OPTIMIZATION OF AZ91D MAGNESIUM ALLOY FRICTION STIR WELDED JOINTS BY TAGUCHI METHOD

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ABSTRACT

Friction stir welding (FSW) of AZ 91D Magnesium alloy has been undertaken with an objective to find the optimal parameter condition for the mechanical properties of the welded joints. Empirical regression equations are developed for all the responses. The variation in mechanical properties at different parameter combination is attributed to change in microstructure during the welding process. Tool tilt angle is governing uttermost while a comprehensive study on all mechanical properties is concerned.

KEY WORDS: FSW, Magnesium Alloy AZ 91D, UTS, Impact Toughness & Micro Hardness

INTRODUCTION

Magnesium alloys are increasingly employed in automotive industry owing to their low density and high stiffness to weight ratio [1]. Fusion welding processes are scarcely used to fabricate these alloys due to their low melting point and high susceptibility to hot crack formation. Friction stir welding process among the solid state welding processes is a prospective method employed to join these alloys effectively and eliminating the formation of weld defects. The friction stir joints of AZ91D magnesium alloy at high speeds resulted in fine grain microstructure with improved mechanical properties [2]. The tensile properties of the AZ31B magnesium alloy friction stir weld joints are superior compared to other welding processes [3]. Apart from the usual, FSW parameters including the parameter axial force were also implemented and mechanical strength of the joint was investigated [4]. Welding of AZ61A magnesium alloy by FSW was investigated and empirical models of response have been developed employing response surface methodology [5]. The tool geometry has played major role in generating the heat and material dispersion which consequently affected the mechanical and metallurgical properties of friction welded aluminum alloy joints [6,7]. The tool geometry in the friction stir welding of AZ31B magnesium alloy has governed major role by changing the microstructure and consequently the mechanical properties [8].

In this investigation effect of process parameters on AZ91D magnesium alloy is conducted in order to have a comprehensive optimal output of the mechanical properties of the joints.
EXPERIMENTAL DETAILS

Materials

The material used in this study was AZ91D magnesium alloy manufactured through die casting process. The chemical composition and mechanical properties of the material are given in table 1 and table 2 respectively.

| Table 1: Chemical Composition of AZ91D Magnesium Alloy |
|------------------------------------------------------|
| Material | Element % in Weight |
|-----------|---------------------|
| AZ91D     | Mg 90.2 Al 8.7 Zn 0.95 Si 0.035 Mn 0.05 Cu 0.003 Fe 0.01 O 0.05 |

| Table 2: Mechanical & Thermal Properties of AZ91D Magnesium Alloy |
|---------------------------------------------------------------|
| Material | UTS (M Pa) | Yield Strength (M Pa) | % Elongation | Thermal Conductivity (W/m K) | Melting Temperature (°C) |
|-----------|------------|-----------------------|--------------|-------------------------------|--------------------------|
| AZ91D     | 230        | 160                   | 3            | 72                            | 533                      |

The materials are available in the form of plates of 5mm thick and machined to a size of 100mmX100mm for metal joining.

Friction Welding Process

A non consumable rotating tool with a specially designed geometry inserted at the interface of the plates to be joined and transverses further. Due to friction, heat is generated and causes the plastic deformation of the metal. The tool shoulder consolidates the material and helps in making a sound joint [9]. The FSW process was carried out on a vertical milling machine as shown in figure 1a. The tool employed for the welding process was shown in figure 1b.

(a) Vertical Milling Machine. (b) FSW Process Tool.

Figure 1: Friction Welding Machine and the Tool.

It has a provision to change the rotational speed, travelling weld speed and angular position of the tool. The parameters employed and the range of each one is given in the table 3.
Table 3: FSW Process Parameters

| Parameters       | Units      | Levels   |
|------------------|------------|----------|
| Rotational Speed | r.p.m      | Low 710  |
| Weld speed       | mm/min.    | Medium 900 |
| Tool tilt Angle  | 0°         | High 1100 |

MECHANICAL AND METALLURGICAL PROPERTY EVALUATION

Tensile Test

The tensile test was performed on a Universal Testing Machine (figure 2) at a cross head speed of 0.5 mm/minute.

The specimen is fabricated as per ASTM E08 standard (figure 3a & figure 3b) and is employed for evaluation of ultimate tensile strength of the joints.

Impact Test

The Charpy Impact test (figure 4) was carried out at room temperature and the specimen were sectioned from the weldment with specimen axis transverse to the weld joint with notch location at the weld centre.
The specimen is made as per ASTM E23 standard as shown in (figure.5).

Hardness

Micro hardness test was carried out using Olympus digital micro hardness tester at a load of 100 gram. The hardness machine employed for the evaluation is shown in (figure.6). The hardness of the welded joint is measured at an interval of 0.5 mm.
Metallography

Olympus optical microscope was used for examining the microstructure of welded joints (figure7). The base metal and the welded joint microstructure are captured for analysis.

![Olympus Optical Microscope](image)

**Figure 7: Olympus Optical Microscope.**

Taguchi Analysis

In this investigation, three process parameters at three levels each have been taken and design of experiments is conducted as per L9 Taghuchi array [10,11], which is shown in table 4.

| Run | Speed(rpm) (X1) | Feed (mm/min) (X2) | Angle(*) (X3) |
|-----|-----------------|--------------------|---------------|
| 1   | 710             | 16                 | 2             |
| 2   | 710             | 20                 | 2.5           |
| 3   | 710             | 25                 | 3             |
| 4   | 900             | 16                 | 2.5           |
| 5   | 900             | 20                 | 3             |
| 6   | 900             | 25                 | 2             |
| 7   | 1100            | 16                 | 3             |
| 8   | 1100            | 20                 | 2             |
| 9   | 1100            | 25                 | 2.5           |

Table 4: L9 Orthogonal Array

Regression Analysis

The data have been subjected to regression analysis and the response regression equations are developed. The Analysis Of Variance (ANOVA) is conducted using Yate’s algorithm [12]. The regression equation for the response (y) is developed in the coded values of the parameters that is undertaken in the investigation:

$$Y=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_1x_2+b_5x_1x_3+b_6x_2x_3$$

RESULTS AND ANALYSIS

The experimentation has been carried out as per Taguchi array and performed randomly with a view to reduce bias and error. The results have been compiled in Table5.
Table 5: Mechanical Properties of AZ91D Magnesium alloy FSW Joints

| Run | UTS (MPa) | Impact Toughness (Joules) | Hardness |
|-----|-----------|---------------------------|----------|
|     | Trial1    | Trial2        | Trial1 | Trial2 | Trial1 | Trial2 |
| 1   | 102       | 100.45        | 1.25   | 1      | 84.31  | 85.74  |
| 2   | 32        | 31.3          | 2.75   | 2.5    | 90     | 91     |
| 3   | 115       | 113.96        | 1.25   | 1      | 114    | 118    |
| 4   | 113       | 110           | 2.25   | 2      | 90     | 91     |
| 5   | 66        | 67.06         | 0.75   | 0.5    | 90     | 91     |
| 6   | 67        | 67.06         | 0.75   | 0.5    | 90     | 91     |
| 7   | 115       | 114.04        | 1.75   | 1.5    | 103    | 104    |
| 8   | 80        | 81.93         | 0.75   | 0.5    | 96     | 95     |
| 9   | 103       | 104.53        | 1.75   | 1.5    | 90     | 89     |

The data have been analyzed and ANOVA is conducted for all the responses. The regression equations for the responses are shown in Table 6.

Table 6: Regression Equation

| S. No. | Property       | Regression Equation                                      | Coefficient of Correlation |
|--------|----------------|----------------------------------------------------------|----------------------------|
| 1      | UTS            | $Y=87.963+5.766X_1-4.663X_2+5.146X_3-0.668X_1X_2+2.256X_1X_3+3.795X_2X_3$ | 0.7                        |
| 2      | Impact Toughness | $Y=1.4311-0.0111X_1-0.167X_2+0.194X_2+0.11X_1X_3$     | 0.72                      |
| 3      | Hardness       | $Y=94.781-0.336X_1+1.886X_2+4.497X_3-4.497X_2X_3+2.553X_1X_3+0.781X_2X_3$ | 0.65                      |

A typical ANOVA table for UTS is given in Table 7.

Table 7: ANOVA for UTS of the Weld Joint

| Coef | Est | SS    | DOF | MS     | F      |
|------|-----|-------|-----|--------|--------|
| b0   | 87.963 | -     | -   | -      | -      |
| b1   | 5.766   | 598.465 | 2   | 299.232 | 0.135075081 |
| b2   | -4.663  | 391.440  | 2   | 195.720 | 0.088349103 |
| b3   | 5.146  | 476.581  | 2   | 238.291 | 0.10756569 |
| b4   | -2.668  | 128.107  | 2   | 64.053  | 0.028914023 |
| b5   | 2.256   | 91.576   | 2   | 45.788  | 0.020668848 |
| b6   | 3.795   | 259.236  | 2   | 129.618 | 0.058510362 |
| SSR  | 1945.405 | 12     |     |        |        |
| SSE  | 11076.519 | 5      |     | 2215.304 |        |
| SST  | 13021.924 | 17     |     |        |        |
The data given in table 5 is written in the form of Taghuchi S/N Equations:

**Table 8: S/N Equations**

| Criterion          | S/N Equation                                      |
|--------------------|---------------------------------------------------|
| Higher the Better  | $-10 \log \left( \frac{1}{n} \sum \frac{1}{y_i^2} \right)$ |
| Lower the Better   | $-10 \log \left( \frac{1}{n} \sum y_i^2 \right)$     |

Higher the better criterion is applied to strength and impact toughness while lower the better is applied to hardness, as shown in Table 8. The average of the S/N values of the responses is given in the table 9. The modified Taguchi analysis is conducted by taking the average of all S/N values of the responses into consideration [11].

**Table 9: S/N Values of Responses**

| Run | Average S/N |
|-----|-------------|
| 1   | 0.169046    |
| 2   | -0.13502    |
| 3   | -0.00034    |
| 4   | 0.862623    |
| 5   | 0.096696    |
| 6   | -0.95291    |
| 7   | 0.489581    |
| 8   | -0.82191    |
| 9   | 0.535755    |

**DISCUSSIONS**

The tensile strength was highest when rotational speed was at the lowest level while the other two parameters were at their highest levels. To the contrary, the strength was lowest and impact toughness was highest when the rotational speed was lowest while weld speed and tool tilt angle were at their mid level. When the rotational speed was high resulting in high heat input and slower cooling rate causes excessive grain growth (figure8) and subsequently gives rises lower tensile strength and high impact strength [5]. The lowest hardness of the joint was obtained when all the parameters were at their lowest level. A typical hardness survey shows that the hardness was high at weld centre. It has reduced while travelling towards base metal (figure9).

![Figure 8: Microstructure of AZ 91D Base Metal and Weld Zone.](image)

It is attributed to the difference in grain size at different zones in (figure9).
The regression equations developed shall be employed for estimating the responses at different input parameter values. The coefficient of correlation indicates a good relationship between parameters and the responses. The S/N data was subjected to analysis of means Table 10 indicating that the tool tilt angle is playing the major role while weld speed and tool rotational speed governs the responses in the descending order respectively.

Table 10: Analysis of Means

| Parameter | L1    | L2    | L3    | Range      | Rank |
|-----------|-------|-------|-------|------------|------|
| $X_1$     | 0.01123 | 0.002137 | 0.067809 | 0.065672621 | 3    |
| $X_2$     | 0.507083 | -0.28674 | 0.195313 | 0.793826139  | 2    |
| $X_3$     | -0.53526 | 0.42112 | 0.195313 | 0.95637636   | 1    |

The optimal parameter conditions were given in Table 11. The weld speed should be low while the tool tilt angle should be kept at the mid level for having all the responses at optimal conditions. The tool tilt caused the vortex flow occurred in lower half of the work piece for the stir zone resulting in dynamic recrystalization predicted optimal value is found from the equation: $m + \Sigma d_i$; where $m$ is grand mean and $d_i$ is the deviation of the larger S/N value from the grand mean.

Table 11: Optimal Parameter Conditions

| Parameters   | Notations | Level of Parameters |
|--------------|-----------|---------------------|
| Rotational Speed | $X_1$   | L3                  |
| Weld Speed   | $X_2$   | L1                  |
| Tilt Angle   | $X_3$   | L2                  |

A confirmation experiment is conducted and the responses obtained are given in Table 12.

Table 12: Optimal Responses

| UTS (MPa) | Impact Toughness (Joules) | Hardness (Hv) |
|-----------|----------------------------|---------------|
| 99        | 1.75                       | 80            |

CONCLUSIONS

- Empirical model for responses have been developed with moderate degree of coefficient of correlation between the responses and parameters and can be effectively used to predict the responses with 90% confidence level.

- Tool tilt causes vortex flow in the stir zone and recrystalization has occurred resulting in variation of mechanical properties.
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