

# Analysing the strength of friction stir welded dissimilar aluminium alloys using Sugeno Fuzzy model

V R Barath, R Vaira Vignesh, R Padmanaban<sup>1</sup>

Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India

dr\_padmanaban@cb.amrita.edu

**Abstract.** Friction stir welding (FSW) is a promising solid state joining technique for aluminium alloys. In this study, FSW trials were conducted on two dissimilar plates of aluminium alloy AA2024 and AA7075 by varying the tool rotation speed (TRS) and welding speed (WS). Tensile strength (TS) of the joints were measured and a Sugeno – Fuzzy model was developed to interconnect the FSW process parameters with the tensile strength. From the developed model, it was observed that the optimum heat generation at WS of 15 mm.min<sup>-1</sup> and TRS of 1050 rpm resulted in dynamic recovery and dynamic recrystallization of the material. This refined the grains in the FSW zone and resulted in peak tensile strength among the tested specimens. Crest parabolic trend was observed in tensile strength with variation of TRS from 900 rpm to 1200 rpm and TTS from 10 mm.min<sup>-1</sup> to 20 mm.min<sup>-1</sup>.

## 1. Introduction

Aerospace aluminium alloys, such as highly alloyed 2xxx and 7xxx series are non-weldable because of their poor solidification microstructure and porosity in the fusion zone [1]. These factors have been inhibiting aluminium alloys in aerospace structure, as the weldments require high-strength, fatigue and fracture resistance. Friction stir welding (FSW) process is more attractive and successful than other fusion joining techniques in dissimilar metal joining. Extensive research is conducted on FSW especially in the area of dissimilar joints, thereby making it inevitable for critical applications such as aviation and automotive industries. FSW is a solid state process that utilizes friction heat generated by translation of rotating tool under an axial load to accomplish joining. Details about the process and operational principles can be found in the literature.

Mishra and Ma [1] detailed the substantial advantages of FSW justifying it as a perfect choice in most of the industries and for innovative applications. The strength and the efficiency of the joints created by FSW process are decided by the process parameters such as tool rotation speed (TRS) and welding speed (WS). Research has been carried out in improvement of FSW process as a distinguished solid state joining process ever since its invention. Peel et al., [2] studied the influence of WS on the mechanical behaviour of friction stir welded (FSWed) joints of aluminium alloy AA5083. The effect of TRS and WS on the TS of FSWed joints of AA6061-T651 alloy was studied by Lim et al. [3]. Minton and Mynors developed a new methodology to determine the FSW process window for a material [4]. A study on the effect of TRS and WS on the thermal and mechanical behaviour of FSWed joints of

<sup>1</sup> Corresponding author



aluminium alloy AA2014 was made by Rajamanickam and Balusamy [5]. A mathematical model to estimate the tensile strength of the FSWed joints of aluminium alloy AA2219 for different FSW parameters using empirical relations was developed by Elangovan et al. [6].

A comprehensive review on the FSW process for similar and dissimilar metals was presented by Murr [7]. Da Silva et al. [8] investigated the effect of joining parameters on the material flow, microstructural characteristics and mechanical behaviour of FSWed dissimilar joints of aluminium alloys AA2024-T3 and AA7056-T6. Bahemmet et al. [9] studied the effect of pin profile and TRS on the hardness, TS and the grain size of the FSWed dissimilar joints of aluminium alloys AA2024-T4 and AA7075-O. Padmanaban et al., [9] developed a mathematical model to study the effect of TRS and WS on the TS of dissimilar FSWed AA2024-AA7075 joints.

In recent decades, soft computing techniques are frequently adopted for the optimization of the process parameters to get a desirable outcome in a manufacturing process. Response surface methodology (RSM) is one of the widely used techniques to develop an empirical model to develop relationships between FSW input parameters and its desirable responses. Elangovan et al., [6] and Padmanaban et al., [9] used RSM to develop a mathematical model to study the influence of FSW process parameters on the TS of FSWed joints of AA2219 alloy and dissimilar FSWed joints of AA2024-AA7075. In addition to RSM technique, some of the other soft computing techniques like Taguchi technique, ANN and ANFIS also gaining their importance in analysing the manufacturing process.

Bozkurt [10] generated the optimal FSW parameters for achieving high TS in FSWed polyethylene sheets using the Taguchi optimization technique. Roshan et al., [11] used adaptive neuro-fuzzy inference system to develop an optimal relationship between the FSW process parameters and the mechanical behaviour of the FSWed joints of AA7075 alloy. Vaira Vignesh et al., [12] used Fuzzy based soft computing technique to develop a model for tensile shear failure load of FSWed joints of AA6061, incorporating TRS, shoulder diameter and dwell time as the input process parameters. Dewan et al., [13] predicted the ultimate tensile strength of FSWed joints of aluminium alloys, incorporating spindle speed, plunge force and welding speed as the input parameters using ANFIS and Artificial neural network soft computing techniques.

Survey of the published research works reveals that soft computing techniques are gaining momentum to aid the optimization of FSW joining process. The critical application of joints created using the FSW process requires a defect free joint with superior mechanical, corrosion and tribological properties which is possible at optimized FSW process parameters. In the current research work, the influence of the FSW parameters namely TRS and WS on the TS of the dissimilar FSWed joints of aluminium alloys AA2024 and AA7075 was studied using Sugeno Fuzzy based soft computing technique.

## **2. Materials and Methods**

### *2.1. Materials*

Aluminium alloy AA2024 and AA7075 plates of thickness 5 mm were machined to workpiece of dimension 150 x 60 mm. The edges of the workpieces were paralleled to ensure smooth surface contact between the workpieces and good clamping in the fixture. The fixture was made of mild steel plate of thickness 20 mm. The FSW tool was made of high speed steel and had shoulder diameter of 17.5 mm, pin diameter of 5 mm and pin height of 4.65 mm.

### *2.2. Friction Stir Welding.*

The plates were cleaned and degreased with acetone before FSW trial. A dwell time of 60 seconds was adopted for each FSW trial and the trials were performed in a numerically controlled vertical milling center. The FSW process parameters TTS and WS were varied at three levels. Process parameter was coded as -1 for low level, 0 for middle level and +1 for high level. The corresponding linguistic term in the coded and real form is given in the Table 1. The FSW process parameters were varied as per central composite design, as given in the Table 2.

**Table 1.** Coded value, Real value and Linguistic term of the FSW process parameter

Sl.	Coded value	Real value		Linguistic term	
		<i>TRS</i> (rpm)	<i>WS</i> (mm.min <sup>-1</sup> )	<i>Coded term</i>	<i>Real term</i>
1	-1	900	10	L	Low
2	0	1050	15	M	Medium
3	+1	1200	20	H	High

### 2.3. Tensile strength

The specimens for tensile test were sliced from the FSWed plates and prepared as outlined by the standard ASTM E8M-04. Three tensile test specimens were prepared from the each of the FSWed plate specimens. The tensile tests were performed in a computerized tensile testing machine at a cross head speed of 0.1 mm.min<sup>-1</sup>.

### 2.4. Sugeno – Fuzzy logic model

Fuzzy logic is a mathematical tool to detect the uncertainty in a system [14]. The output of the fuzzy logic system depends on the rules framed by the user and hence it is an expert system [15]. In this study, Sugeno – Fuzzy logic system was utilized to predict the TS of the FSWed specimen. Sugeno inference mechanism uses Adaptive Neuro Fuzzy Inference System (ANFIS), which is a networked architecture that efficiently maps the inputs and outputs through membership functions and associated parameters. ANFIS efficiently tunes the membership function parameters, which helps it to learn the data and model the relationship efficiently.

## 3. Results and Discussion

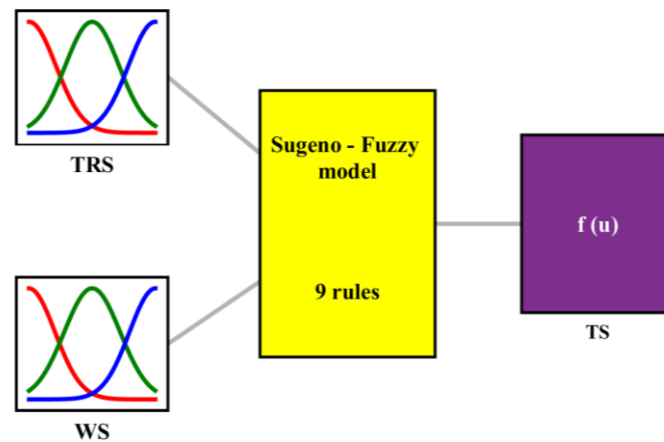
### 3.1. Tensile strength

The average TS of the specimens was found from the tensile test results and it is given in the Table 2. The maximum TS obtained was found to be 273 MPa for specimen obtained from the workpiece, which was FSWed at WS of 15 mm.min<sup>-1</sup> and TRS of 1050 rpm.

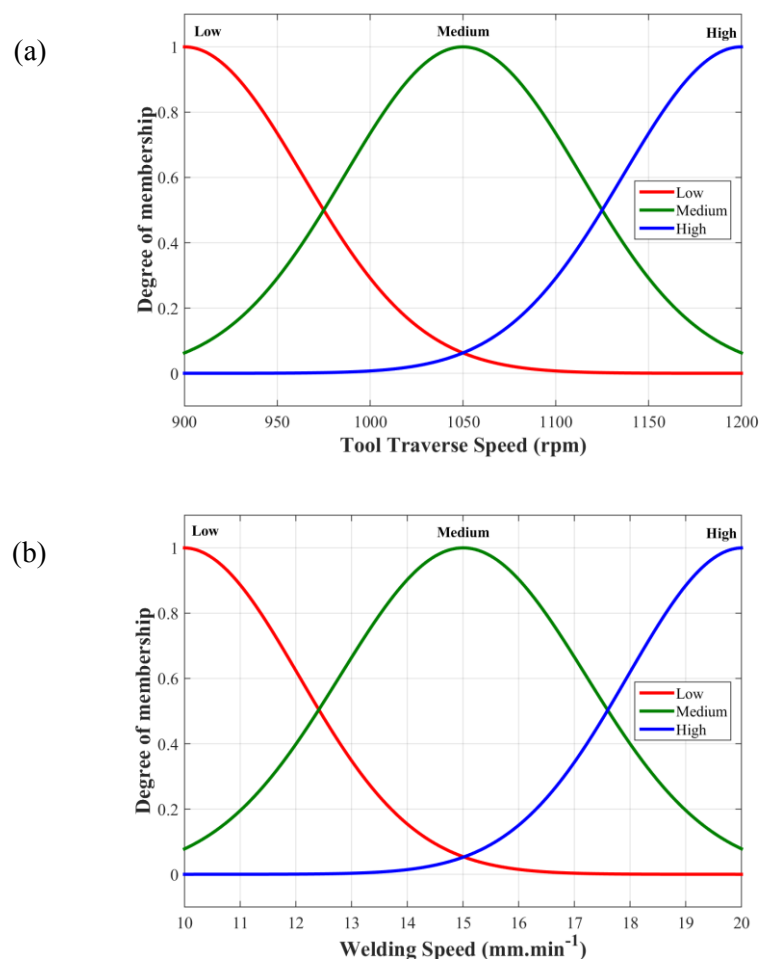
### 3.2. Sugeno Fuzzy Model

The schematic of the developed model is shown in the Figure 1. The fuzzy logic model consists of inputs, fuzzification module, inference mechanism, defuzzification module and output. The FSW process parameters TRS and WS were inputs to the fuzzification module and TS is the output from the defuzzification module.

Gaussian membership function was used to assign a membership value to the element, which has high efficiency in assigning the membership value to the element [16]. Gaussian membership functions for the low, medium and high values of TRS and TTS is shown in the Figure 2 (a) and Figure 2 (b) respectively. This process of assigning a membership value for crisp quantity is known as fuzzification.



**Figure 1.** Layout of Sugeno – Fuzzy model



**Figure 2.** Gaussian membership function for a) Tool Rotation Speed; (b) Welding Speed

The fuzzified values are given as input to the Sugeno inference mechanism. In the Sugeno inference system, the ANFIS is trained using the training data. In this study, 80% of arbitrarily chosen experimental data was used for training the network.

The remaining data were used for testing and validation. The ANFIS was trained with zero error tolerance. Epoch number signifies the maximum number of times the network could be trained with training data. As over training of the network reduces the generalizing ability of the network, the epoch number was chosen as three. The predicted values of is given in the Table 2.

**Table 2.** Experimental design for FSW, experimental and predicted TS

Sl.	Coded Value		Real Value		Tensile Strength (MPa)	
	N	V	TRS	WS	Experimental	Predicted
1	-1	-1	900	10	178	178
2	1	-1	1200	10	210	210
3	-1	1	900	20	169	169
4	1	1	1200	20	198	198
5	-1	0	900	15	220	220
6	1	0	1200	15	252	252
7	0	-1	1050	10	223	223
8	0	1	1050	20	210	210
9	0	0	1050	15	273	271
10	0	0	1050	15	272	271
11	0	0	1050	15	267	271
12	0	0	1050	15	269	271
13	0	0	1050	15	268	271

The percentage error in prediction was calculated using the equation (1).

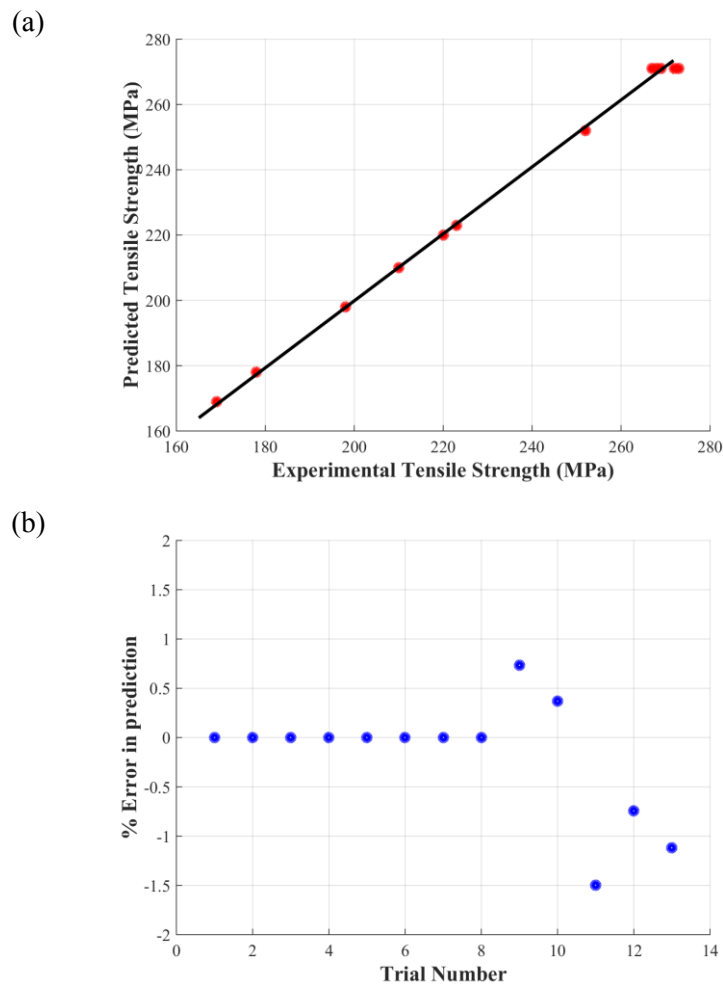
$$\% \text{ Error in Prediction} = \left( 1 - \frac{\text{Predicted value}}{\text{Experimental value}} \right) \times 100 \quad (1)$$

As observed from the Figure 3 (a), a linear relation was observed between the experimental and predicted TS, indicating high efficiency of the developed model. The variation in prediction error is plotted as a graph shown in the Figure 3 (b). The percentage error in prediction varied between -0.02 and 0.02 for all the predictors of the specimen's tensile strength. This shows that the developed model has high accuracy in prediction.

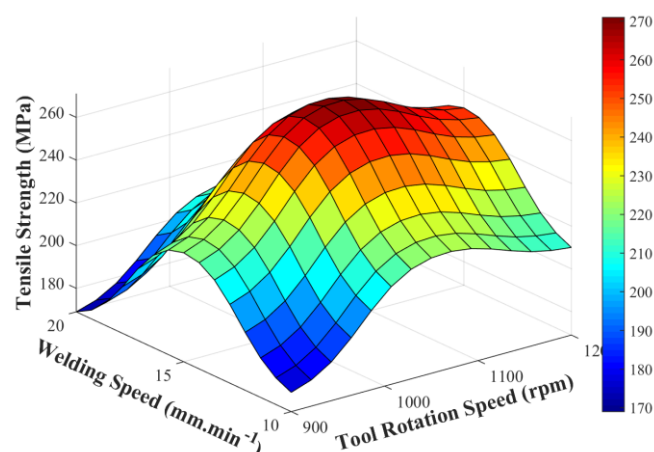
### 3.2.1. Effect of FSW process parameters

The effect of FSW process parameters TRS and WS on the TS of the joint is shown in the Figure 4. FSW process parameters influence heat input into the material, which governs the dynamic recovery and dynamic recrystallization [17]. When the heat generation is optimum, effective dynamic recovery and dynamic recrystallization occurs, refining the grains at the FSW zone [18]. The refinement of grains increased the strength of the material in line with the Hall Petch relation.

At the low TRS of 900 rpm, the heat generation is insufficient for effective dynamic recovery and dynamic recrystallization. Hence the FSW zone had coarse grains, which reduced the TS of the joints. The TS of the FSWed specimens increased with increase in TRS.



**Figure 3.** (a) Experimental vs. Predicted TS; (b) Variation in prediction error among the specimens



**Figure 4.** Effect of TRS and WS on the tensile strength of FSWed joints

Beyond a TRS of 1050 rpm, the TS of the FSWed specimens decreased. However the TS of the FSWed specimens at 1200 rpm was found to be greater than the TS of the FSWed specimens at 900 rpm. The formation of weld defects such as flash and pores reduced the TS of the specimens FSWed at high TRS of 1200 rpm.

The heat generation at the interface of the FSW tool and the workpiece is inversely proportional to the WS. At low WS of  $10 \text{ mm.min}^{-1}$ , excess heat input into the material resulted in coarsening of the grains, reducing the TS of the specimens. FSW of specimens at high TTS of  $20 \text{ mm.min}^{-1}$  resulted in insufficient heat for dynamic recovery and dynamic recrystallization. It resulted in coarse grains and reduction in TS as a consequence. It is observed that the WS of  $15 \text{ mm.min}^{-1}$  and TRS of 1050 rpm produced optimum heat for grain refinement, resulting in peak TS among the tested specimens.

#### 4. Conclusion

Dissimilar welding of aluminium alloy AA2024 and AA7075 was achieved using Friction Stir Welding process. The FSW trials were conducted by varying the FSW process parameters as per central composite design and the TS of the joints were measured. The specimens FSWed at WS of  $15 \text{ mm.min}^{-1}$  and TRS of 1050 rpm produced optimum heat for grain refinement, which resulted in peak TS among the FSWed specimens. A Sugeno – Fuzzy model was developed using gaussian membership function for process parameter and Adaptive Neuro Fuzzy Inference System was developed to interrelate the FSW process parameters with the response (TS). The results demonstrate that TRS and WS are high influential parameters in friction stir welding of dissimilar aluminium alloys.

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