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Research Paper

OPTIMIZATION OF PROCESS PARAMETERS FOR FRICTION STIR WELDING OF ALUMINUM ALLOY AA6061 USING SQUARE PIN PROFILE

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Friction stir welding (FSW) is an innovative solid state joining technique and has been employed in aerospace, rail, automotive and marine industries for joining aluminium, magnesium, zinc and copper alloys. AA6061 aluminum alloy (Al-Mg-Si alloy) has gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to-weight ratio and good corrosion resistance. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. In present study, friction stir butt welds made of 6061 Al Alloys were performed with various welding parameters such as Tool Rotational Speed, Welding Speed and Axial Force using tool has Square Pin Profile. Experiment has been carried out on Twenty-Seven joints have been made on 6061 Al Alloy plates of 6.35 mm thick of same nature and tested for its Tensile, Impact and Hardness properties. Using ANOVA, influence of FSW Process Parameters is evaluated and optimum welding conditions for maximizing mechanical properties of the joint is determined. An Artificial Neural Network (ANN) model was developed for the analysis and a comparison was made between experimental and predicted data.

Keywords: Friction Stir Welding, Aluminum Alloy, Tool Rotational Speed, Welding Speed, Axial Force, Tensile Strength, Impact Strength, Hardness, ANOVA, ANN

INTRODUCTION

Friction Stir Welding (FSW) was invented at The Welding Institute (TWI) of the United Kingdom (Cambridge) in 1991 as a solid-state joining technique and was initially applied to Aluminum Alloys (Dawes C and Thomas W, TWI Bull, 1995; Thomas W M, *et al.*, 1991). Friction Stir Welding is a solid state joining process combining deformation heating and mechanical work to obtain high quality, defect free joints. Friction Stir Welding is especially well suited to joining Aluminum Alloys in a large range of plate thickness and has particular advantages over fusion welding when joining of highly alloyed Aluminum is considered. It is proving to be far more forgiving to use then arc welding techniques

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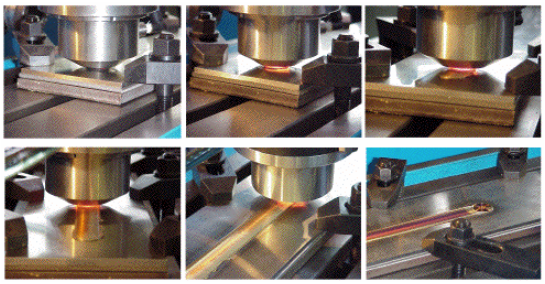
and can consistently produce long welds, especially between extrusions, of high quality and with very low distortion. FSW can be applied to most geometric structural shapes and to various types of joints, such as butt, lap, T-butt, and fillet shapes (Dawes C J and Thomas W M, Weld J, 1996; Mishra R S and Ma Z Y, 2005). The most convenient joint configurations for FSW are butt and lap joints.

Principle of Operation

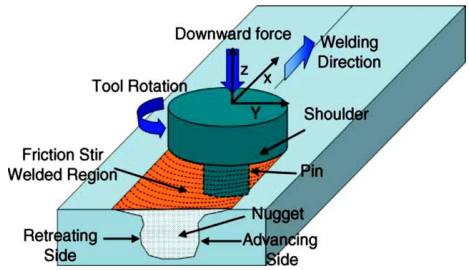
The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and subsequently traversed along the joint line. Figure 1 illustrates process definitions for the tool and workpiece.

Figure 1: Illustrates Process Definitions for the Tool and Workpiece



Most definitions are self-explanatory, but advancing and retreating side definitions require a brief explanation. Advancing and Retreating Side orientations require knowledge of the tool rotation and travel directions (Liu G, *et al.*, 1997; Rhodes C G, *et al.*, 1997). In Figure 1, the FSW tool rotates in the counterclockwise direction and travels into the plunge (or left to right). In Figure 2 the advancing side is on the right, where the tool rotation direction is the same as the tool travel direction (opposite the direction of metal flow), and the retreating side is on the left, where the tool rotation is opposite to the tool travel direction (parallel to the direction of metal flow) (London B, *et al.*, 2001).

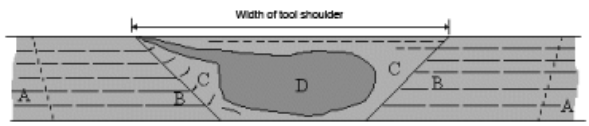
Figure 2: Schematic Drawing of Friction Stir Welding



The tool serves three primary functions, that is, heating of the workpiece, movement of material to produce the joint, and containment of the hot metal beneath the tool shoulder.

The first attempt at classifying Friction Stir Welded microstructures was made by Threadgill (Threadgill P L, TWI Bull, 1997). Figure 3 identifies the different micro structural zones existing after FSW, and a brief description of the different zones is presented.

Figure 3: Various Microstructural Regions in the Transverse Cross Section of a Friction Stir Welded Material



A, Unaffected material or parent metal; B, Heat-affected zone; C, Thermo-mechanically affected zone; D, Weld nugget.

EXPERIMENTAL SET UP

The base material used in the investigation is 6061 Aluminum Alloy and rolled plates of 6.35 mm thickness have been used as the

base material for preparing single pass welded joints. Aluminum 6061 is a precipitation hardening Aluminum Alloy, containing magnesium and silicon as its major alloying elements. It has good mechanical properties and exhibits good weld ability. The following Tables 1 & 2 shows the chemical, mechanical and physical properties of AA6061.

Table 1: Chemical Composition of AA6061

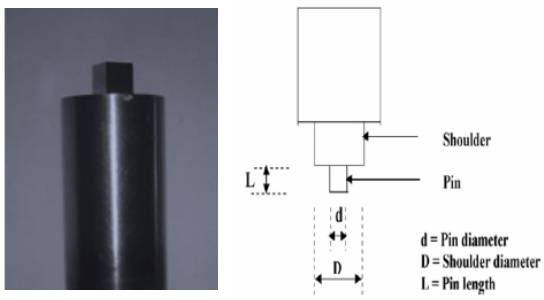
Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6061	0.4-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Remainder

Table 2: Mechanical and Physical Properties of AA 6061

Young's Modulus (G Pa)	Yield Strength (M Pa)	Ultimate Tensile Strength (M Pa)	% of Elongation	Density (Kg/m^3)	Hardness (VHN)	Melting Range °C	Thermal Conductivity W/m-k	Specific Heat J/Kg-°C
68.9	235	283	26.4	68.9	107	582-652	167	0.896

The Friction Stir Welding technique uses a non-consumable rotating tool to make the joint. The tool consists of shank, body, shoulder, probe (or) pin. The tool used in this process was made of Tungsten carbide which has a Square Pin profile has shown in Figure 4.

Figure 4: Tool Used for Friction Stir Welding



TAL Vertimech V-350 Vertical Machining Centre is used to fabricate the required joints. It is equipped with high precision and heavy loading series linear guide ways on 3 axes.

METHODOLOGY

Three process parameters Tool Rotational Speed (N), Welding Speed (S), Axial Force (F), which contribute to heat input and subsequently influence friction stir welded aluminium joints, were selected for this study. The parameters and their levels are shown in Table 3. This paper, by using full factorial

Table 3: Process Parameters and their Levels

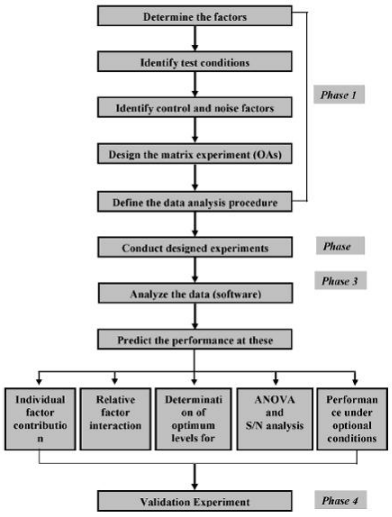
Process Parameters	Level 1	Level 2	Level 3
Tool Rotational Speed (N), rpm	1200	1600	2000
Welding Speed (S),mm/min	48	60	72
Axial Force (F),KN	1.5	2.0	2.5

experimental design L27 (3^3) with taguchi's design concept. Taguchi proposed a standard procedure for applying his method for optimizing any process shown in Figure 5. The experimental results were analyzed with the analysis of variance (ANOVA), analyses effect of Tool Rotational Speed, Welding Speed and Axial Force for Optimum Tensile Strength (TS), Impact Strength (IS) and Hardness (HV) of friction stir welded joints of AA6061 alloy.

The following procedure was adopted while carrying out the experimentation

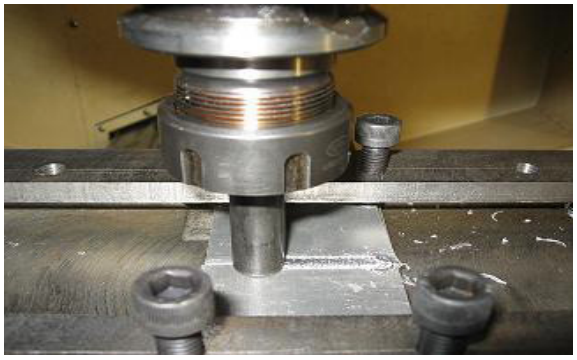
Job Preparation: The methodology for joint

Figure 5: Steps in Taguchi Methodology



considered in FSW process consist 6061 Al Alloy of 6.35 mm thickness plate (150 mm x 75 mm) (Figure 6).

Figure 6: Processing of the Joint



Welding: The tool has Square Pin with flat shoulder was used to fabricate the joints. Friction Stir Welding (FSW) was carried out according to the following sequence by using Vertical Machining Centre (VERTIMACH V-350) (Figure 7). The initial joint configuration was obtained by securing plates in position using proper clamps. Based on the literature coupled with availability of speeds on the machine, three different Tool Rotational

Figure 7: Sample of the FSW Joint

Speeds and Welding Speeds and Axial Forces were selected to carry out the experiment.

Analysis of the Joint: The analysis is carried on the joints for their mechanical properties.

Tensile specimens were prepared to required dimensions as per ASTM E8M-04 standards. Tensile test was carried out in Universal Testing Machine (Figure 8) and results are presented in Table 4.

Figure 8: Specimens After Tensile Testing

Impact Strength of the material can be found by using Impact Testing Machine. (Figure 9). Charpy test is one of the methods to find out Impact Strength of the material and results are presented in Table 4.

Figure 9: Specimens After Impact Testing

Vicker's Hardness tester was employed to measure the hardness of the welds. The hardness of each welded specimen was evaluated and results are presented in Table 4.

RESULTS AND DISCUSSIONS

Analysis of Variance (ANOVA): In order to access influence of factors on response means for each control factor to be calculated. The experimental results were analysed with the analysis of variance (ANOVA), which is used to investigation

Table 4: Shows Experimental Results of FSW Joints Using Square Pin Profile

S.No.	Tool Rotational Speed (N) in rpm	Welding Speed(S) in mm/min	Axial Force(F) in KN	Tensile Strength (TS) in MPa	Impact Strength (IS) in KN/mm^2	Hardness (HV)
1	1200	48	1.5	118.52	1.00417	28
2	1200	48	2	127.91	1.20511	32
3	1200	48	2.5	139.38	1.73175	30
4	1200	60	1.5	129.74	1.09214	31
5	1200	60	2	138.19	1.23105	34
6	1200	60	2.5	151.36	1.70415	33
7	1200	72	1.5	136.29	0.75325	34
8	1200	72	2	147.43	0.91269	32
9	1200	72	2.5	155.97	1.38734	30
10	1600	48	1.5	139.14	0.98814	31
11	1600	48	2	146.68	1.43019	30
12	1600	48	2.5	158.23	1.61023	33
13	1600	60	1.5	137.85	1.10719	32
14	1600	60	2	151.09	1.48364	31
15	1600	60	2.5	163.12	1.75963	34
16	1600	72	1.5	140.34	0.94182	30
17	1600	72	2	153.52	1.36210	33
18	1600	72	2.5	161.96	1.61832	34
19	2000	48	1.5	135.23	0.89450	31
20	2000	48	2	144.67	1.19206	33
21	2000	48	2.5	153.54	1.50673	35
22	2000	60	1.5	140.47	0.99370	32
23	2000	60	2	154.72	1.35821	34
24	2000	60	2.5	166.18	1.59613	37
25	2000	72	1.5	148.24	0.91840	35
26	2000	72	2	156.96	1.16927	33
27	2000	72	2.5	169.48	1.53704	36

which design parameters significantly affect the characteristic. The contributions of input parameters on tensile strength are identified by ANOVA. Table 5 shows the ANOVA results for responses.

Table 5: Shows ANOVA Results for FSW Joints Using Square Pin Profile

Factors	Percentage of Contribution (%)		
	Tensile Strength (TS)	Impact Strength (IS)	Hardness (HV)
N	25.6647	4.7754	27.07
S	16.5686	7.2701	13.8636
F	52.6757	80.7544	16.0314
RES	5.0910	7.2001	43.035
TOTAL	100	100	100

Estimation of Optimum Process Parameters for Tensile Strength

Based on the highest values of the Mean Levels for the significant factors N, S and F the overall optimum condition thus obtained were N3, S3 and F3. The estimated mean of the response characteristics can be computed as Tensile Strength,

(TS) = N3+S3+F3-2TS ---------- Equation.

Substituting the values of various terms in the above equation then,

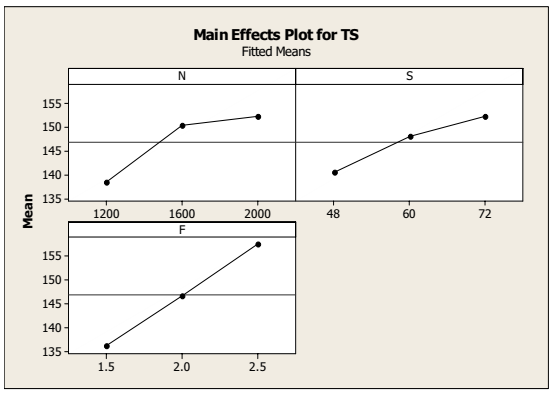
Tensile strength, TS = 152.16 + 152.24 + 157.69 - (2*146.89) = 168.31 MPa

The final step is verifying the improvement in responses by conducting experiments using optimal conditions. The confirmation test result for Tensile Strength is shown in Table 6 and Figure 10a.

Table 6: Confirmation Test for Tensile Strength

	Optimal Tensile Parameters	
	Predicted	Experimental
Setting Level	N3,S3,F3 (2000, 72, 2.5)	N3,S3,F3 (2000, 72, 2.5)
Tensile Strength (MPa)	**168.31**	**169.48**

Figure 10a: Graph of Means for Responses Using Square Pin Profile (a) Tensile Strength



Estimation of Optimum Process Parameters for Impact Strength

Based on the highest values of the Mean Levels for the significant factors N, S and F the overall optimum condition thus obtained were N2, S2 and F3. The estimated mean of the response characteristics can be computed as Impact Strength,

(IS) = N2+S2+F3-2IS ---------- Equation.

Substituting the values of various terms in the above equation then,

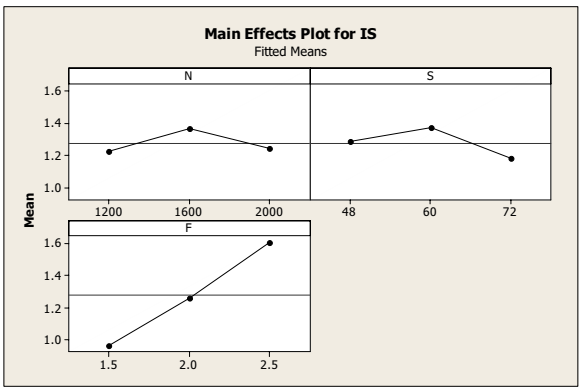
Impact Strength, IS = 1.36681+ 1.36954 + 1.60571 - (2*1.27736) = 1.78734 KN/mm2

The final step is verifying the improvement in responses by conducting experiments using optimal conditions. The confirmation test result for Impact Strength is shown in Table 7 and Figure 10b.

Table 7: Confirmation Test for Impact Strength

	Optimal Impact Parameters	
	Predicted	Experimental
Setting Level	N3,S3,F3 (1600, 60, 2.5)	N3,S3,F3 (1600, 60, 2.5)
Impact Strength (KN/mm^2)	**1.78734**	**1.75963**

Figure 10b: Graph of Means for Responses Using Square Pin Profile (b) Impact Strength



Estimation of Optimum Process Parameters for Hardness

Based on the highest values of the Mean Levels for the significant factors N, S and F the overall optimum condition thus obtained were N3, S2 and F3.The estimated mean of the response characteristics can be computed as Hardness,

(HV) = N3+S2+F3-2HV---------- Equation.

Substituting the values of various terms in the above equation then,

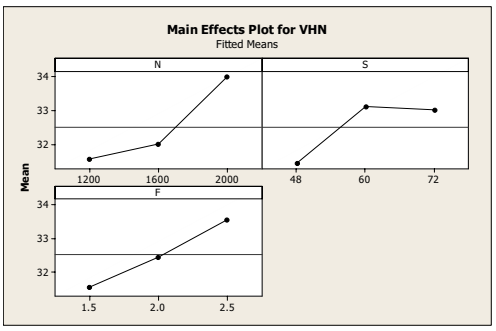
Hardness, HV = 34 + 33.56 + 33.11 - (2*32.51) = 35.65 ~ 36

The final step is verifying the improvement in responses by conducting experiments using optimal conditions. The confirmation test result for Hardness is shown in Table 8 and Figure 10c.

Table 8: Confirmation Test for Hardness

	Optimal Hardness Parameters	
	Predicted	**Experimental**
Setting Level	N3,S3,F3 (2000, 60, 2.5)	N3,S3,F3 (2000, 60, 2.5)
Impact Strength (HV)	**36**	**37**

Figure 10c: Graph of Means for Responses Using Square Pin Profile (c) Hardness



Artificial Neural Network (ANN)

ANNs are computational models, which replicate the function of a biological network, composed of neurons and are used to solve complex functions in various applications. Neural networks consist of simple synchronous processing elements that are inspired by the biological nerve systems. The basic unit in the ANN is the neuron. Neurons are conn- ected to each other by links known as synapses; associated with each synapse there is a weight factor. Details on the neural network modeling approach are given in elsewhere (Zhang Z and Friedrich K, 2003). In this present study, BP algorithm is used with a single hidden layer improved with numerical optimization techniques called Levenberg-Marquardt (LM) (Arcakhoglu E, *et al*., 2004)

DEVELOPMENT OF ANN

For this work sigmoid function is used to predict the responses. The training parameters used in this investigation are shown in Table 9. The neural network described in this paper, after successful training, will be used to predict the tensile strength of friction stir welded joints of 6061 aluminium alloy within the trained range. In present work, a three layer feed forward ANN (3-10-3) is developed as shown in Figure 11.

Figure 11: Shows Developed Feed Forward Network

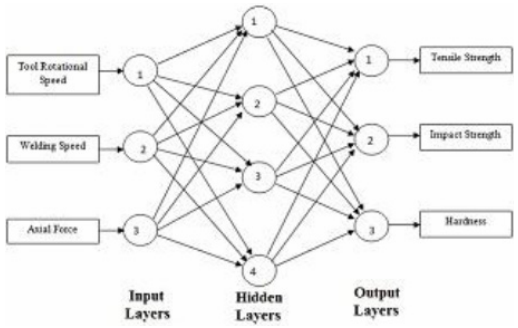


Table 9: Training Parameters used for Building Network

Number of input nodes	3
Number of hidden nodes (feed forward)	10
Number of output nodes	3
Learning rule	Levenberg-Marquardt
No. of epochs	1000
Mu	0.001
Transfer function	TANSIG (layer 1), PURELIN (layer 2)
Sample pattern vector	19 (for training), 4 (for validation), 4(for testing)

Table 10: Shows the Experimental Values vs. Predicted Values of FSW Joints

S. No.	N	S	F	Tensile Strength (TS) MPa		Impact Strength (IS) KN/mm^2		Hardness (HV)	
				Experimental Values	Predicted Values	Experimental Values	Predicted Values	Experimental Values	Predicted Values
1	1200	48	1.5	118.52	118.52	1.00417	1.00608	28	28.00
2	1200	48	2	127.91	127.90	1.20511	1.17030	32	32.00
3	1200	48	2.5	139.38	139.37	1.73175	1.53687	30	29.99
4	1200	60	1.5	129.74	129.73	1.09214	1.09819	31	31.00
5	1200	60	2	138.19	139.99	1.23105	1.23839	34	33.99
6	1200	60	2.5	151.36	151.36	1.70415	1.68837	33	32.99
7	1200	72	1.5	136.29	143.21	0.75325	0.80032	34	34.38
8	1200	72	2	147.43	147.43	0.91269	1.24249	32	31.99
9	1200	72	2.5	155.97	158.38	1.38734	1.68725	30	33.09
10	1600	48	1.5	139.14	139.13	0.98814	1.00401	31	30.28
11	1600	48	2	146.68	146.66	1.43019	1.42430	30	33.84
12	1600	48	2.5	158.23	158.15	1.61023	1.62276	33	32.99
13	1600	60	1.5	137.85	139.36	1.10719	1.10220	32	32.00
14	1600	60	2	151.09	151.08	1.48364	1.48275	31	31.31
15	1600	60	2.5	163.12	163.10	1.75963	1.75766	34	33.99
16	1600	72	1.5	140.34	148.62	0.94182	1.03280	30	30.00
17	1600	72	2	153.52	154.10	1.3621	1.36131	33	32.99
18	1600	72	2.5	161.96	161.95	1.61832	1.63083	34	31.27
19	2000	48	1.5	135.23	135.22	0.8945	0.92936	31	30.99
20	2000	48	2	144.67	144.61	1.19206	1.26872	33	32.99
21	2000	48	2.5	153.54	157.46	1.50673	1.47629	35	36.97
22	2000	60	1.5	140.47	140.46	0.9937	1.00328	32	32.22
23	2000	60	2	154.72	151.03	1.35821	1.35185	34	33.99
24	2000	60	2.5	166.18	166.09	1.59613	1.55606	37	37.00
25	2000	72	1.5	148.24	148.24	0.9184	1.03974	35	34.99
26	2000	72	2	156.96	156.95	1.16927	1.17612	33	32.99
27	2000	72	2.5	169.48	169.44	1.53704	1.52196	36	35.99

The input layer consists of three nodes for the variables Tool Rotational Speed, Welding Speed and Axial Force. The output layer consists of three nodes, for the response variable Tensile Strength (TS), Impact Strength (IS) and Hardness (HV).

ANN RESULTS

The results obtained after training and testing of Artificial Neural Networks are shown in the Table 10.

Figure 12a: Shows ANN Training Performance Graph for Responses (a) Tensile Strength

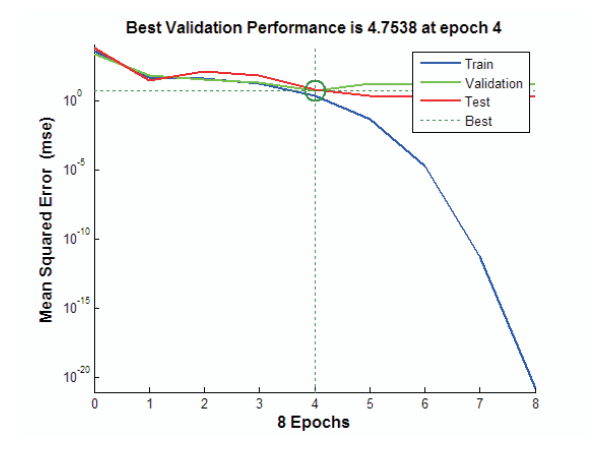


Figure 12b: Shows ANN Training Performance Graph for Responses (b) Impact Strength

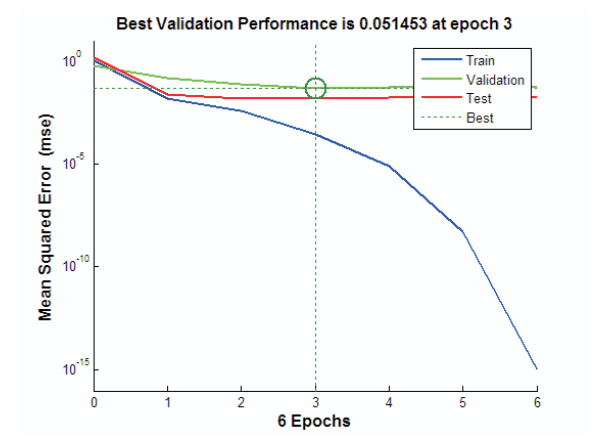
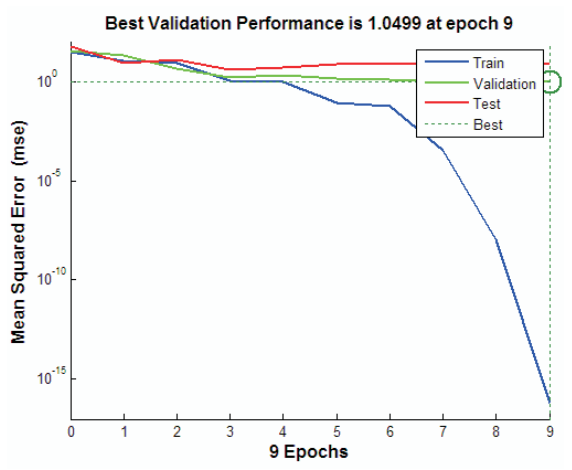


Figure 12c: Shows ANN Training Performance Graph for Responses (c) Hardness



The input-output dataset consisting of 27 patterns was divided randomly into three categories: Training dataset consist of 70% of the data, Testing dataset consist of 15% of the data and Validation dataset consist of 15% of the data. The results that are obtained for the responses (Tensile, Impact Strengths and Hardness) in ANN model are compared with experimental data and shows that the values predicted by ANN are very close to the experimental values.

CONCLUSION

This paper has describes two models for Predicting the Tensile strength of friction stir welded AA6061 aluminium alloy using ANOVA analysis and Artificial Neural Network(ANN).From this investigation, the following important conclusions are derived:

- From ANOVA results it can be concluded that the Tool Rotational Speed and Axial Force are the dominant parameters that have influence on the mechanical properties than the Welding Speed acting on the joints (Table 5).

- From the results obtained it can be concluded that
- As the Tool Rotational Speed increases, effectively Tensile Strength also increases, and the same result will be observed from Welding Speed and Axial Force for Tensile Strength.
- As the Tool Rotational Speed increases, effectively Impact Strength will be increases up to 1600rpm and decreases at 2000rpm, and in the same manner Welding Speed also effects(increases up to 60mm/min and decreases at 72mm/min), if Axial Force increases, effectively Impact Strength also increases.
- As the Tool Rotational Speed increases, effectively Hardness also increases, and in the same manner Axial Force also effects, if Welding Speed increases, effectively Hardness will be increases up to 60mm/min and slightly decreases at 72mm/min.
- It is observed that the Impact Strength initially increased with an increase in Tool Rotational Speed, Welding Speed and Axial Force. But the Impact Strength decreased with further increase in these parameters after reaching a maximum value.
- From the Tensile Test result, it is observed that the weld sample prepared at 2000 rpm Tool Rotation Speed and 72 mm/min Welding Speed and 2.5 KN Axial Force with Square Pin Profile possessed the highest Tensile Strength i.e. 169.48 MPa than the joints at other process parameters.
- From the Impact Test result, it is observed that the weld sample prepared at 1600 rpm Tool Rotation Speed and 60 mm/min Welding Speed and 2.5 KN Axial Force with Square Pin profile possessed the highest Impact Strength i.e. 1.75963 KN/mm2 than the joints at other process parameters.
- From the Hardness test result, it is observed that the weld sample prepared at 2000 rpm Tool Rotation Speed and 60 mm/min Welding Speed and 2.5 KN Axial Force with Square Pin profile possessed the highest Hardness i.e. 37 than the joints at other process parameters.
- Finally it can be concluded that the shape of the tool pin and shoulder play a very important role in obtaining better mechanical properties for the weld joints. This is evident from the results obtained for the Square Pin profile due to flat faces produces a pulsating stirring action in the flowing material.
- ANN model has been developed for prediction of responses as a function of welding parameters. The model has been proved to be successful in terms of agreement with experimental results. The proposed model can be used in optimization of welding process for efficient and economic production by forecasting the properties in welding operations.
- The results that are obtained for the response Tensile strength in ANN model and ANOVA analysis are compared with experimental data. Among these methods ANN model is easier and effective methodology in order to find out the performance output and welding conditions.

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