas it is asymmetric between the advancing side and the retreating side [19]. Razal et al concluded that the axial forces influence the tensile properties of the FSW magnesium welds [24]. The voids are formed on the FSP zone at high rotational speed due to the release of the excessive materials to the upper surface. The rotational speed of the tool is varied from 1000 rpm to 2000 rpm in many literatures [16- 25].The tool pin profile also influences the flow at stir zone which significantly enhances the mechanical properties of the joints [8].After critically examining the literatures the rotational speed, axial load and tool profile were considered as the significant process parameters considered for optimisation and their levels were listed in the table 1.

Tab. 1 - Process parameters values and their three levels

Level	Rotational speed (rpm)	Tool Pin Profile (Shape)	Axial load (KN)
Symbol	A	B	C
Level 1	1700	Hexagonal	3.0
Level 2	1900	Square	3.5
Level 3	2100	Taper Cylindrical	4.0

TAGUCHI METHODOLOGY

Taguchi is considered one among the quality guru addresses the concepts of quality on both off line as well as on line quality. Off-line quality control refers to the improvement in quality in the product and process development stages and on line refers to monitor the current manufacturing process for the desired output. The steps involved in Taguchi optimization are

Step 1: Determine the quality characteristic to be optimized [10-11].
Step 2: Identify the noise factors and test conditions.
Step 3: Identify the control factors and their alternative levels.
Step 4: Design the matrix experiment and define the data analysis procedure.
Step 5: Conduct the matrix experiment.
Step 6: Analyze the data and determine optimum levels for control factors.
Step 7: Predict the performance at these levels.

The tensile strength of the dissimilar Friction Stir welded joints of ZM21to AZ31 is the quality function considered to be maximised. The repletion of the experiments will control the noise factors and the FSW process parameters (rotational speed, tool geometry and axial load) are the control factors and their levels were identified based on the literatures listed in the table 1.

SELECTION OF ORTHOGONAL ARRAY (OA)/DESIGNED MATRIX

The selection of which orthogonal array to use predominately depends on these items in order of priority:

1. The number of factors and interactions of interest
2. The number of levels for the factors of interest
3. The desired experimental resolution or cost limitations

As three levels and three factors are taken into consideration, L9 OA is used in this investigation. Only the main factor effects are taken into consideration and not the interactions. The degrees of freedom (dof) for each factor is 2(No of levels -1,ie 3-1=2) and therefore the total degrees of freedom will be 3x2=6.Generally the dof of the OA should be greater than the total dof of the factors. As the dof of L9 is 8 it can be suitable for the study.

EXPERIMENTAL PROCEDURE

Single pass butt welds were produced in 5 mm thick plates of dissimilar magnesium alloys ZM 21 and AZ 31 using indigenously designed friction stir welding machine. A cylindrical taper tool (M2 tool steel) of hardness 50 -55 VHN with shoulder diameter 15 mm and pin diameter 5 mm with three different profiles (Hexagonal, Square and Tapered Cylindrical) is used for this work is shown in figure 1. The length of the tool pin is 4.5 mm. The chemical composition and mechanical properties of the plate are given in the table 2and 3 respectively.

Tab. 2 - Chemical Composition of the Magnesium Alloys.

Material	Al	Mn	Zn	Mg
ZM 21	-	1	2	Remaining
AZ 31	3	-	1	Remaining

Tab. 3 - Mechanical properties of the Magnesium Alloys.

Base Metal	Yield Strength/Mpa	Ultimate Tensile strength/Mpa	% Elongation
ZM 21	106	173	5
AZ 31	196	262	11.8

The rolled plates of 5 mm thickness plate were cut into required shapes (300 mm x 150 mm) using shaper and milling machine. The mechanical clamps are used to clamp the plate in the work table of the machine. The butt joints were fabricated normal to the rolling direction. The experiments were conducted using parameters of the designed matrix. The American Society for Testing Materials (ASTM –E8) guidelines were followed for preparing the tensile test specimens. The wire cut EDM is used to cut the smooth profile tensile specimens and shown in figure 1. To minimize the machining error (noise) three specimens were prepared at each levels of the designed matrix. The 18 prepared tensile specimens were subjected to tensile test and its ultimate tensile strength is evaluated. The photograph of prepared tensile samples is shown in figure 2.The experiments were conducted according to the designed L9 OA. The following table no 4 will give the values of designed experimental layout.

a. Tapered Cylindrical **b. Square** **c. Hexagonal**

Fig. 1 - Tool Pin Profile of the FSW tool

Tab. 4 - L9 Designed Experimental Layout

Sl No	Input Parameter Coded Values			Input Parameter Uncoded Values		
	A	B	C	Rotational speed (rpm)	Tool Pin Profile (Shape)	Axial load (KN)
1	1	1	1	1700	Hexagonal	3.0
2	1	2	2	1700	Square	3.5
3	1	3	3	1700	Taper Cylindrical	4.0
4	2	1	2	1900	Hexagonal	3.5
5	2	2	3	1900	Square	4.0
6	3	3	1	1900	Taper Cylindrical	3.0
7	3	1	3	2100	Hexagonal	4.0
8	3	2	1	2100	Square	3.0
9	3	3	2	2100	Taper Cylindrical	3.5

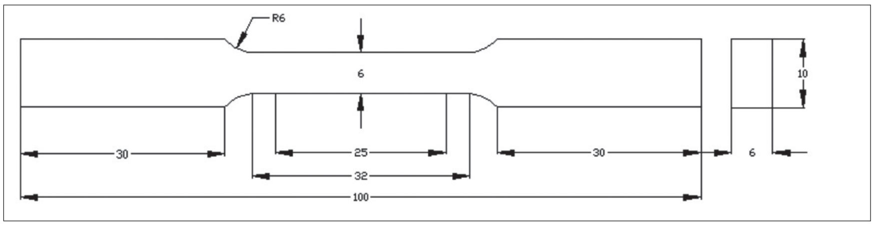

Fig. 2 - Dimensions of tensile specimen

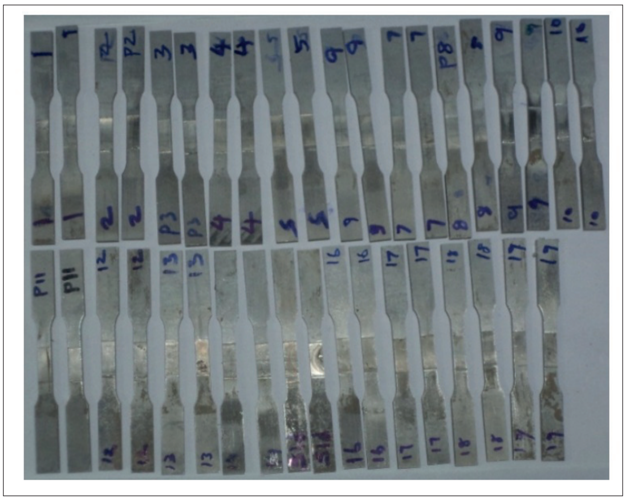

Fig. 3 - Photograph of EDM Wire Cut Tensile Samples

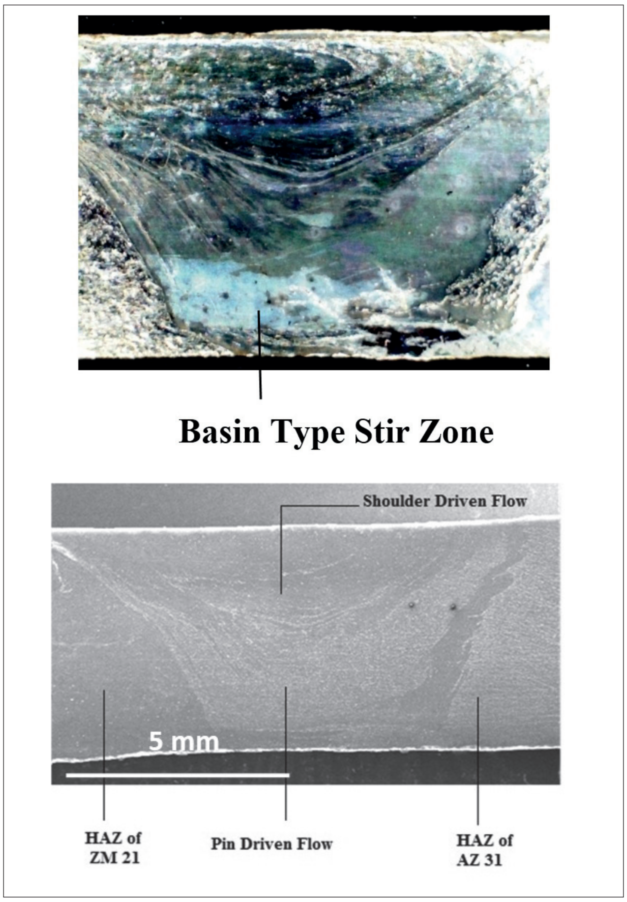

Fig. 4 - Macro Structure of the weld

RESULTS AND DISCUSSION

Macro Structure

The Figure 4 shows the macro structure at the cross section of the weldment. The three distinct micro structural zones i.e., stir zone, weld nugget, the thermo mechanically affected zone and heat affected zone are cleanly visualised. As the shape of the stir zone is highly influenced by the process parameter the basin type stir zone is formed at optimised process parameters. The onion ring formation is seen at the top of the welds. The pin driven and the shoulder flow material flow also seen on the macro structure. The defect free welds are obtained.

Microstructure

The optical micrograph of the joints at different locations are captured and displayed in the Figure 5 a-h. The micro structure of the base metals ZM 21 and AZ 31 are shown in the figure 5a and 5b and the different region such as the advancing side, retreating side, ZM21 interface, AZ 31 Interface, weld nugget and heat affected zones are shown in figure 5c,5d,5e,5f,5g, and 5h respectively. From the micro graph it is understood and noticed that there is an approximate difference in the grain size at different locations or regions of the weld. The average grain diameters of the weld region of all the joints were measured by Heyn's line intercept method (ASTM: E112-10). The average grain size of the base metal ZM 21 and AZ31 are 40 µm and 70 µm respectively. At the advancing and retreating interfaces the sizes of the grain reduces to 9.5 to 6.5 µm. The heat-affected zone showed only slight grain coarsening size of 10.95 µm. The weld nugget shows the very fine re crystallised grains of size 5.45 µm, a characteristic feature of friction stir welding improves the mechanical properties of the joints.

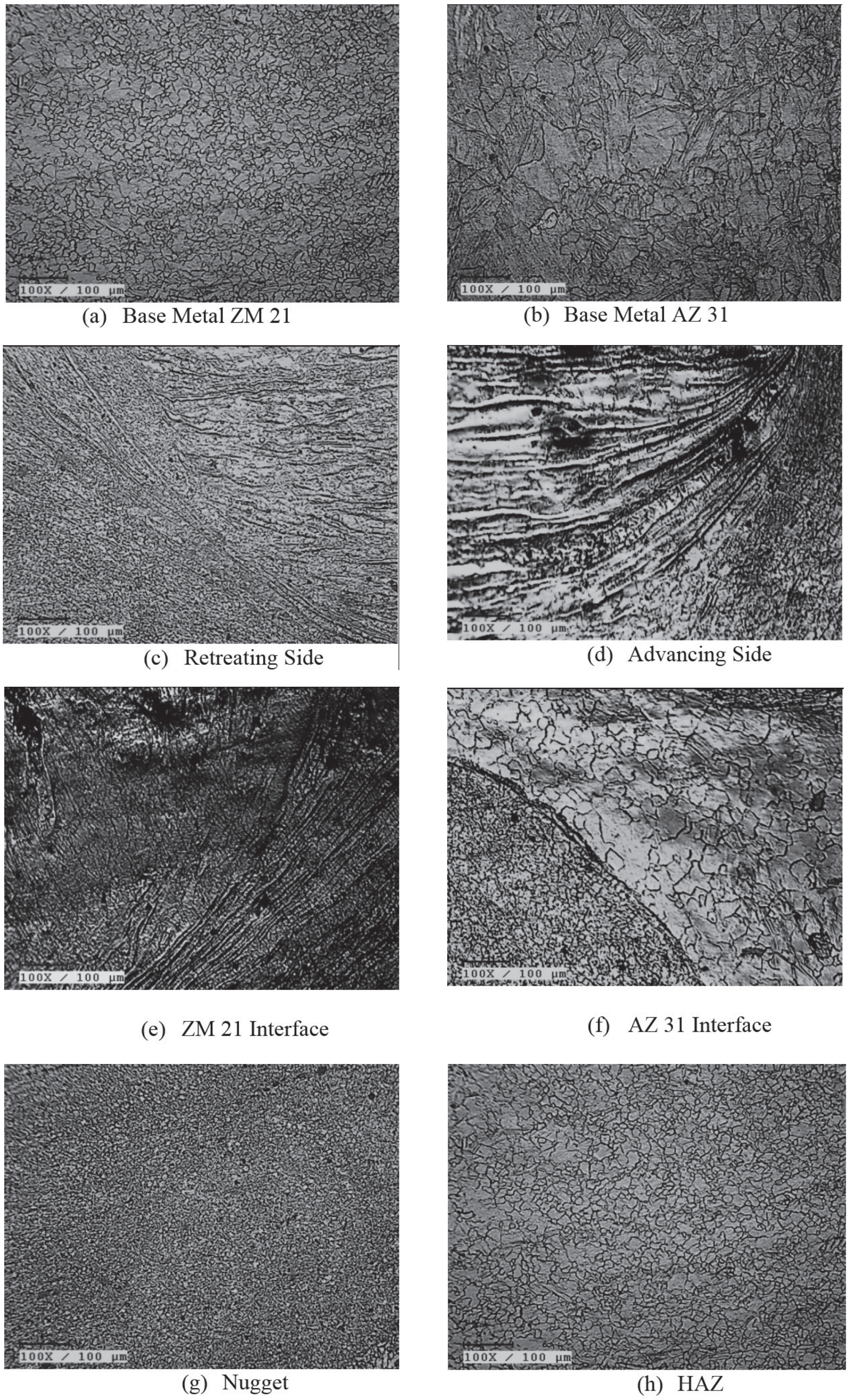

Fig. 5 - Micro Structure of the weld at different location

Signal to Noise Ratio

The SN Ratio is calculated based on the quality of the characteristics intended. The objective function described in this investigation is maximization of the tensile strength so, the Larger the best SN ratio is to calculated. The formula used for calculating the SN ratio is given bellow

Larger the Best

$$\text{S/N Ratio } (\eta) = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \qquad \text{Eq 1}$$

where n - number of replications
y_i - observed response value

The Tensile strength of the Friction Stir welding joints values is analyzed to study the effects of the FSW process parameters. The experimental data's are converted into mean and SN ratio. The calculated mean and SN ratio values are tabulated in the table 5.The main effects, average mean and SN ratio values of all levels are calculated and listed in the table 6, 7 & 8. The table 6 clearly visualise how the main effects has affected the response as the process parameters switches from one level to other level and its capture the trend (positive or negative).The table 7 and 8 qualifies the rank of the process parameter based on the range (maximum- minimum) of the levels average with respect to mean and signal to noise ratio. Irrespective of the objective function whether maximization or minimization the larger SN Ratio corresponds to the better quality characteristics [10-11].Based on both mean and SN ratio values the optimal level setting is $A_3B_2C_2$ ie., the rotational speed is to set at 2100 rpm, the square pin tool geometry and the axial force is to be 4.0 KN based on the experimental results.

Tab. 5 - Mean value and SN value

Sl No	Input Parameter			Tensile Strength (Mpa)		Mean value (Mpa)	SN Ratio
	A	B	C	T1	T2		
1	1	1	1	159	167	163.0	44.2359
2	1	2	2	145	149	147.0	43.3439
3	1	3	3	135	138	136.5	42.7011
4	2	1	2	170	174	172.0	44.7088
5	2	2	3	165	169	167.0	44.4525
6	3	3	1	134	138	136.0	42.6680
7	3	1	3	197	201	199.0	45.9757
8	3	2	1	192	195	193.5	45.7328
9	3	3	2	159	167	163.0	44.2359

Tab. 6 - Main effects of the process parameters

Process Parameter	Level	Mean (Mpa)			SN Ratio		
		A	B	C	A	B	C
Average value	L1	145.0	132.5	163.7	43.17	42.43	44.12
	L2	158.5	178.0	164.3	43.95	44.97	44.22
	L3	176.2	169.2	151.7	44.79	44.51	43.57
Main effects	L2-L1	13.5	45.5	0.6	0.78	2.54	0.1
	L3-L2	17.7	-8.8	-12.6	0.84	-0.46	-0.65

Tab. 7 - Response Table for Signal to Noise Ratios

level	A	B	C
1	43.17	42.43	44.12
2	43.95	44.97	44.22
3	44.79	44.51	43.57
Delta	1.63	2.54	0.65
Rank	2	1	3

The optimal setting is $A_3B_2C_2$ based on SN ratio

Tab. 8 - Response Table for Means

level	A	B	C
1	145.0	132.5	163.7
2	158.5	178.0	164.3
3	176.2	169.2	151.7
Delta	31.2	45.5	12.7
Rank	2	1	3

The optimal setting is $A_3B_2C_2$ based on Mean

Analysis of Variance (ANOVA)

The purpose of ANOVA is to find the significant factor statistically. It gives a clear picture how far the process parameter affects the response and the level of significance of the factor considered. The ANOVA table for both mean and SN ratios are calculated, the process parameters contribution are quantified and listed in the table no 9 & 10.The main effects for mean and SN ratio is plotted in the Figure 6&7. The F test is being carried out to study the significances of the process parameter. The high F value indicates that the factor is highly significant in affecting the response of the process. In our investigation, the rotational speed and the tool pin profile are highly significant factor and play a major role in affecting the tensile strength of the weld. The effect of axial force doesn't make any impact in the responses.

Tab. 9 - Analysis of Variance for Means

Source	DoF	Seq SS	Adj SS	Adj MS	F	% Contribution
A	2	1465.7	1465.7	732.86	14.09	27.30745
B	2	3492.7	3492.7	1746.36	33.57	65.07247
C	2	304.9	304.9	152.44	2.93	5.68059
Residual Error	2	104.1	104.1	52.03		
Total	8	5367.4	5367.4			

R-Sq = 98.1%   R-Sq (adj) = 92.2%

Tab. 10 - Analysis of Variance for SN Ratio

Source	DoF	Seq SS	Adj SS	Adj MS	F	% Contribution
A	2	3.9692	3.9692	1.98462	22.88	24.97813
B	2	11.0208	11.0208	5.51042	63.53	69.35377
C	2	0.7272	0.7272	0.36358	0.193	4.576262
Residual Error	2	0.1735	0.1735	0.08673		
Total	8	15.8907				

R-Sq = 98.9%   R-Sq (adj) = 95.6%

DoF - Degrees of freedom, Seq SS- Sequencial sum of squares, Adj SS- Adjusted sum of square, Adj MS- Adjusted mean square, SS'-Pure sum of squares, F- Fisher ratio

Effects of process parameters

The effects of the process parameters of FSW welding parameters on dissimilar welding ZM21to AZ31 magnesium alloys is cleanly witnessed by plotting the main effects of the process parameters to the concern response considered. And it is summarized below with respect to the process parameter.

Rotational Speed

The Rotational speed is directly proportional to the tensile strength of the weld. The frictional heat input increases with increase in rotational rate of the tool. Thus the increase in the Rotational speed enhances the heat input of the process which in turn results in better material flow and increases the material to be displaced in a unit time. The maximum tensile strength of the weld is also seen when the process parameter rotational speed set at higher level in the process window. Thus the rotational speed at 3rd level is the best possible level for the desired responses considered i.e., the rotational speed of the tool is to set at 2100 rpm to join magnesium alloys of ZM21 to AZ31.

Tool pin Profile

The tool pin profile plays a major role in affecting the tensile strength of the welded joints. The tool profiles with flat surfaces are associated with eccentricity, which allows the material to flow around the pin. The square pin profile produces the pulsating action as the ratio between the static volume to the dynamic volume is more than one. Where there is no such pulsating action in the case of cylindrical, tapered and threaded pin profiles. In our investigation the square tool pin profile is found to be optimum tool pin profile among the hexagonal and tapered cylindrical.

Axial Load

As axial load is one of the important process parameters, the considered level doesn't affect the responses as the variation in the level average is not appreciable. This implies within the selected range of process window the levels can be fixed at any level to have a desired output.

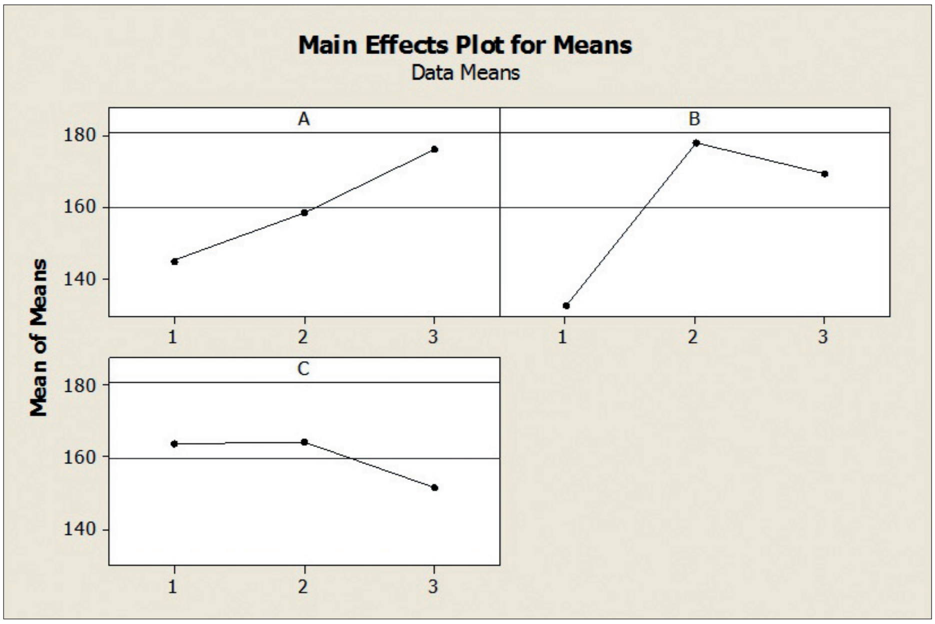

Fig. 6 - Main Effect for Mean

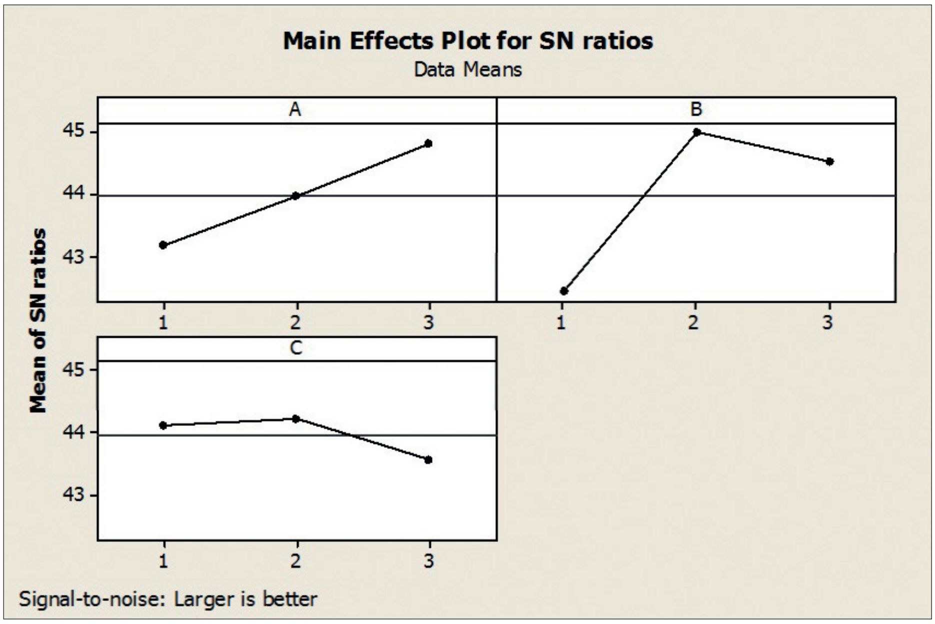

Fig. 7 - Main Effect for S/N Ratio

Predicted value of tensile strength

Based on the experiments, the optimum level setting is $A_3B_2C_2$. The additive model to evaluate the predicted tensile strength is taken from the literature [10-11]. The average values of the factors at their levels are taken from the table 7 and the predicted value of the response is given bellow.

Tensile strength (predicted) $=A_3+B_2+C_2-2T$

$=176.2+178.0+164.3-2(159.9)$

$=198.7$Mpa

Where

A 3: Average mean value of Rotational speed at 3rd level.

B 2: Average mean value of Square Tool profile.

C 2: Average mean value of Axial Force at 2nd level.

T : Overall Mean

Confirmation Run

The confirmation experiments were carried out by setting the process parameter at optimum levels. The rotational speed, Tool geometry, and axial force were set at 2100 rpm, Square tool pin profile and 4 KN respectively. Three tensile specimens were subjected to tensile test and the average value of the Friction Stir welded between AZ 31 and ZM 21 was 208 Mpa.

CONCLUSIONS

1. The L9 Taguchi orthogonal designed experiments of Friction Stir Welding on dissimilar Magnesium alloy between AZ 31 and ZM 21 were successfully conducted.
2. The FSW process parameters are optimized with respect to the tensile strength of the joint and the optimum level of

settings were found out. The optimum levels of the rotational speed, Tool geometry, and axial force are 2100 rpm, square pin profile and 4 kN respectively.

3. The tool pin profile plays a vital role, and contributes 69.35 % to the overall effect. The axial force doesn't affect the response significantly.

ACKNOWLEDGEMENTS

The authors are grateful to the Management of SSN College of Engineering, Kalavakkam, Chennai, Tamil Nadu, India for extending the facilities of Workshop and Materials Testing Laboratory to carry out this investigation. The authors wish to express their sincere thanks to SSN Trust for the financial support to carry out this investigation through internal sponsored project and CEMAJOR, Annamalai University for extending their experimental setup to carry out our experiments.

REFERENCES

[1] Lechosław Tuz, Paweł Kołodziejczak and Andrzej Kolasa (2013), " Friction stir welding of AZ-91 and AM-Lite magnesium alloys", Welding International, Vol. 27, No. 4, 265–267.

[2] Lechosław Tuz, Paweł Kołodziejczak and Andrzej Kolasa (2016), "Structure of butt joint of as-cast magnesium alloys", Welding International, Vol. 30, No. 1, 43–47.

[3] Shirano, Kokamoto, Mdoi, Hokamura, Minagaki and Yaono, "Microstructure of the interface in magnesium alloy to aluminium alloy dissimilar joints produced by friction stir welding", Welding International 18 (9) 702–708.

[4] Xie G M, Ma Z Y, Geng L, Chen R S. (2007), "Microstructural evolution and mechanical properties of friction stir welded Mg-Zn-Y-Zr alloy", Materials Science and Engineering A, 2007, 471:63.

[5] YU Sirong , CHEN Xianjun , HUANG Zhiqiu , LIU Yaohui ,(2010), "Microstructure and mechanical properties of friction stir welding of AZ31B magnesium alloy added with cerium",Journal of Rare Earths, Vol. 28, No. 2, Apr. 2010, p. 316.

[6] Thomas, W.M.; Nicholas, E.D.; Needham, J.C.; Murch, M.G.;Templesmith, P.; Dawes, C.J. Improvements to Friction Welding. GB Patent Application No. 9125978.8, December 1991.

[7] Dawes, C.; Thomas, W. Friction stir joining of aluminium alloys.TWI Bulletin 1995, 6: 124.

[8] Elangovan, K.; Balasubramanian, V. (2007), "Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminum alloy", Materials Science and Engineering A, 459, 7–18.

[9] Liu, H.J.; Chen, Y.C.; Feng, J.C. (2006), "Effects of zig zag line on the mechanical properties of friction stir welded joints of an Al–Cu alloy", Scripta Materialia, Vol.55, 231–234.

[10] Vijayan S., Raju R. and Rao S.R.K. (2011), 'Multi-Objective Optimization of Friction Welding Process Parameters on Aluminum Alloy AA 5083 Using Taguchi Based Grey Relation Analysis', Accepted in Materials and Manufacturing Processes, Vol. 25, No. 11, pp. 1206-12.

[11] Vijayan S., Raju R., Subbaiah K., Sridhar N. and Rao S.R.K. (2010), 'Friction Stir Welding of Al-Mg alloy-Optimization of process parameters using Taguchi Method', Experimental Techniques, Vol. 34, No. 5, pp. 37-44.

[12] Sato Y.S., Urata M., Kokawa H. and Ikeda K. (2003), 'Effect of Friction Stirring on Microstructure in Equal Channel Angular Pressed Aluminum Alloys', Material Science Forum, Vols. 426-432, pp. 2947-2952.

[13] Hassan A.AK., Norman A.F. and Prangnell P.B. (2002), 'The effect of the welding conditions on the nugget zone in friction stir welds in an AA7010 alloy', Sixth International Trends in Welding Research Conference Proceeding, pp. 287-292

[14] Liu H.J., Fujii H. and Maeda M. (2003), 'Tensile properties and fracture locations of friction stir welded joints of 2017-T351 aluminium alloy', Journal of Material Processing and Technology, Vol. 142, pp. 692-696.

[15] Ouyang J.H. and Kovacevic R. (2002), 'Material flow during friction stir welding (FSW) of the same and dissimilar aluminum alloys', Journal of Material Engineering and Performance, Vol. 11, No. 1, pp. 51-63.

[16] S.Ugender, A.Kumar , A. Somi Reddy (2014), 'Microstructure and Mechanical Properties of AZ31B Magnesium alloy by Friction stir Welding', Procedia Materials Science 6, pp.1600 – 1609.

[17] W. Yuan, R.S. Mishra, B. Carlsonc, R. Vermac, R.K. Mishra (2012)' 'Material flow and microstructural evolution during friction stir spot welding of AZ31 magnesium alloy', Materials Science and Engineering A 543, pp 200– 209.

[18] Inderjeet Singh, Gurmeet Singh Cheema, Amardeep Singh Kang (2014), 'An experimental approach to study the effect of welding parameters on similar friction stir welded joints of AZ31B-O Mg alloy', Procedia Engineering 97,pp.837 – 846.

[19] L. Commin, M. Dumont, J.-E. Masse , L. Barrallier (2009), 'Friction stir welding of AZ31 magnesium alloy rolled sheets:Influence of processing parameters", Acta Materialia Vol.57,pp.326–334

[20] K.L. Harikrishna, J.J.S. Dilip, K. Ramaswamy Choudary, V.V. Subba Rao, S.R. Koteswara Rao,G.D. Janaki Ram, N. Sridhar and G. Madhusudhan Reddy,(2010), "Friction stir welding of magnesium alloy ZM21",Transactions of The Indian Institute of Metals Vol. 63, Issue 5, October 2010, pp. 807 – 811.

[21] H.Tanabea and T.Watanabeb (2008), "Friction stir welding between CPTi and AZ31B magnesium alloy: effect of rotating tools on the welding strength of the joint",Welding International,Vol. 22, No. 9, 588–596.

[22] Kazuhiro Nakata (2009), "Friction stir welding of magnesium alloys",Welding International,Vol. 23, No. 5, 328–332.

[23] S.M. Chowdhury, D.L. Chena, S.D. Bhole, X. Cao, E. Powidajkoc, D.C. Weckman, Y. Zhou,(2010), "Tensile properties and strain-hardening behavior of double-sided arc welded and friction stir welded AZ31B magnesium alloy", Materials Science and Engineering A 527 (2010) 2951–2961.

[24] Razal rose, K.Manisekar, V. Balasubramanian (2011), "Effect of axial force on microstructure and tensile properties of friction stir welded AZ61A magnesium alloy", Transactions of Non Ferrous Metal Society of China, Vol 21, 974-984.

[25] Lorele Commina, Myriam Dumont, René Rotinat, Fabrice Pierron, Jean-Eric Masse, Laurent Barrallier, (2012), "Influence of the microstructural changes and induced residual stresses on tensile properties of wrought magnesium alloy friction stir welds",Materials Science and Engineering A,Vol.551, 288– 292.