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# Development of Acoustic Emission and Motor Current Based Fuzzy Logic Model for Monitoring Weld Strength and Nugget Hardness of FSW Joints

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## Abstract

Friction stir welding (FSW) is a solid-state welding process that is ideally suitable for joining materials with low melting point, such as aluminium alloys. In this paper, development of a fuzzy logic model to monitor weld strength and nugget hardness of friction stir butt-welded AA6063-T6 aluminium alloy plates is presented. FSW experiments were carried out with different process parameters in vertical spindle milling machine. The generated acoustic emission (AE) and machine spindle motor current during the FSW process were acquired with the aid of data acquisition system. A fuzzy logic model based on AE signal and motor current was developed to predict the weld strength and nugget hardness. The fuzzy model accuracy was validated with experimental data. The proposed model could be used for online weld monitoring of FSW process within a range of process parameters.

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*Keywords:* Friction Stir Welding; Acoustic Emission; Motor Current; Fuzzy Logic.

## 1. Introduction

Friction Stir Welding (FSW) a solid-state welding process that is suitable for joining light materials such as aluminium and magnesium alloys. This paper presents the development and validation of fuzzy logic model to monitor the weld strength and nugget hardness of friction stir butt-welded AA6063-T6 plates, which are widely used

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to produce components in ship building, aerospace, automobile and furniture manufacturing industries. The weld tensile strength and nugget hardness are important parameters in deciding the quality of the welded joint. Since the FSW process is carried out in machine tools, monitoring of FSW process is quite complex due to non-linearity in process parameter interactions, machine tools and drives dynamics. Hence, it requires advanced sensor and soft computing techniques, such as fuzzy logic to develop monitoring systems.

Acoustic emission technique is one of the advanced evaluation tools, which has the potential application for real time monitoring of machining process. Acoustic emission is the phenomenon by which transient elastic waves are generated by rapid release of energy from localized sources within a deforming material. Acoustic emission monitoring technique has been used extensively to study various deformation and welding processes in different materials [1, 2]. AE technique is found to be a feasible approach for detecting tool profile, material flow pattern, microstructures and mechanical properties in FSW process [3]. FSW process generally produces signals that represent burst acoustic emissions, which characterizes the unsteady processes [4]. The studies revealed the frequency range considered for the friction stir welding process is between 100 kHz and 300 kHz.

As compared to AE techniques, the application of motor current measurement technique is a cost effective method for process control and machining operations. This method of non-invasive measurement increases the potential for industrial applications. In electrical monitoring methods, the stator current of an induction motor is used to monitor various kinds of machine tool and process defects. The method of spindle motor current and voltage measurements were employed for online estimation of tool wear monitoring in milling operations [5].

In order to develop an intelligent monitoring system for FSW process, the data processing is essential. Soft computing techniques are necessary for processing these data. Fuzzy logic technology is one of the artificial intelligent strategies, which is widely used because of its practical impact on dynamic process control. Fuzzy modelling was used to analyse the emitted electromagnetic radiation fundamental frequencies during the tensile failure of the FSW welds produced at different process parameters [6]. Zhang et al [7] have developed a systematic data-driven fuzzy modelling approach to model FSW behaviour relating to AA5083 aluminium alloy with micro structural features, mechanical properties and overall weld quality. It is found that the fuzzy logic approach is widely adopted for monitoring the FSW process. It is observed from the literature that the technique of weld strength and nugget hardness monitoring through acoustic emission and motor current is not yet reported. This paper presents the application of acoustic emission and motor current measurement techniques for monitoring weld tensile strength and hardness during friction stir welding of AA6063-T6 aluminium alloy plates.

## 2. Experimental setup

In the present work, FSW experimental setup was developed in a conventional vertical milling machine with a vertical spindle attachment to accommodate FSW tools. Automatic feed system in the milling machine is used to control the traverse speed of the work table. Since the FSW involves large forces, fixture with proper clamps was indigenously designed to prevent slipping of specimens during FSW process. Data acquisition systems (DAQ) with suitable instrumentation were integrated for acquiring the AE and motor current to monitor the process. Fig. 1 shows the AE sensor mounted on FSW fixture to measure the AE signal features during the process. R80D AE sensor from Physical Acoustic Corporation was used with a data acquisition system to acquire the AE signals during the process. AEWin<sup>®</sup> software was used to analyse the acquired AE signals. Fig. 2 represents the arrangement for Hall Effect non-contact current sensor to measure the line current of main spindle motor using PCI based data acquisition system from National Instruments. Labview software is used to acquire and analyse the signal acquired from the current sensor.

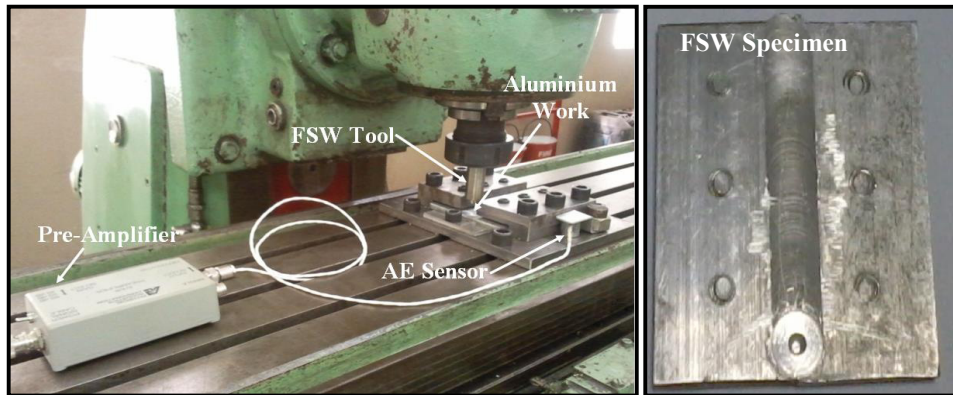


Fig. 1. AE sensor arrangement on FSW fixture and FSW specimen



Fig. 2. Hall Effect current sensor and data acquisition system

AA6063-T6 aluminium alloy plates of size 100 mm x 50 mm x 6 mm were used as work materials and FSW tool was fabricated from SS316 stainless steel rod with 18 mm shoulder diameter and 6 mm pin diameter. The FSW experiments to make butt joint between pair of aluminium alloy plates are carried out with by varying the process parameters such as, spindle rotational speed, tool feed and tool shoulder plunge depth, up to three levels. Table 1 presents the selected process parameters and levels.

Table 1. Process parameters and levels

Parameters	Levels		
	1	2	3
Spindle rotation (rpm)	710	1000	1400
Tool traverse feed (mm/min)	20	40	80
Tool shoulder plunge (mm)	0.2	0.3	0.4

### 3. Acoustic emission and motor current measurements

In the present work, 27 experiments were carryout with three levels of process parameter combinations. During each experimental run, acoustic emission and motor current signals were acquired using DAQ systems.

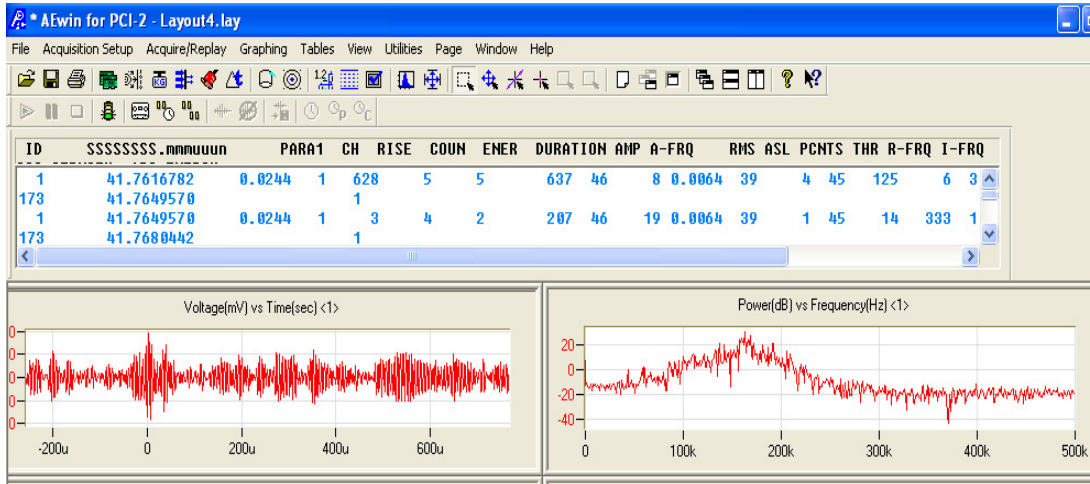


Fig. 3. Measurement of AE signal during FSW at 1000 rpm and 40 mm /min

Fig. 3 illustrates the AE signal acquired during FSW experiment conducted at tool rotational speed of 1000 rpm and traverse feed of 40 mm/min. The FSW experimental results show that AE parameters, such as total hits, average counts, rise time and AE energy have significant effect on the tensile strength and weld nugget hardness of FSW specimen. Among these AE parameters, AE total hits and average counts have better correlation with output parameters and show different trends in relation to tensile strength and nugget hardness [8]. Fig. 4 shows the motor line current measurement during FSW at a tool rotational speed of 1000 rpm and traverse feed of 40 mm /min. For all the 27 FSW experimental trials with different process parameter combinations, AE parameters such as AE total hits, average counts and motor line current Root Mean Square values were measured.

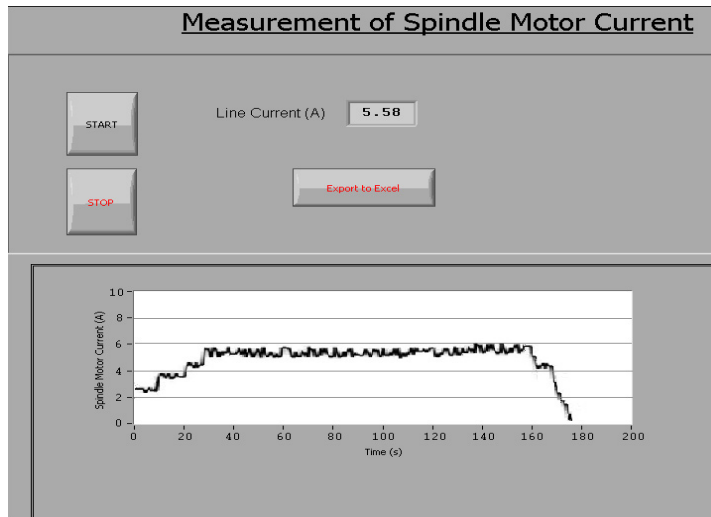


Fig. 4. LABVIEW interface for motor current measurement during FSW at 1000 rpm and 40 mm /min

Further, three standard test specimens were prepared from the components obtained from each FSW experimental trial and weld tensile strength and nugget hardness were assessed using standard test equipments.

### 4. Development of Fuzzy Logic model

Fuzzy logic can handle problems with imprecise and incomplete data and it can model nonlinear functions of arbitrary complexity. A fuzzy logic system can match any set of input-output data. The number of conditional "if-then" rules used in fuzzy logic models provide more accurate representations of real world behaviour of systems. If the system is varying, then fuzzy will produce a better solution than conventional techniques.

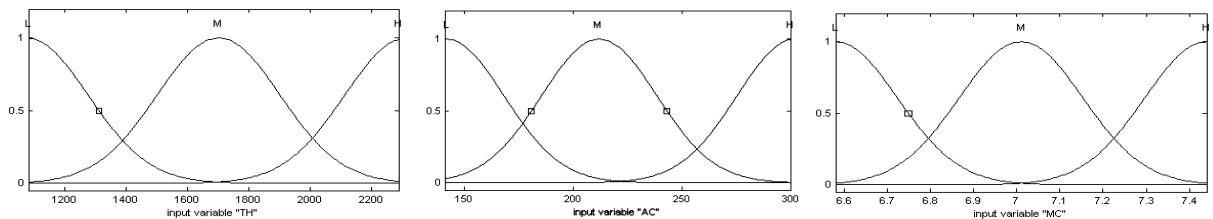
Table 2 shows the framework for the fuzzy logic model based on AE parameters and spindle motor current. A fuzzy logic model of Mamdani type with three input variables and two output variables is developed to study, analyze and verify the behaviour of FSW process with 27 rules.

Fuzzification is the process of converting a precise value to a fuzzy quantity. The proposed fuzzy logic model takes AE total hits, AE average counts and motor current value as input variables. The weld tensile strength and nugget hardness are considered as output variables. Each input and output variables are fuzzified into three fuzzy sets, which are Low, Medium and High. The fuzzy linguistic variables and range of values for input and output parameters are shown in Table 2.

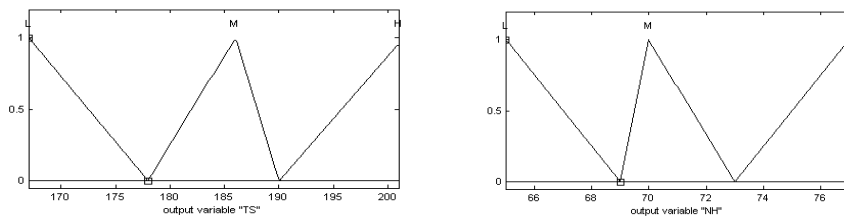
Table 2. Process parameters and fuzzy linguistic variables

Input variables		Range of values acquired during FSW experiments
Process response parameters	Linguistic variables	
TH - Total hits	L- Low; M- Medium; H- High	1082 - 2287
AC - Average counts		141 - 300
MC - Motor current (A)		6.58 – 7.44
Output variables		
TS - Weld Strength (MPa)	L- Low; M- Medium; H- High	167 - 201
NH - Nugget Hardness (Hv)		65 - 77

Membership functions are the graphical representation of fuzzy sets. The membership functions for FSW fuzzy model input and output variables are shown in Fig. 5. Gaussian membership function is used in this fuzzy model to describe the fuzzy sets for input variables. The output fuzzy variables are inferred by triangular membership functions.



(a) Membership functions for AE total hits; (b) Membership functions for AE average counts; (c) Membership functions for spindle motor current



(d) Membership functions for FSW joint tensile strength; (e) Membership functions for FSW nugget hardness

Fig. 5. Input and output membership functions

Based on the relationship from the FSW experimental data, fuzzy rules are formed, which are describing the relationship between the input and output variables. A set of 27 rules have been formulated based on experimental trials and the fuzzy rules are shown in Fig. 6. The fuzzy model was simulated in the MATLAB 8.1 software. The overall fuzzy output of Mamdani fuzzy model is obtained by adopting 'AND' operation to trigger rules.

1. If (TH is L) and (AC is L) and (MC is L) then (TS is M)(NH is L) (1)
2. If (TH is L) and (AC is H) and (MC is H) then (TS is L)(NH is M) (1)
3. If (TH is L) and (AC is H) and (MC is H) then (TS is L)(NH is M) (1)
4. If (TH is M) and (AC is L) and (MC is L) then (TS is H)(NH is M) (1)
5. If (TH is H) and (AC is M) and (MC is L) then (TS is H)(NH is M) (1)
6. If (TH is L) and (AC is H) and (MC is H) then (TS is L)(NH is L) (1)
7. If (TH is M) and (AC is L) and (MC is L) then (TS is M)(NH is M) (1)
8. If (TH is H) and (AC is L) and (MC is L) then (TS is H)(NH is M) (1)
9. If (TH is M) and (AC is M) and (MC is H) then (TS is M)(NH is M) (1)
10. If (TH is H) and (AC is L) and (MC is L) then (TS is H)(NH is M) (1)
11. If (TH is H) and (AC is L) and (MC is L) then (TS is H)(NH is M) (1)
12. If (TH is L) and (AC is M) and (MC is H) then (TS is M)(NH is L) (1)
13. If (TH is H) and (AC is L) and (MC is L) then (TS is H)(NH is M) (1)
14. If (TH is H) and (AC is L) and (MC is L) then (TS is H)(NH is H) (1)
15. If (TH is H) and (AC is L) and (MC is L) then (TS is H)(NH is H) (1)
16. If (TH is H) and (AC is L) and (MC is L) then (TS is H)(NH is M) (1)
17. If (TH is H) and (AC is L) and (MC is M) then (TS is H)(NH is M) (1)
18. If (TH is M) and (AC is L) and (MC is H) then (TS is M)(NH is M) (1)
19. If (TH is L) and (AC is L) and (MC is M) then (TS is M)(NH is L) (1)
20. If (TH is M) and (AC is L) and (MC is M) then (TS is M)(NH is M) (1)
21. If (TH is M) and (AC is H) and (MC is H) then (TS is L)(NH is L) (1)
22. If (TH is M) and (AC is M) and (MC is M) then (TS is M)(NH is M) (1)
23. If (TH is H) and (AC is M) and (MC is L) then (TS is H)(NH is H) (1)
24. If (TH is M) and (AC is H) and (MC is H) then (TS is L)(NH is L) (1)
25. If (TH is L) and (AC is H) and (MC is H) then (TS is L)(NH is L) (1)
26. If (TH is L) and (AC is H) and (MC is H) then (TS is M)(NH is L) (1)
27. If (TH is L) and (AC is H) and (MC is H) then (TS is L)(NH is L) (1)

Fig. 6. Fuzzy rule set for AE parameters and motor current based fuzzy logic model

Defuzzification is the conversion of a fuzzy quantity to a precise crisp value. In this fuzzy logic model, Centroid of Area (COA) defuzzification scheme is applied to determine the crisp value for weld tensile strength and nugget hardness of FSW joints for given inputs. Since COA scheme provides appropriate steady state performance and capable to provide good results, it is used as a standard defuzzification method in experimental and industrial fuzzy controllers.

The main spindle motor current is combined with AE parameters as fuzzy model inputs and the fuzzy model predicts the weld tensile strength and weld nugget hardness of friction stir butt-welded aluminium alloy plates

## 5. Results and discussions

A graphical user interface in MATLAB 8.1 software is used to predict the weld tensile strength and nugget hardness for the given input values of AE parameters and motor current. The experimental FSW response parameters, such as AE total hits, AE average counts and motor current are fed as input to fuzzy logic model and the output variables, weld tensile strength and nugget hardness are observed. The weld strength and nugget hardness 3D surface plots are obtained by simulating the fuzzy logic model in LABVIEW software environment.

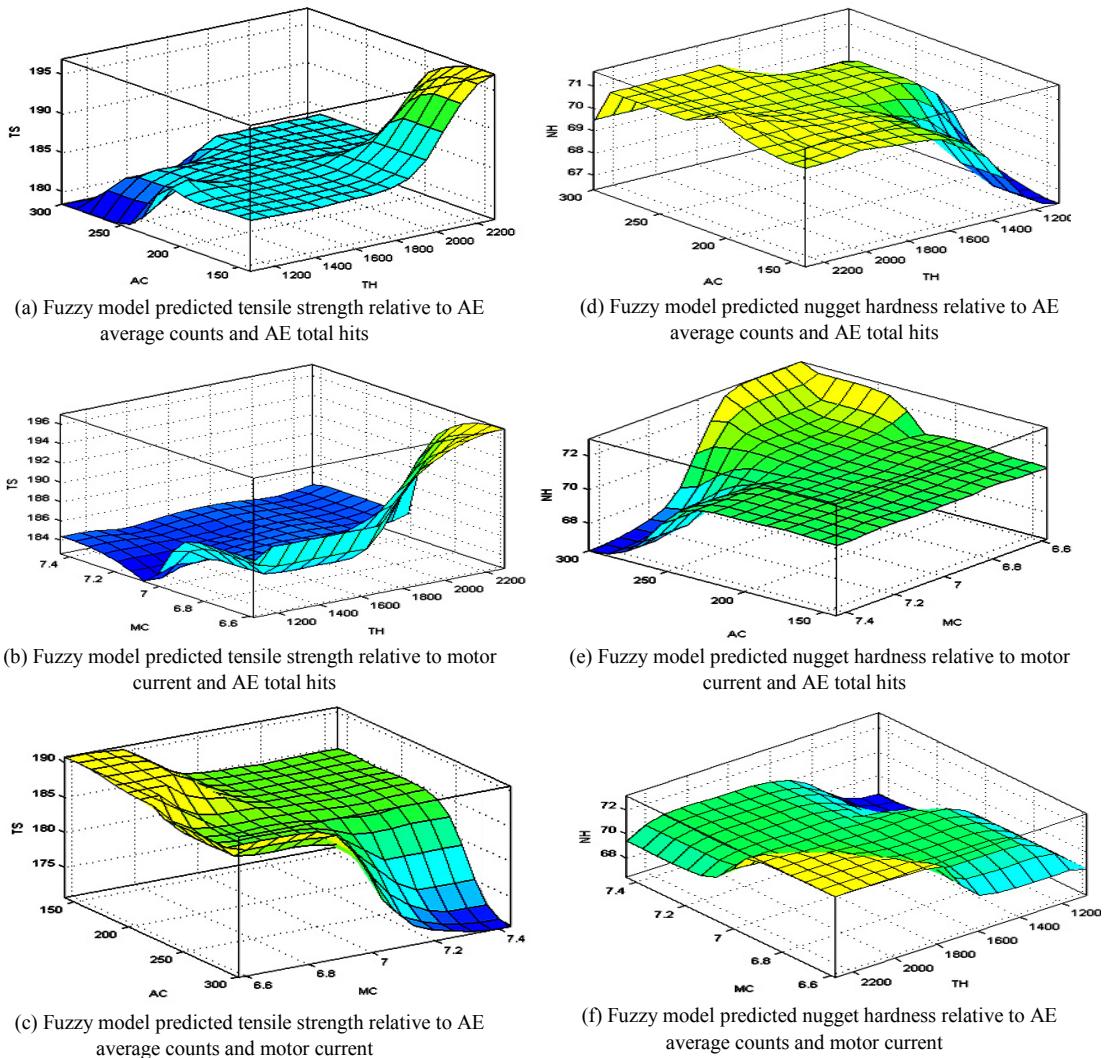


Fig. 7. Fuzzy Logic model 3D response plots

Fig. 7(a), Fig. 7(b) and Fig. 7(c) shows the surface plots obtained by defuzzification to illustrate the relationship of AE total hits, AE average counts and motor current with tensile strength of FSW joint. As it can be seen in Fig. 7(a), there is significant increase in weld tensile strength of FSW joint with the decrease in AE average counts and increase in AE total hits. However, the weld tensile strength reaches a maximum value, when AE total hits of 2200 and AE average counts of 150. It is clearly seen that both AE parameters are very significant to influence the tensile strength. However, at the lower levels of AE average counts and AE total hits, the weld tensile strength does not undergo any change. It is observed from Fig. 7(b), there is an increase in tensile strength of FSW joint at low motor current and higher value of AE total hits. The weld tensile strength reaches a maximum value at motor current of 6.6 A and AE total hits of 2200. It is found that, when motor current is more than 7 A, the weld tensile strength is considerably low, irrespective of the change in AE total hits. When the motor current is less than 7 A, the weld tensile strength of FSW joint increases with increase in AE total hits.

Fig. 7(c) illustrates the relationship between tensile strength with AE average counts and motor current. There is an increase in tensile strength of FSW joint at low motor current and AE average counts values. The tensile strength reaches a maximum value when motor current less than 6.6 A and AE average counts of 150. It is observed that,

when motor current is less than 6.8 A, the tensile strength is considerably higher, irrespective of change in AE average counts.

Fig. 7(d), Fig. 7(e) and Fig. 7(f) shows surface plots relating the weld nugget hardness with AE total hits, AE average counts and spindle motor current. Fig. 7(d) shows the effect of AE total hits and average counts on FSW nugget hardness. It is found that the nugget hardness reaches a maximum value, when AE total hits are above 1400 and AE average counts are 200. The AE average counts do not have significant effect on nugget hardness when AE total hits are above 1600. As it can be observed in Fig. 7(e), there is significant increase in nugget hardness of FSW joint at motor current is 6.6 A and AE total hits are 2200. However, nugget hardness reaches maximum value when motor current is in the range of 6.6 A to 7 A and AE total hits are above 1800. The nugget hardness is very low when motor current is 7.4 A and AE total hits is 1200. It is observed from Fig. 7(f), there is a considerable increase in nugget hardness, when motor current is less than 7 A and AE average counts are in the range of 250 to 300. The maximum value of nugget hardness is obtained when AE average counts are 300 and motor current values are in the range of 6.6 to 5.8 A. It is obvious that the intense reduction in nugget hardness occurs when motor current increase from 7 A and AE average counts are 300. There is no significant variation in nugget hardness, when the AE average counts are in the range of 150 to 250, irrespective of variation in spindle motor current.

The predicted values of weld tensile strength and nugget hardness using fuzzy model and the corresponding experimental values for the given AE parameters and motor current are used to quantify the performance of the proposed fuzzy model in terms of percentage prediction error, which is calculated using the equation (1),

$$\% \text{ Prediction Error} = \frac{(\text{Experimental data} - \text{Fuzzy predicted data})}{\text{Experimental data}} \times 100 \tag{1}$$

The individual error percentage for each experimental trial is calculated with reference to experimental data. Fig. 8 depicts the comparison between fuzzy model estimated values of output parameters with experimental results. The fuzzy logic model estimated results demonstrated a close agreement with experimental data with an accuracy of 98.5% for joint tensile strength and 98.6% for weld nugget hardness.

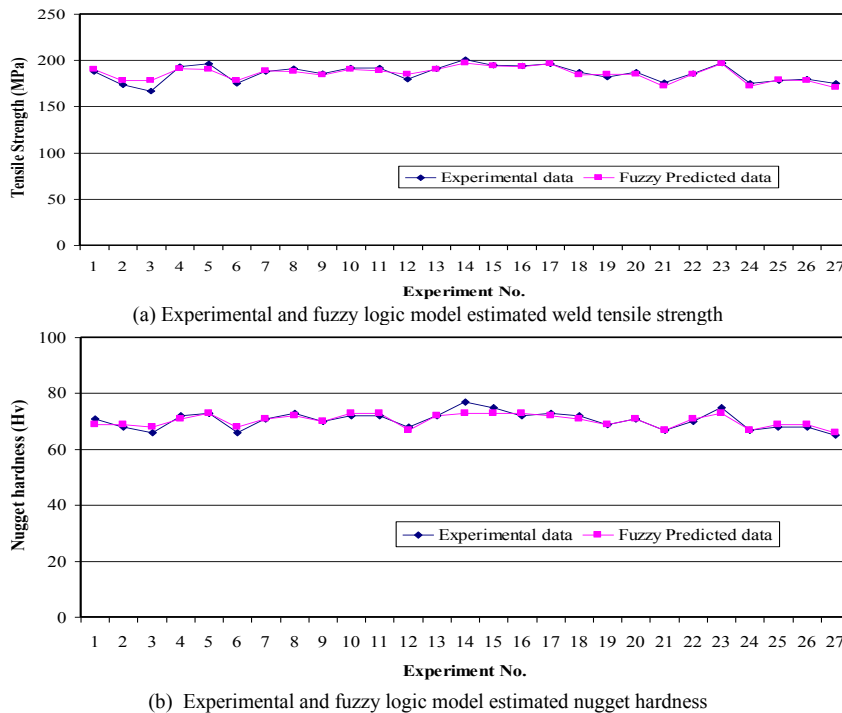


Fig. 8. Comparison between experimental and fuzzy logic model estimated weld properties



These results established that the proposed fuzzy logic model provides a proficient approach to analyse the relationship between different FSW process and response parameters on weld tensile strength and nugget hardness, graphically. Hence, it will be helpful to identify the AE parameters and motor current values, which provides a maximum weld tensile strength of the FSW joints within a range of process parameters.

## 6. Conclusions

Experimental investigation was carried out to understand the influence of variation in process parameters on mechanical properties of FSW joints. The measured acoustic emission signal parameters and motor current values were used to develop fuzzy logic model to monitor joint tensile strength and nugget hardness of friction stir butt-welded AA6063-T6 plates. It was observed that the FSW process parameters, such as tool rotational speed, feed rate and plunge depth were notably influencing weld tensile strength and nugget hardness, which were well indicated by AE and motor current signals. The developed fuzzy logic model was found with absolute error percentage of 1.5% and 1.4% for weld tensile strength and weld nugget hardness of FSW joint respectively. Hence, the developed fuzzy logic model could be used to predict the weld tensile strength and nugget hardness within the specified range of input parameters considered.

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