OPTIMIZATION OF FRICTION STIR WELDING PARAMETERS FOR MAGNESIUM ALLOY AZ91D USING TAGUCHI DESIGN

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Friction stir welding of magnesium alloy, AZ91D casting materials has been welded and their tensile strength is investigated. Evaluation of FSW process parameters such as tool rotational speed, welding speed and axial force on tensile strength was carried out using Taguchi parametric design and optimization approach. Optimized process parameters are established using ANOVA technique and the percentage contribution of process parameters are also determined.

Keywords: *magnesium alloy, Taguchi, ANOVA, friction stir welding, tensile strength.*

Friction stir welding (FSW) is a metal joining process in which heat is generated by friction between the tool and the workpiece to produce solid state welding [1]. A recent report reveals that the tensile strength of aluminium and magnesium materials at the joints is lower than that of the base material except during elongation. Hence determination of the optimum values of welding parameters such as welding speed, rotational speed helps in increasing the tensile strength at the weld joints [2]. Won-Bae Lee et al. analyzed the joint characteristics of friction stir welded AZ91D magnesium alloy of 4 mm thickness plate. The microstructure analysis reveals that the grain size decreases with increase in welding speed at the stir zone [3]. An attempt was made by Elangovan and Balasubramanian to understand the influences of rotational speed and pin profile of the tool on the friction stir processed (FSP) zone formation in AA2219 aluminium alloy [4]. The AZ31B magnesium alloy was successfully joined without any macro level defects by using this process. The optimum tool rotational speed, welding speed, and axial force are 1600 rpm, 0.67 m/s and 3 kN respectively. It is also reported that the tensile properties are higher when compared with other joining process [5]. Many researchers evaluated the tensile strength to determine the optimum welding parameters, namely rotational speed and welding speed. However, the axial force was seldom considered while determining the optimum process parameters. Taguchi technique and ANOVA technique are considered to be a robust effective tool for carrying out experimental work and further processing the experimental data for optimization [6].

The objective of this work is to establish the optimum friction stir welding parameters of AZ91D magnesium alloy. The main parameters to be considered for optimization are rotational speed, welding speed and axial force. Optimization of process parameters is done with the help of ANOVA technique.

Experimental details. ***Materials and processes*.** The experiments were carried out using 6 mm thick plates of AZ91D magnesium alloys. The chemical composition of AZ91D Mg alloy (mass.%): 9.1 Al; 0.0027 Ni; 0.001 Cu; 0.65 Zn; Bal. Mg and mechanical properties: tensile strength – 293 MPa; yield strength – 222.7 MPa; elongation – 13%.

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Welding parameters such as tool rotational speed, traverse speed and axial force play a major role in deciding the weld quality. Experiments were carried out to join the AZ91D magnesium alloy plates of size 100 mm (length) × 100 mm (width) × 6 mm (height). High speed steel is used as FSW tool material. Fig. 1 shows the tool used for welding and the welded specimens are presented in Fig. 2. Magnesium alloys are most widely used to absorb shock and vibration energy. For instance, cast Mg alloy AZ91D containing 9% Al and 1% Zn has been most widely used in aircraft and engine building industries due to its high castability, low density, and good mechanical properties. The initial joint configuration was obtained by securing the plates in position using mechanical clamp. Single pass welding procedure was used to fabricate the joints. The tensile specimens were prepared to evaluate the ultimate tensile strength. Tensile test was carried out in 60 tones capacity, hydraulic universal testing machine.

Fig. 1. Friction stir welding tool.

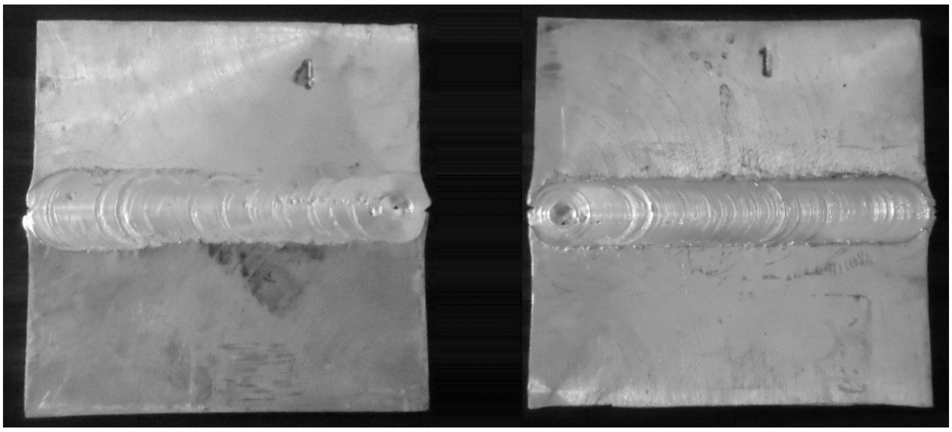

Fig. 2. Images of the welded specimens.

Procedure of experiments. Two major tools used in the Taguchi method are the orthogonal array (OA) and the signal to noise ratio (*S*/*N* ratio). The orthogonal array L_9 is selected as shown in Table 1, which has 9 rows corresponding to the number of tests with the required columns. OA is a matrix of numbers arranged in rows and columns. A typical L_9 orthogonal array is shown in Table 1. In this array, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur, thus giving an equal number of times. Here, there are three parameters: *A*, *B*, and *C*, each at three levels. This is called an “L9” design, the 9 representing the nine rows, configurations or prototypes to be tested. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, L9 means that nine experiments are to be

Table 1. L_9 Orthogonal array

Experiments	Factors		
	A	*B*	*C*
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Note: *A* – rotational speed, rpm; *B* – welding speed, mm/min; *C* – axial force, kN.

carried out to study three variables at three levels. The number of columns of an array represents the maximum number of parameters that can be studied using that array.

The plan of experiments comprises 9 tests, where the second column is assigned to the rotational speed, the third column is assigned to welding speed and the third column is assigned to axial force. The factors and assigned levels are presented in Table 2. By conducting trail experiments the factors values were determined. If rotational speed was lower than 1200 rpm, the weld nugget was observed and it produced insufficient heat generation and insufficient metal transportation. When the rotational speed was higher than 1600 rpm, a tunnel defect was observed and it caused turbulence. Similarly, when the welding speed was lower than 25 mm/min, a pinhole type of the defect occurred. For the welding speed higher than 75 mm/min, the insufficient heat was generated thus giving the inadequate flow of the material. When the axial force was lower than 2 kN, a tunnel and crack like defect occurred at the middle of the weld cross section. If the force increased above 8 kN, large mass of flash and excessive thinning were observed due to a higher heat input. The ranges of process parameters selected are presented in Table 2.

Table 2. Process parameter values at three levels

Level	*A*, rpm	*B*, mm/min	*C*, kN
1	1200	25	2
2	1400	50	4
3	1600	75	6

The Taguchi methodology for optimization can be divided into four phases: planning, conducting, analysis and validation. Each phase has a separate objective and contributes towards the overall optimization process. The Taguchi method for optimization can be presented as a flowchart, shown in Fig. 3.

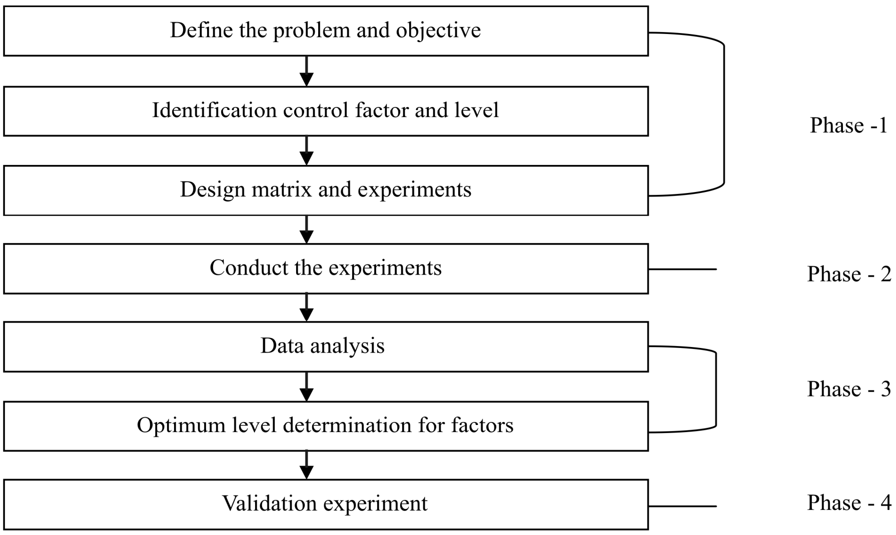

Fig. 3. Flowchart representing the Taguchi method for optimization:
phase 1 – planning; phase 2 – conducting; phase 3 – analysis; phase 4 – validation.

Results and discussion. Quality of the tensile strength is to be considered for investigation in FSW joints. Taguchi suggests that the response values for each test condition are processed by determining the signal to noise ratios (*S*/*N*) for each factor. The *S*/*N* ratio (η) is the ratio of signal to noise in terms of power. Another way to look at it is that it represents the ratio of sensitivity to variability. The higher the SNR, the better quality of product is. The idea is to maximize the SNR and thereby minimizing the effect of random noise factors which has significant impact on the process performance. Therefore, the method of calculating the *S*/*N* ratio depends on whether the quality characteristic is smaller-the-better, larger-the-better, or nominal-the-best. We adopt the “Smaller is better” approach. The *S*/*N* ratio for this type of response was used by employing formula,

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum Y_{ijk}^{2}\right), \tag{1}$$

where n is the number of tests and Y_{ijk} is the experimental value of the i_{th} quality characteristic in the j_{th} experiment at the k_{th} test [7].

In the present study, the tensile strength results were analyzed to determine the effect of FSW process parameters. The experimental results are transformed into means and signal – to – noise (*S*/*N*) ratio. In this work means and signal to noise ratios are calculated and the values are presented in Table 3. The analysis of the mean for each of the experiment will give the better combination of parameter levels that ensures a high level of precision for tensile strength. The mean for one level was calculated as the average of all the three responses that were obtained with that level. The mean response of raw data and *S*/*N* ratio of tensile strength for each parameter at level 1, 2, and 3 were calculated and given in Table 3. The mean and *S*/*N* ratio of various parameters change from the lower to higher levels and are also given in Table 4. It is clear that a larger *S*/*N* ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of the highest *S*/*N* ratio [7]. The mean effect and *S*/*N* ratio for tensile strength are further processed by statistical software called Design Expert [8].

Table 3. Experimental test conditions and observed data

S.No	Input parameter			Response			Mean value	*S*/*N* ratio
	A, rpm	*B*, mm/min	*C*, kN	T_1	T_2	T_3		
				MPa				
1	1200	25	2	103	112	110	108.33	40.6925
2	1200	50	4	175	170	178	174.33	44.8259
3	1200	75	6	119	115	121	118.33	41.4618
4	1400	25	4	176	179	171	175.33	44.8771
5	1400	50	6	208	200	194	200.67	46.0496
6	1400	75	2	150	146	152	149.33	43.4829
7	1600	25	6	130	138	135	134.33	42.5634
8	1600	50	2	144	148	140	144.00	43.1672
9	1600	75	4	149	140	151	146.67	43.3268

Note: T_1, T_2 and T_3 – tensile strengths; *A* – rotational speed, rpm; *B* – welding speed, mm/min; *C* – axial force, kN.

Table 4. Main effects of tensile strength

Process parameter	Level	Means			*S*/*N* ratio		
		A	*B*	*C*	*A*	*B*	*C*
Average value	L_1	133.66	139.33	133.88	42.33	42.71	42.45
	L_2	175.11	173.00	165.44	44.80	44.68	44.34
	L_3	141.67	138.11	151.11	43.02	42.76	43.36
Main effects	$L_2 – L_1$	41.45	33.67	31.56	2.47	1.97	1.89
	$L_3 – L_2$	–33.44	–34.89	–14.33	–1.78	–1.92	–0.98

Note: *A* – rotational speed, rpm; *B* – welding speed, mm/min; *C* – axial force, kN.

Table 5. ANOVA for main effects of tensile strength based on mean value and *S*/*N* ratio value

Source	*DF*	*SS*, S_{eq}	*SS*, A_{dj}	*MS*, A_{dj}	*SS′*	*F*	*P*	Contribution, %
Rotational speed	2	3002.89 / 9.795	3002.89 / 9.795	1501.44 / 4.898	2975.33 / 9.481	108.98 / 31.17	0.009 / 0.031	44.38 / 41.07
Transverse speed	2	2488.22 / 7.583	2488.22 / 7.583	1244.11 / 3.792	2460.66 / 7.269	90.30 / 24.13	0.011 / 0.0398	36.17 / 30.49
Axial force	2	1154.89 / 5.394	1154.89 / 5.394	577.44 / 2.697	1127.33 / 5.079	41.91 / 17.16	0.023 / 0.055	16.89 / 20.63
Error	2	27.56 / 0.314	27.56 / 0.314	13.78 / 0.157	221.52 / 2.514	–	–	3.32 / 10.89
Total	8	6673.56 / 2308.64						100.00 / 100.00

Note: numerator – mean value; denominator – *S*/*N* ratio value. *DF* – degrees of freedom; *SS*, S_e; *SS*, A_{dj} – sequential and adjusted sum of squares; *MS*, A_{dj} – adjusted mean squares; *SS′* – pure sum of squares; *F* – fisher ratio; *P* – probability that exceeds the 95% confidence level.

To analyze the data obtained from design of experiment, ANOVA technique is employed to evaluate the statistical significance. The practical significance can be evaluated through the sum of squares, line or column charts, and normal probability chart. Therefore, the optimum level of the process parameter is the level of the highest *S*/*N* ratio. Furthermore, a statistical analysis of ANOVA variance can be performed to see which process parameter is statistically significant for each quality characteristic [7]. The purpose of the ANOVA test is to investigate the significance of the process parameters which affect the tensile strength of FSW joints. The ANOVA analysis based on mean and *S*/*N* ratio is given in Table 5. The results of ANOVA indicate that the considered process parameters are highly significant factors that affect the tensile strength of FSW joints in the order of rotational speed, traverse speed and axial force.

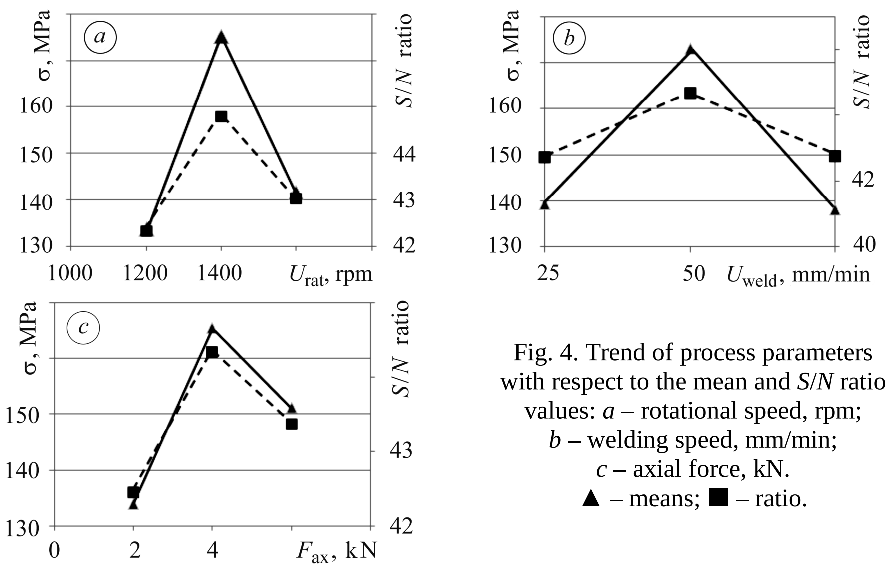

Fig. 4. Trend of process parameters with respect to the mean and *S*/*N* ratio values: *a* – rotational speed, rpm; *b* – welding speed, mm/min; *c* – axial force, kN. ▲ – means; ■ – ratio.

The present study is aimed at identifying the most influencing significant parameter and percentage contribution of each parameter into tensile strength of the friction stir welded AZ91D magnesium alloy joints by conducting minimum number of experiments using Taguchi orthogonal array. Fig. 4 presents the trend of the process parameters with respect to the mean and *S*/*N* ratio values of tensile strength. The factor levels are controlled accurately by the percentage contribution of each factor. The percentage contribution of the rotational speed, welding speed, and axial force are shown in Fig. 5. It must be noted that the above combination of factor levels A_2, B_2, C_2 are not among the nine combinations tested for the experiment. This is expected because of the multifactor nature of the experimental design employed. The optimum parameter value of tensile strength is predicted at the parameters. The estimated mean of the response characteristics for tensile strength can be computed as

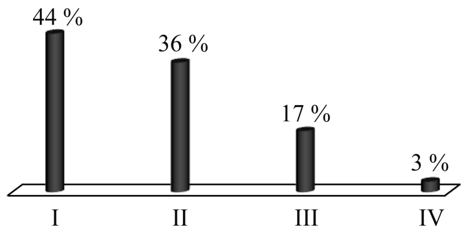

Fig. 5. The % contribution of factors into mean values: I – rotation speed; II – welding speed; III – axial force; IV – error.

$$\text{Tensile strength} = RS_2 + WS_2 + AF_2 - 2T, \quad (2)$$

where RS_2 is the average tensile strength at the second level of rotational speed, 1400 rpm; WS_2 is the average tensile strength at the second level of welding speed, 50 mm/min; AF_2 is the average tensile strength at the second level of axial force 4 kN. Substituting the values of various terms in equation (2), we get

$$\text{Tensile strength} = 175.11 + 173 + 165.44 - 2 \times 150.15 = 213.25 \text{ MPa}.$$

CONCLUSIONS

The percentage contributions of FSW process parameters were determined. It was found that the tool rotational speed had 44% contribution, welding speed – 36% contribution, and axial force – 17% contribution to tensile strength of the welded joints. The optimum value of the process parameters namely, rotational speed, welding speed and axial force, are found to be 1400 rpm, 50 mm/min and 4 kN, respectively.

РЕЗЮМЕ. Досліджували зварювання тертям з перемішуванням (FSW) магнієвих сплавів, литих матеріалів AZ91D та вивчали їх границю міцності на розрив. Оцінювали параметри процесу FSW, а саме: швидкість обертання інструменту, швидкість зварювання та дію осьового навантаження на границю міцності на розрив, використовуючи пристрій Тагучі, та оптимізаційний підхід. Оптимізацію параметрів проводили за методикою ANOVA та із врахуванням процентного внеску параметрів процесу.

РЕЗЮМЕ. Исследовали сварку трением с перемешиванием (FSW) магниевых сплавов, литых материалов AZ91D и изучали их предел прочности на разрыв. Оценивали параметры процесса FSW, а именно: скорость вращения инструмента, скорость сварки и действие осевой нагрузки на предел прочности на разрыв, используя установку Тагучи, и оптимизационный подход. Оптимизацию параметров проводили по методике ANOVA и с учетом процентного взноса параметров процесса.

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