Analysing the influence of FSP process parameters on IGC susceptibility of AA5083 using Sugeno – Fuzzy model

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Abstract. Aluminium alloy AA5083 was friction stir processed to improve the intergranular corrosion (IGC) resistance. FSP trials were performed by varying the process parameters as per Taguchi’s L18 orthogonal array. IGC resistance of the friction stir processed specimens were found by immersing them in concentrated nitric acid and measuring the mass loss per unit area. Results indicate that dispersion and partial dissolution of secondary phase increased IGC resistance of the friction stir processed specimens. A Sugeno fuzzy model was developed to study the effect of FSP process parameters on the IGC susceptibility of friction stir processed specimens. Tool Rotation Speed, Tool Traverse Speed and Shoulder Diameter have a significant effect on the IGC susceptibility of the friction stir processed specimens.

1. Introduction
Aluminium exhibits high resistive property to corrosion in its ultra-pure state [1, 2]. Aluminium alloy 5083 is widely used in railroad cars, drilling rigs, shipbuilding, pressure vessels and in coachwork. The alloy is highly resistant to chemical attack. The strength of the alloy and its intergranular corrosion (IGC) resistance is improved by addition of Zn [3]. In aluminium alloy AA5083, grain boundaries are the sites for segregation and precipitation of secondary phase (β – Mg2Al3) in the matrix. IGC is the chemical reaction occurring along grain boundaries or areas adjacent to it, thereby effectively reducing the strength of the material. Structures made of AA5083 gets weaken over time due to the precipitation of secondary phase from the matrix [4]. The dispersion and disintegration of β phase in the matrix by any heat treatment process or alloying helps in controlling the rate of corrosion. Friction stir processing is one of the surface modification techniques which helps in reducing the corrosion.

In friction stir processing, the rotating tool under vertical load transverses along the surface of the workpiece. The important FSP process parameters are tool traverse speed, tool shoulder diameter, axial plunge force, tool rotation speed, pin profile and backing plate temperature [5]. Dynamic recrystallization occurs due to the material flow and the heat generation, thereby improvising the surface property and grain refinement [6, 7]. Johannes et al., [8] reported improvement in the tensile strength of friction stir processed AA5083. Cui et al., [9] increased the yield strength, hardness and toughness of AA5083 by FSP.

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Soft computing techniques are being widely applied across various fields ranging from intelligent manufacturing, scheduling, process control, design optimization etc. Roshan et al., [10] developed a relationship between mechanical properties of the AA7075 FSW joints and FSW process parameters. Lakshminarayana et al., [11] explored the interdependence of the process parameters with the mechanical properties in friction stir spot welded low carbon steels. Ilker et al., [12] showed that fuzzy logic systems have strong potential for predicting compressive and splitting tensile strength values of recycled aggregate concretes containing silica fume. Osman et al., [13] developed a new approach using fuzzy logic system for predicting the stress-strain curve of steel fiber-reinforced concrete under compression.

In this work the IGC susceptibility of AA5083 alloy is reduced by subjecting it to FSP. The FSP trials were conducted and ASTM G67 Nitric Acid Mass Loss Test (NAMLT) was used for detecting the degree of IGC susceptibility of the alloy. A mathematical model was generated using Sugeno Fuzzy Model to predict and analyse the intergranular susceptibility of FSPed AA5083.

2. Materials and Methods

2.1. Materials
Wrought aluminium alloy AA5083 plates with dimension 150mm x 60mm x 5mm are used for this work. Table 1 shows the nominal composition of the alloy.

| Element | Mg  | Si  | Mn  | Fe  | Cu  | Zn  | Ti  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Composition (%) | 4.5 | 0.20 | 0.80 | 0.7 | 0.26 | 0.04 | 0.05 | Balance |

2.2. Friction stir processing
Vertical milling center was used to perform the friction stir processing of AA5083 plates. The FSP tool was made of AISI 1050 steel whose pin geometry was tapered and threaded. The plates were cleaned carefully before performing the experiment. The experiments were conducted by varying the TTS, TRS and SD as per Taguchi’s L18 orthogonal array.

2.3. IGC Susceptibility
As outlined by the standard ASTM G67-04, the resistance of aluminium alloy to IGC is evaluated. Test specimens with a length of 40mm were cut from the FSPed specimens. Using 300 grit metallographic emery sheet the sharp edges of the specimen were smoothened. The dimension and surface area of the specimen were found for calculation purposes. Desmutting process, which is immersion of the specimen in 5% NaOH at 80°C for 60 seconds was initiated. Then the specimens were immersed in concentrated HNO₃ for 30 seconds after rinsing in distilled water. Again the process of rinsing in distilled water was repeated and the specimen was dried in a blast of hot air.

A weighing balance with readability of 0.001 g was used for weighing the specimens. The specimens were placed in such a way that they rested on the walls of a glass container. The container filled with concentrated HNO₃ was maintaining a ratio of acid volume to specimen surface area at 30000 ml.m⁻², according to ASTM standard. The specimens were removed and rinsed in distilled water after being completely immersed in the solution for 24 hours. The corrosion products and adhering particles were removed with the help of a stiff plastic brush. The weight of the specimens were measured after IGC test.

The IGC susceptibility of aluminium alloy is measured by means of finding the mass loss per unit area of a given specimen, immersed in HNO₃. The mass loss per unit area, Mₐ was calculated with the help of equation (1). The dimensions of the specimen are represented as length (L), breadth (B) and height (H). The surface area can be found using equation (2). The mass loss per unit area after the IGC test are shown in Table 2.
Mass loss per unit area, \( M_a = \frac{\Delta m}{A} \left( \text{mg/cm}^2 \right) \)  

Surface area of specimen, \( A = 2 \times [(l \times b) + (b \times h) + (h \times l)] \) 

2.4. Sugeno – Fuzzy model

Fuzzy logic is a mathematical tool used to ascertain the uncertainty in a system [14]. In fuzzy logic, the output heavily relies on the rules that was used to form the fuzzy logic system in the first place [15]. The functioning of fuzzy logic system is very similar to that of human reasoning. To distinguish members and non-members from the given parameters under consideration, the characteristic function of classical sets assigns a value in the range of 0 and 1 to each individual element of the whole set [16]. The elements are associated with values which in turn denotes the membership grade of the elements and the function that grades the element is known as membership function. Gaussian membership function allocates membership values to the element efficiently [17] and is given by equation (3).

Fuzzification is defined as the process of allocating a membership value for crisp quantity.

\[ f(x; \sigma, c) = e^{-\frac{(x-c)^2}{2\sigma^2}} \]

Fuzzy rules of the Sugeno fuzzy system are generated from the input-output data set. A stereotypical fuzzy rule in Sugeno fuzzy model is given by equation (4). The firing strength weighs the output level of each rule as given by equation (5).

\[ \text{IF } x_1 \text{ is } A \text{ and } x_2 \text{ is } B \text{ and } x_3 \text{ is } C, \text{ THEN } y = f(x_1, x_2, x_3) \]

\[ w_i = \text{AND method}(F_1(x_1), F_2(x_2), F_3(x_3)) \]

Where \( x_i \) denotes input variable, \( y \) denotes crisp function, \( w_i \) denotes the firing strength, \( F_i(x_i) \) is the membership function of variable \( x_i \) and A, B, C are fuzzy sets in the antecedent.

Converting fuzzy quantities into crisp quantity is called defuzzification. Weighted average method for symmetrical membership functions is one of the efficient defuzzification method [18]. Using weighted average method the defuzzified value is given by the equation (6).

\[ y^* = \frac{\sum \mu_c(\bar{y}) \bar{y}}{\sum \mu_c(\bar{y})} \]

Here \( y^* \) is the defuzzified value, \( \sum \) denotes algebraic sum, \( \mu_c(\bar{y}) \) is fuzzy relation, and \( \bar{y} \) is average.

3. Results and Discussions

3.1. Experimental results

Aluminium alloy series with Mg content greater than 3% may suffer from IGC when treated with HNO\(_3\) and at temperature range of 60°C to 200°C. At these temperatures Al-Mg alloys are susceptible to IGC by precipitation of \( \beta - \text{Mg}_2\text{Al}_3 \) along the grain boundaries. This is the root cause for huge mass loss as it emboldens \( \alpha \) phase grains to shed away from the alloy matrix. The mass loss for specimen subjected to IGC test will be in range of 25 to 75 mg.cm\(^{-2}\). HNO\(_3\) attack the \( \beta \) phase selectively in the alloy matrix.
Figure 1. FE-SEM image of the specimens after IGC test (a) Base material with many cracks and vast pits indicating poor corrosion resistance; (b) Specimen FSP13 with a few small pits indicating high IGC resistance

The homogenous distribution of β phase on the surface of the specimen prevents huge mass lose from α grains shedding. This random distribution of the β phase in matrix reduces the mass loss to a range of 15 mg.cm$^{-2}$ to 25 mg.cm$^{-2}$ as outlined in the ASTM standard. Hence a minimal mass loss less than 15 mg.cm$^{-2}$ will be born by IGC resistance material as per ASTM standards.

An intermediate mass loss of 19.967 mg.cm$^{-2}$ was observed for the base specimen. The metallographic examination which assess the IGC susceptibility becomes a necessity since this value falls in the range of 15 mg.cm$^{-2}$ to 25 mg.cm$^{-2}$. The SEM image in Fig.1 of the corroded base specimen clearly shows the pits and the cracks. The intermediate mass loss in the base specimen is the result of agglomeration of the β phase particles in the matrix. The mass loss of the specimens subjected to IGC test is given in the Table 2.
### Table 2. Layout of FSP experimental trials, experimental and predicted mass loss per unit area of the specimens post IGC test

| Sl. | FSP Process Parameters | Mass loss per unit area (M_a) mg.cm⁻² | % Prediction error |
|-----|------------------------|---------------------------------------|--------------------|
|     |                         | Experimental | Predicted |                     |
| 1   | 700 rpm, 30 TTS (mm.min⁻¹), 15 SD (mm) | 5.5340 | 5.53 | 0.07256 |
| 2   | 700 rpm, 30 TTS (mm.min⁻¹), 18 SD (mm) | 3.7233 | 3.72 | 0.08969 |
| 3   | 700 rpm, 30 TTS (mm.min⁻¹), 21 SD (mm) | 3.1825 | 3.18 | 0.07953 |
| 4   | 700 rpm, 45 TTS (mm.min⁻¹), 15 SD (mm) | 2.6472 | 2.64 | 0.27267 |
| 5   | 700 rpm, 45 TTS (mm.min⁻¹), 18 SD (mm) | 5.1349 | 5.13 | 0.09607 |
| 6   | 700 rpm, 45 TTS (mm.min⁻¹), 21 SD (mm) | 2.2878 | 2.28 | 0.34100 |
| 7   | 700 rpm, 60 TTS (mm.min⁻¹), 15 SD (mm) | 2.8642 | 2.86 | 0.14903 |
| 8   | 700 rpm, 60 TTS (mm.min⁻¹), 18 SD (mm) | 5.2144 | 5.21 | 0.08512 |
| 9   | 700 rpm, 60 TTS (mm.min⁻¹), 21 SD (mm) | 2.6394 | 2.63 | 0.35823 |
| 10  | 1000 rpm, 30 TTS (mm.min⁻¹), 15 SD (mm) | 3.5998 | 3.59 | 0.27405 |
| 11  | 1000 rpm, 30 TTS (mm.min⁻¹), 18 SD (mm) | 3.7057 | 3.70 | 0.15552 |
| 12  | 1000 rpm, 30 TTS (mm.min⁻¹), 21 SD (mm) | 3.3207 | 3.32 | 0.02279 |
| 13  | 1000 rpm, 45 TTS (mm.min⁻¹), 15 SD (mm) | 2.0149 | 2.01 | 0.24428 |
| 14  | 1000 rpm, 45 TTS (mm.min⁻¹), 21 SD (mm) | 2.5815 | 2.58 | 0.06116 |
| 15  | 1000 rpm, 60 TTS (mm.min⁻¹), 15 SD (mm) | 3.5224 | 3.52 | 0.07057 |
| 16  | 1000 rpm, 60 TTS (mm.min⁻¹), 21 SD (mm) | 4.0019 | 4.00 | 0.04970 |
| 17  | 1000 rpm, 60 TTS (mm.min⁻¹), 18 SD (mm) | 2.7487 | 2.85 | -3.93639 |
| 18  | 1000 rpm, 45 TTS (mm.min⁻¹), 18 SD (mm) | 2.4684 | 2.36 | 4.108229 |

**Base material** 19.967

### 3.2. Modelling Results

The generated Sugeno Fuzzy Model was used to access the mass loss per unit area of AA5083 joints fabricated using FSP. In this work, TTS (mm/min), TRS (rpm) and SD (mm) are fed as input parameters and mass loss is the output parameter. Degree of membership for the input space is defined by a curve named membership function. Gaussian membership function was chosen to ensure smooth boundaries in preference to membership functions.
Figure 2. Layout of Sugeno Fuzzy inference system displaying the input process parameters (TRS, TTS, SD), output parameter (Mₐ).

Fuzzy logic designer relating input membership function and output crisp function is shown in Fig. 2. The design matrix defines the number of input parameters and output parameter. Three membership functions of TRS, TTS and SD are chosen as shown in Fig. 3 (a), Fig. 3 (b) and Fig. 3 (c) respectively as the design matrix had three levels of variations.
The model was validated by calculating the percentage error between the experimental value and the predicted value. The error percentage in the prediction made is calculated by Equation (1) [7].

\[
\text{% Error in prediction} = \left(1 - \frac{\text{Predicted value}}{\text{Experimental value}}\right) \times 100
\]  

(7)

The average error percentage of the $M_a$, computed by the model was found to be 0.144%. The experimental and computed $M_a$ were plotted on a graph as shown in Fig. 4. The trend line was found to be a straight line, indicating linear relationship between the experimental and predicted mass loss.

3.2.1. Effect of process parameters

The corrosion susceptibility of the material depends on the dispersion and disintegration of $\beta$ phase in the matrix [19, 20]. Dispersion of the $\beta$ material depends on the tool geometry and material flow [5, 21]. The effect of the process parameters on the mass loss per unit area is illustrated in the Fig. 5.
a) TRS and TTS

Figure 5 (a) discloses the collaborative effect of TTS and TRS on the mass loss of FSPed AA5083. At low TRS of 700 rpm, mass loss remains almost high at all levels of TTS. Whereas at low TTS, a decrease in mass loss can be observed till TRS of 850 rpm followed by a steep increase.

![Figure 5](image)

**Figure 5.** Effect of process parameters (a) TRS and TTS; (b) TRS and SD; (c) TTS and SD on the mass loss per unit area of the specimens
The mass loss remains at its lowest value at TRS value of 850 rpm throughout the TTS variation. A very low mass loss is observed over a large region of TTS and TRS values ranging from 40 mm.min\(^{-1}\) to 60 mm.min\(^{-1}\) and 800 rpm to 1000 rpm respectively. The high TTS and TRS values generates high heat and causes good material flow which results in good IGC resistance.

b) TRS and SD
The combined effect of SD and TRS on the mass loss is shown in the Fig. 5 (b). For incremental change of TRS the variation of mass loss remains similar for low or high SD. A crest parabolic curve is observed at lower TRS when processed for incremental SD values. Mass loss of the specimen was found to remain lowest at 850 rpm of TRS for all values of SD. The sag parabolic curve is found for specimen processed at high TRS of 1000 rpm with incremental SD values.

c) TTS and SD
Figure 5 (c) shows the interaction of SD and TRS on mass loss per unit area. The FSPed specimen was found to have a maximum mass loss per unit area or 0.9 mg.cm\(^{-2}\) when processed with TTS of 35 mm.min\(^{-1}\) and median SD of 18 mm. The variation of mass loss is found to follow sag curve for low and high SD values with incremental TTS values. As a result of insufficient heat generation, least IGC resistance was observed for the specimen FSPed at low TRS of 700 rpm and low SD of 15 mm.

4. Conclusion
Aluminium alloy AA5083 was friction stir processed by varying the process parameters TRS, TTS and SD as per Taguchi’s L18 orthogonal array. The IGC susceptibility of the processed specimen was found and an efficient Sugeno Fuzzy logic model was developed using the experimental data. The results indicated the following.

- Friction stir processing of AA5083 resulted in dispersion and partial disintegration of the secondary phases in the matrix.
- FSP process parameters TRS, TTS and SD had significant contribution towards the metallurgical refinement and hence the IGC susceptibility of the specimens.
- Friction stir processing of specimen FSP13 at TRS of 1000 rpm, TTS of 45 mm.min\(^{-1}\) and SD of 15 mm resulted in the least mass loss per unit area of 2.01 mg.cm\(^{-2}\).

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