Chapter

Experimental Investigations on AA 6061 Alloy Welded Joints by Friction Stir Welding

Pothur Hema

Abstract

Aluminum and aluminum composites play important role in aerospace, automobile, marine and structural applications. Literature shows that some of the conventional fusion welding processes in joining of aluminum metals result in defects like porosity, distortion owing to elevated thermal conductivity and solidification shrinkage. To overcome such issues, experimental investigations are conducted using Friction Stir Welding (FSW) process in joining of metal plates of aluminum 6061 alloy. Weld joint samples are cut to required sizes and secured them in position by mechanical clamps. The setup is loaded onto Vertical Machining Centre. Nonconsumable tool tips of four different shapes of tungsten carbide and H13 materials are prepared and attached to the spindle. The machine is started and allowed spindle to rotate the tool to plunge onto metal plates along joint line. An axial force is continuously applied until sufficient heat is generated at mating surfaces for joining. Experiments are repeated at different levels by varying welding parameters. Joints are tested for their mechanical properties. The microstructural analysis is studied by SEM. Artificial Neural Network (ANN) simulation model is developed for validation. ANOVA is applied for validation of output results of mechanical properties and optimal process parameters are determined. Research shows that joints are influenced by profile of tool pin and, therefore, the rotational speed of the tool.

Keywords: AA6061 alloy, FSW, experiments, machining centre, joints

1. Introduction

Hardenable aluminum alloy namely AA6061 has played a key role in the production arena, to meet not only the strength to weight ratio but also light in weight. Magnesium and silicon are AA6061 main alloy components and thus Al-Mg-Si aluminum alloy is of medium strength and is widely used due to its superior formability, weldability, machinability, and corrosion resistance compared to other aluminum alloys. Magnesium and silicon forms Mg_2Si which in turn forms a simple eutectic system with aluminum. It is the precipitation of Mg_2Si after artificial aging and then allows the alloys to reach their full strength. Therefore, AA6061 alloy is extensively employed in ship building, marine frames, pipelines, storage tanks and applications of aircraft. Even though Al-Mg-Si alloys are without difficulty weldable, owing to reversion (dissolution) of Mg_2Si precipitates during the welding thermal cycle, they suffer from serious softening in the HAZ. This sort of mechanical deficiency poses a significant engineering issue. To enhance the mechanical characteristics of welding, it will be more suitable to overcome or minimize HAZ softening. AA 6061 aluminum alloy cannot be Tungsten Inert Gas [TIG] welded without filler wire because it leads to solidification cracking.

Moreover, the weld fusion area of aluminum alloys typically has coarse columnar grains due to the prevailing heat circumstances during solidification of the welded metal. This often results in lower mechanical welding characteristics and bad cracking resistance to hot. Hence, such is particularly suited in accordance with monitoring solidification structure of welds, but such control is often tough because on higher temperatures then thermal gradients between welds between rapport in accordance with castings yet the epi-axial makeup about growth procedure. Further, into the past as inoculation with heterogeneous nucleants, micro-cooler additions, floor nucleation triggered by using gas impingement and commencement on physical disturbance.

So as to beat these troubles between the fusion welding tactics to that amount are mechanically chronic in imitation of be a part of structural alloys, the Friction Stir Welding (FSW) is an emerging solid-state joining process in which the metal is not softened and recast. In 1991, Friction Stir Welding (FSW) was created as a solid-state joining method at the United Kingdom's Welding Institute (TWI) and applied originally to aluminum alloys [1]. FSW's fundamental concept is remarkably easy. Friction Stir Welding is an uninterrupted, hot shear, auto-genous and environmentally friendly method with a non-consumable rotating tool of a harder material than the substrate. It is found that a contraption of onion circle structure during aluminum alloy FSW welds relies upon the extent of material mixing and between dispersion, whereas the thickness of twisted aluminum lamellae, and material stream designs exceptionally rely on the geometry of the apparatus [2]. Further the temperature of welding and the stress on the material flow are depending on the axial force. In additionally, opined so much at low axial force, the structure about non-symmetrical semi-circular capabilities at the top surface concerning the weld suggests poor plasticization yet consolidation on the material underneath the have an effect on about the device shoulder.

A non-consumable rotating tool along an exceptionally designed pin and shoulder is put into the edges of the sheets or plates in conformity to be joined and after that navigated along the joint line. **Figure 1** suggests the schematic sketch of FSW. The new FSW method is noted to offer several benefits over fusion welding due to the lack of parent metal melting.

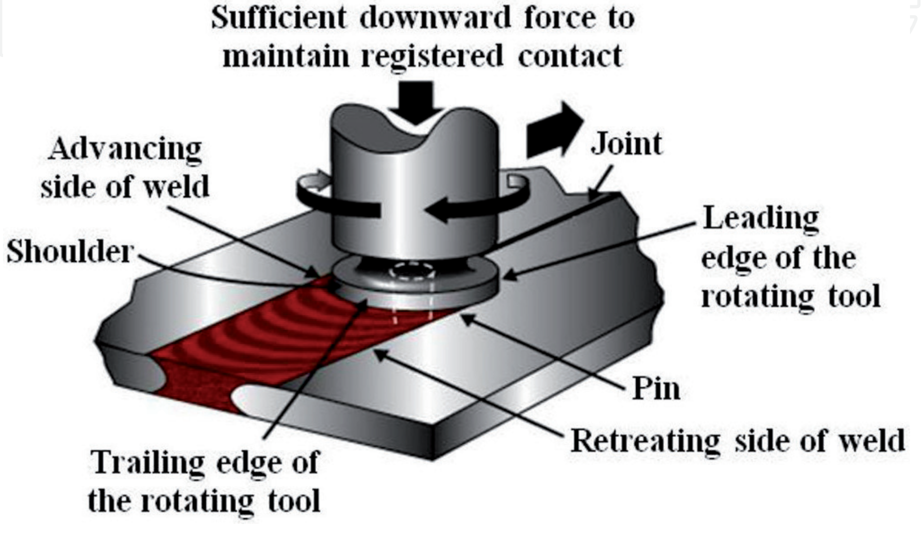

Figure 1.
Schematic representation of FSW principle.

2. Literature review

A brief literature review is presented based on the earlier publications on FSW, to start with:

- CFD analyses the pin profile and shows that it plays a vital part in the material flow and controls the welding speed of the FSW process and is concentrated for refining weld fusion zones on the basis of several experimental methods but with only partial success [3]. Since the FSW is also dependent on the temperature distribution, the micro-structural evolution of the FSW of 6061 aluminum alloy (T6-temper condition) to copper [4] has been analysed. In FSW, the shoulder force is directly accountable for plunging the tool pin's depth into the work piece and load characteristics of linear friction stir welds. At steady state, the shoulder force varies depending upon the rotational speed. Increase in rotational speed is results in drop in initial axial force with increasing time [5]. Different micro-structural zones have been identified which show the hardness distribution on single and overlapped layers [6]. The nugget region with severe plastic deformation and exposure to elevated temperatures being characterized by fine and equiaxed recrystallized grains. Further, the thermo-mechanically affected region experiencing medium temperature and deformation having deformed and un-recrystallized grains and the heat-affected zone have been experienced based on temperature, characterized by precipitate coarsening. Transient and quasi-stationary phases of FSP are revealed by roughness mapping. Just as each high rotational rates could raise strain rate, and there by impact the recrystallization procedure; which thus could impact the FSW procedure [7].

- The FSW is also extended to join the AA 6061 T-6 aluminum alloy and AZ31 alloy and to study hybrid laser FSW's microstructure and mechanical properties [8]. It is followed by the experimental study of butt joints of AA 6061 and ZRB2 metals in-situ Composite materials and studied the effect of those materials on sliding wear [9].

The literature also shows that a number of modelling techniques are developed for the analysis of FSW process parameters and their influence on the joints. In this context, the optimization of process parameters is studied by Taguchi method on cast aluminum alloy A319, it is followed by the modelling of AA6061-T6 butt joints and studied the tensile properties [10–13]. Further, a case study is presented with a review on the optimization of process parameters of 6061 Al alloy using Taguchi method [14]. Though noted research has been taken place, the literature shows that there is no consideration on the effect of the various pin profiles on the joint geometry at various rotational speeds of FSW is still limping. Therefore the present chapter deals with experimentation on FSW.

Figure 2 shows the different regions of FSW joints. It consists of four elements: (a) unaffected base metal, (b) heat affected zone (HAZ), (c) thermo mechanically affected zone (TMAZ) and (d) friction stir processed (FSP) zone weld nugget zone. Structure of the above areas is influenced by the behaviour of the material stream under the activity of pivoting un-consumable instruments. Even though, the FSW tool profiles, FSW tool dimensions and FSW process parameters [5] predominantly influence the material flow behaviour. In fusion welding of aluminum amalgams, the imperfections like porosity, slag consideration, cementing splits and so on break down the weld quality and joint properties. Usually, FSW joints are free of such defects as there is no fusion during welding and the metals are joined by solid-state

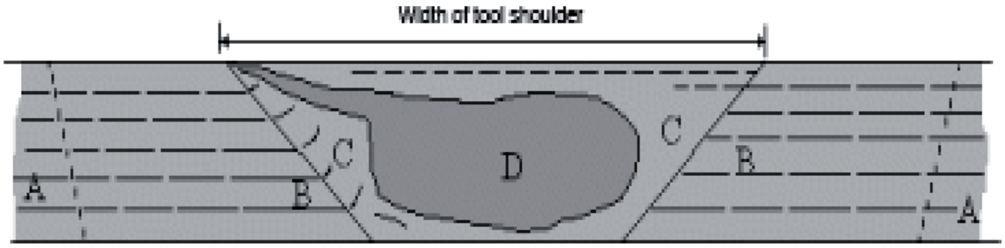

Figure 2.
Different regions of FSW joint. A = unaffected metal base; B = Heat Affected Zone (HAZ); C = Thermo-Mechanically Affected Zone (TMAZ); D = Friction Stir Processed (FSP) zone.

because of the heat produced by the friction and the metal flow through the stirring action. On the other hand, owing to incorrect metal flow and inadequate metal consolidation in the FSP region, FSW Joints are susceptible to other defects such as cracks, tunnel defect, kissing bond, piping defect, pin hole, etc. Existing literature focuses on the impact of welding parameters and tool profiles on the formation of defect-free FSP is very limited.

Objectives of this present work: a Solemn attempt is made in the present investigation to conquer the limitations identified and to conduct experimentation on AA6061 Al alloys with the objectives as given in the following:

1. To fabricate FSW joints with different tool pin profiles and identify the process parameters

2. Investigation of the impact of tool pin profile and welding parameters (rotational speed, welding speed and axial force) on the formation of defect-free FSP as well as on tensile, impact properties and the hardness of the welded joints.

3. The ANN modelling of the process and to attain maximum tensile strength and analysis of variance for optimal process parameters.

4. Evaluation of the microstructure of FSP zone for different pin profiles.

5. Conducting the SEM analysis to analyse the flow of material.

3. Experimental work

Experimental work starts with the preparation of work pieces to be joined. Each work-piece of the base material of size 300 × 150 × 6.35 mm by power hacksaw cutting and milling. Configuration of the square butt joints is prepared to make FSW joints. The unique joint configuration is achieved by using mechanical clamps to secure the plates in place. The welding direction is normal for the rolling direction. The joints are manufactured using a single pass welding procedure. Non-consumable tools made of tungsten carbide material are utilized to fabricate the joints. **Tables 1** and **2** show the chemical composition and mechanical characteristics of base metal.

Vertimach V-350. Vertical Machining Centre is used to fabricate the required joints**.** Three distinctive tool pin profiles are utilized to create the joints as appeared in **Figure 3** and nearly 81 joints are manufactured to study the impact of tool pin profile, rotational velocity, welding velocity and axial force on stir welded AA6061 aluminum alloy tensile properties. **Table 3** shows the levels of the experiment based on the Taguchi method. The experimental results are shown in **Tables 4–6**.

Mn	Si	Fe	Cu	Cr	Zr	Mg	Ti	Al
1.2	0.8	0.7	0.4	0.35	0.25	0.15	0.15	Balance

Table 1.
AA6061 alloy (weights %) chemical composition.

Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Reduction in cross-sectional area (%)	Hardness (VHN)
276	310	18	12.24	105

Table 2.
AA6061 mechanical characteristics.

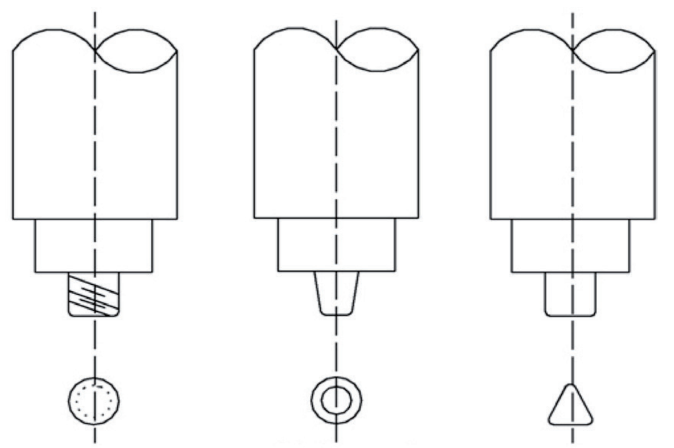

Figure 3.
Tool pin profiles of FSW.

Process parameters	Symbol	Units	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

Table 3.
Important factors and their levels for AA6061.

Using power hacksaw, the welded joints are sliced and then tensile specimens are machined to the necessary sizes. Guidelines for the preparation of sample samples are followed by the American Society for Testing of Materials (ASTM). In 400 KN, Electro-Mechanical Controlled Universal Testing Machine Tensile test has been carried. The specimen is recorded when the neck fails and the load versus the displacement. Charpy Impact Test is also conducted for the specimens. The Rockwell Hardness Test is conducted by indenting the test material with a diamond cone indenter. The indenter is compelled into tare using a Light Optical Microscope (Make: NIKON-LV 150) built into an Image Analysis Software. The specimens for metallographic examination are divided into FSP, TMAZ, HAZ and base metal areas according to the necessary dimensions. The samples are polished using various grades of emery documents. Final polishing is performed in the Disc Polishing Machine

	Setting level	Predicted	Experimental
Tensile strength (MPa)	N3, S3, F3	162.84	163.23
Impact strength (N/mm^2)	N1, S2, F3	1.02	1.260
Hardness	N3, S3, F3	31	33

Table 4.
Optimum parameters for the threaded pin profile.

	Setting level	Predicted	Experimental
Tensile strength (MPa)	N3, S3, F3	159.84	160.23
Impact strength (N/mm^2)	N3, S3, F2	0.766	0.770
Hardness	N3, S3, F3	28	30

Table 5.
Optimum parameters for the conical pin profile.

	Setting level	Predicted	Experimental
Tensile strength (MPa)	N3, S3, F3	218.34	215.82
Impact strength (N/mm^2)	N3, S3, F2	0.880	0.901
Hardness	N3, S3, F3	29	31

Table 6.
Optimum parameters for the triangular pin profile.

using the diamond compound (1 mm particle size). Specimens are etched with the Keller's reagent, to reveal the macro and micro structures. SEM analysis is conducted using the Scanning Electron Microscope. SEM produces a range of signals exterior of sample specimens by utilizing the high energy focused electrons. Signals derived from SEM reveal information on the sample, including exterior morphology (texture), chemical composition, crystalline structure and orientation of the sample material.

4. Effect of tool pin profile

The fundamental role of the non-consumable rotating tool pin is to stir and transfer the plasticized metal behind it to a good joint. Pin profiles with flat faces (square and triangular) are associated with eccentricity. This eccentricity allows incompressible material to pass around the pin profile. **Figure 4** shows the effect of aluminum alloys of AA6061 on the FSW joints of tensile features. From this inquiry, it is discovered that the joints manufactured using the triangular pin tool profile have improved tensile characteristics for aluminum alloy. **Figure 5** shows the impact of the tool pin profile on AA6061 aluminum alloy FSW joints. From this study, it is discovered that the joints manufactured using Triangular pin tool profile improved impact strength for aluminum alloy. **Figure 6** shows the impact of tool pin profile on AA6061 aluminum alloy FSP area hardness. The FSP zone hardness is also maximum in the case of joints fabricated using **threaded** pin profile. **Figures 7–9** show the different zone of the microstructure of FSW joints of AA6061 aluminum alloys. The joint's FSP area made from threaded pin profile contains very fine equiaxed microstructure (**Figure 9**) compared to other joints.

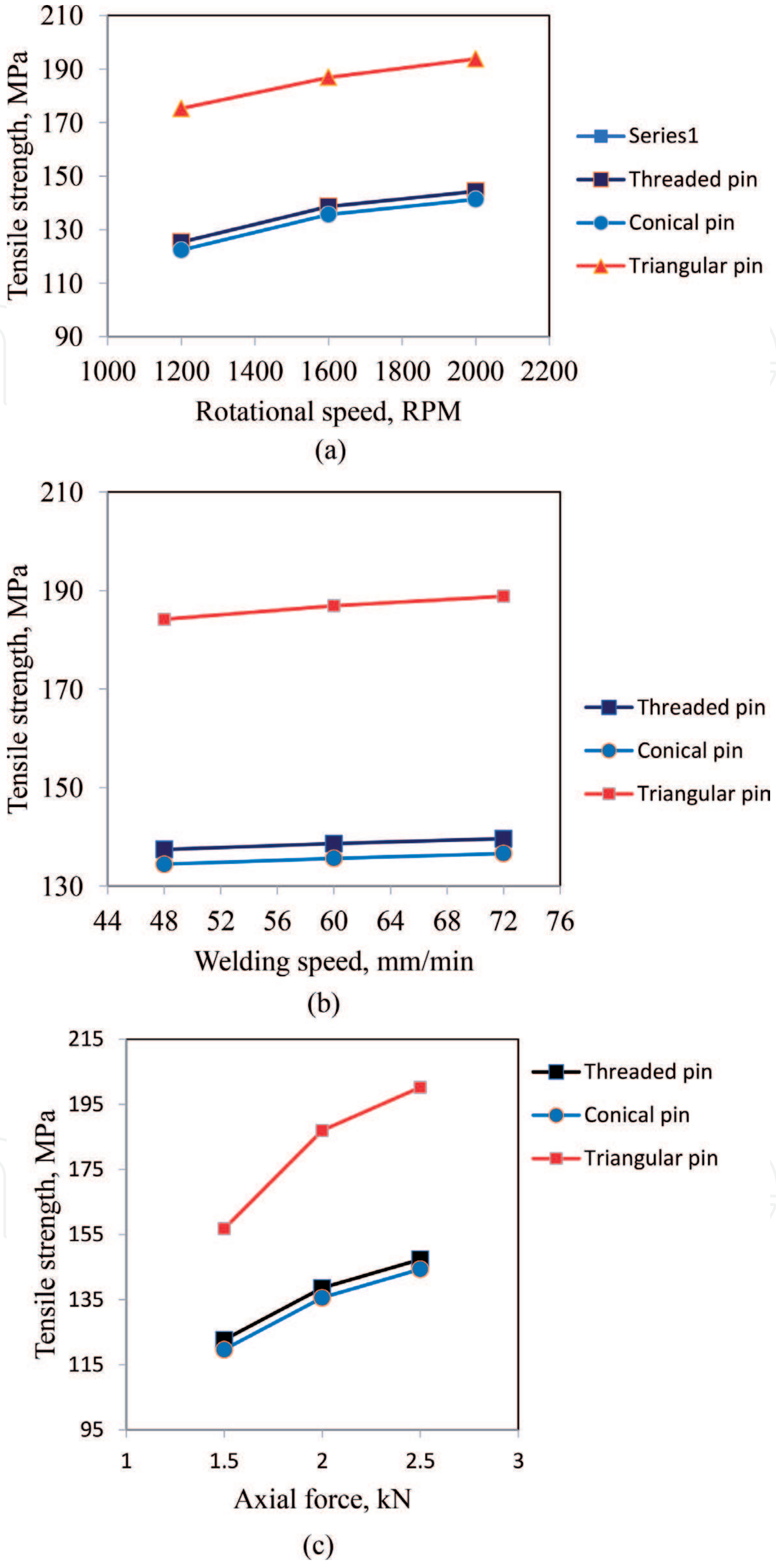

Figure 4.
Effect of FSW parameters on tensile strength: (a) effect of rotational speed; (b) effect of welding speed; and (c) effect of axial force.

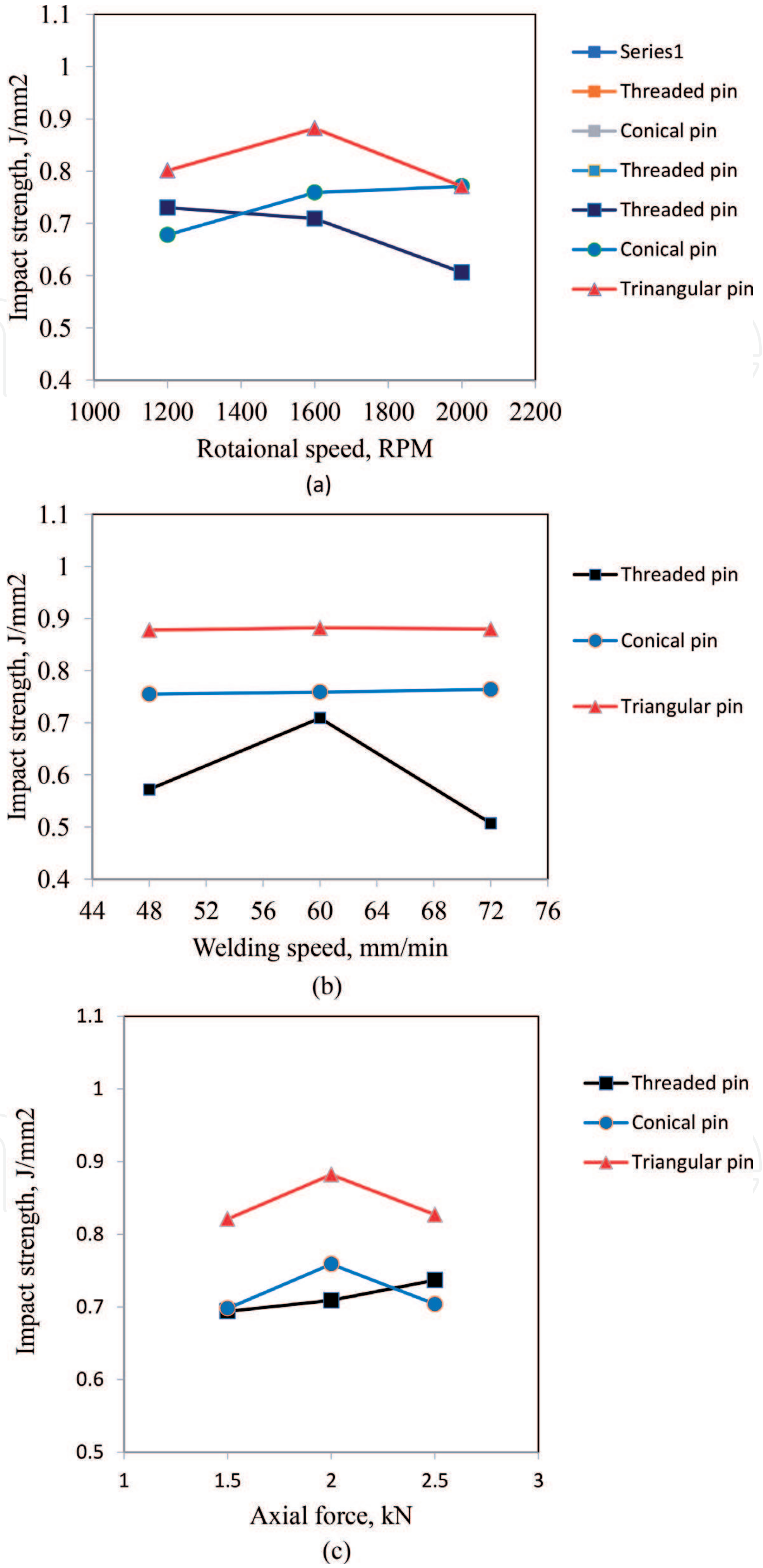

Figure 5.
Effect of FSW parameters on impact strength: (a) effect of rotational speed; (b) effect of welding speed; and (c) effect of axial force.

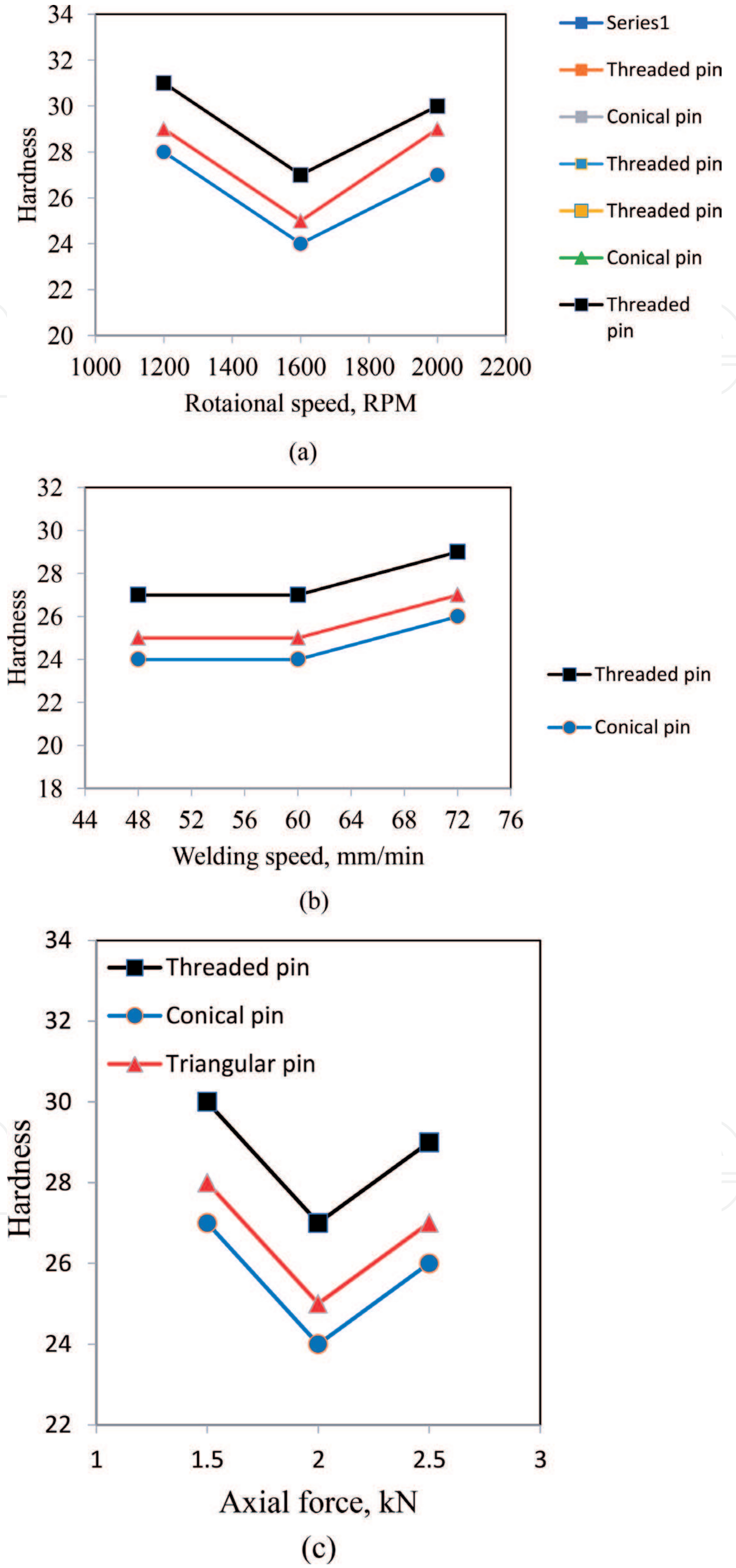

Figure 6.
Effect of FSW parameters on hardness: (a) effect of rotational speed; (b) effect of welding speed; and (c) effect of axial force.

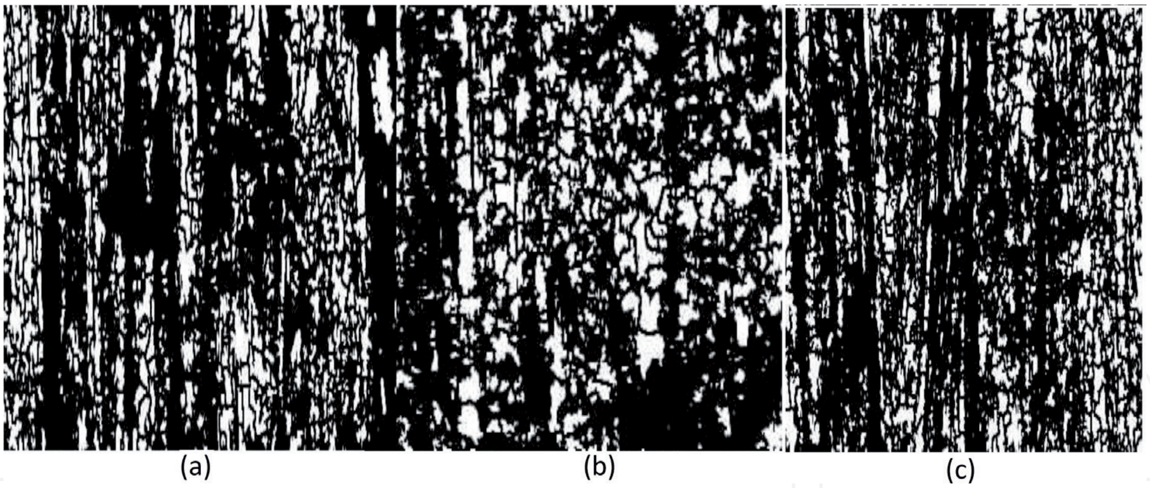

Figure 7.
Effect of conical pin profile on the microstructure of AA 6061: (a) FSP zone; (b) TMAZ; and (c) HAZ.

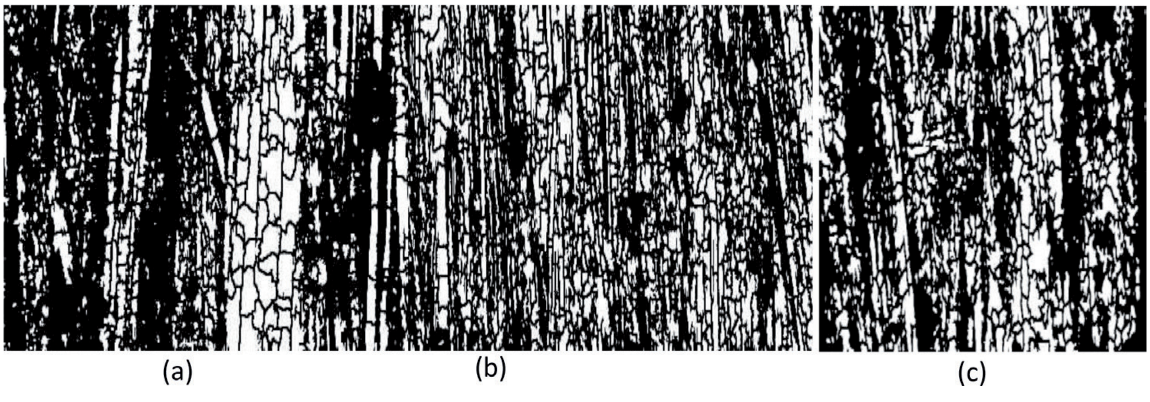

Figure 8.
Effect of triangular pin profile on the microstructure of AA 6061: (a) FSP zone; (b) TMAZ; and (c) HAZ.

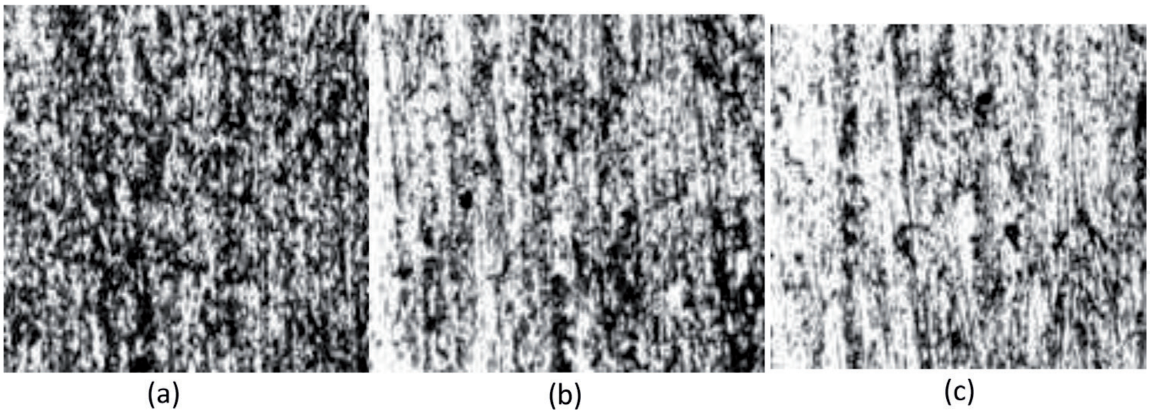

Figure 9.
Effect of threaded pin profile on the microstructure of AA 6061: (a) FSP zone; (b) TMAZ; and (c) HAZ.

5. Effect of tool rotational speed

To know the impact of rotational speed on FSW joints 'tensile characteristics, three distinct rotational speeds were selected to manufacture the joints. **Figure 4(a)** indicates that rotational speed affects the tensile strength of AA606l aluminum alloy of FSW joints. **Figure 5(a)** demonstrates the impact of rotational speed on AA606l aluminum alloy FSW joints impact strength. **Figure 6(a)** demonstrates the impact of AA6061 aluminum alloy rotational speed on FSP zone hardness. Rotational speed seems to be the most important variable of the process since it also affects the transfer speed. Higher tool rotational speed in the FSP area identified after soldering led in greater temperature and slower cooling rate. Higher rotation speed leads to excessive discharge from the top layer of the stirred materials which therefore leave voids in the FSP area. Lower heat entry situation owing to reduced rotational speed caused no stirring. As the speed of rotation rises, the stressed region expands and the place of the highest stress lastly shifts from the initial advancing side of the joint to the progressing side. This means that the position of the joint fracture is also influenced by the speed of rotation. The tensile characteristics of the joints under distinct welding circumstances led in the smallest tensile strength and ductility for a specified traverse speed at the smallest spindle speed. As the speed of the spindle increased, both power and elongation enhanced to a peak before dropping again at elevated rotational speeds. It is evident that the heat input increases in FSW as the rotational speeds increase. There are two reasons why this phenomenon can be explained: first, when a local melt happens, the coefficient of friction reduces and then reduces with heat input; secondly, some heat input is absorbed by latent heat. From this investigation, it is discovered that in the case of AA6061 aluminum alloy, the joints manufactured at a rotational speed of 2000 RPM produced better tensile strengths.

6. Effect of welding speed

To know the impact of welding speed on FSW joints' tensile strengths, three distinct welding speeds were selected to fabricate the joints. **Figure 4(b)** indicates the impact of welding speed on AA6061 aluminum alloy FSW joints tensile strength. **Figure 5(b)** demonstrates the impact of welding speed of AA606l aluminum alloy FSW joints. **Figure 6(b)** demonstrates the impact of welding speed on AA6061 aluminum alloy FSP zone hardness. Decreased welding speed reduces the cooling ratio resulting in larger equi-axed granules in the stirring region. Poor welding speed in the FSP region resulted in sub grain coarsening. Due to the restricted moment available for regeneration, greater welding speed led in a structure with greater dislocation density. Increase in welding speed can reduce the volume of grain owing to the reduction in heat input. As a result of this exploration, it was discovered that aluminum alloy in the case of AA6061, the joints manufactured at a welding speed of 72 mm/min had better tensile strengths.

7. Effect of axial force

In order to understand the impact of axial force on the tensile strengths of FSW joints, three distinct axial forces were selected to fabricate the joints. **Figure 4(c)** shows the axial force impact on the tensile strength of the FSW AA 6061 aluminum joints. **Figure 5(c)** shows the axial force effect of FSW aluminum joints AA 6061. The **Figure 6(c)** demonstrates the axial force impact of AA6061 aluminum alloy FSP zone hardness. The flow of materials within the weld area is affected by an extrusion method where the material has experienced plastic deformation by the applied axial force and movement of the tool pin profile.

The difference in the measured forces is due to the decrease of the material flow stress at elevated weld temperature. Despite the fact that weld joint is great, the arrangement of shear lips or flashes with intemperate stature on both progressing and withdrawing sides of the weld line because of higher pivotal power brought about inordinate diminishing of the metal in the weld region yielding poor tensile properties. The axial force should therefore, be optimized in order to achieve an FSP region that is metal consolidated and does not dilute the base material. The results of this research showed that in the event of AA6061 aluminum alloy, the joints made with an axial force of 2 KN had better tensile strengths. **Table 4** shows the optimized welding conditions.

8. Process parameters modelling using ANN

The input layer in this work consists of four neurons that correspond to each of the three control factors and one neuron in the output layer that corresponds

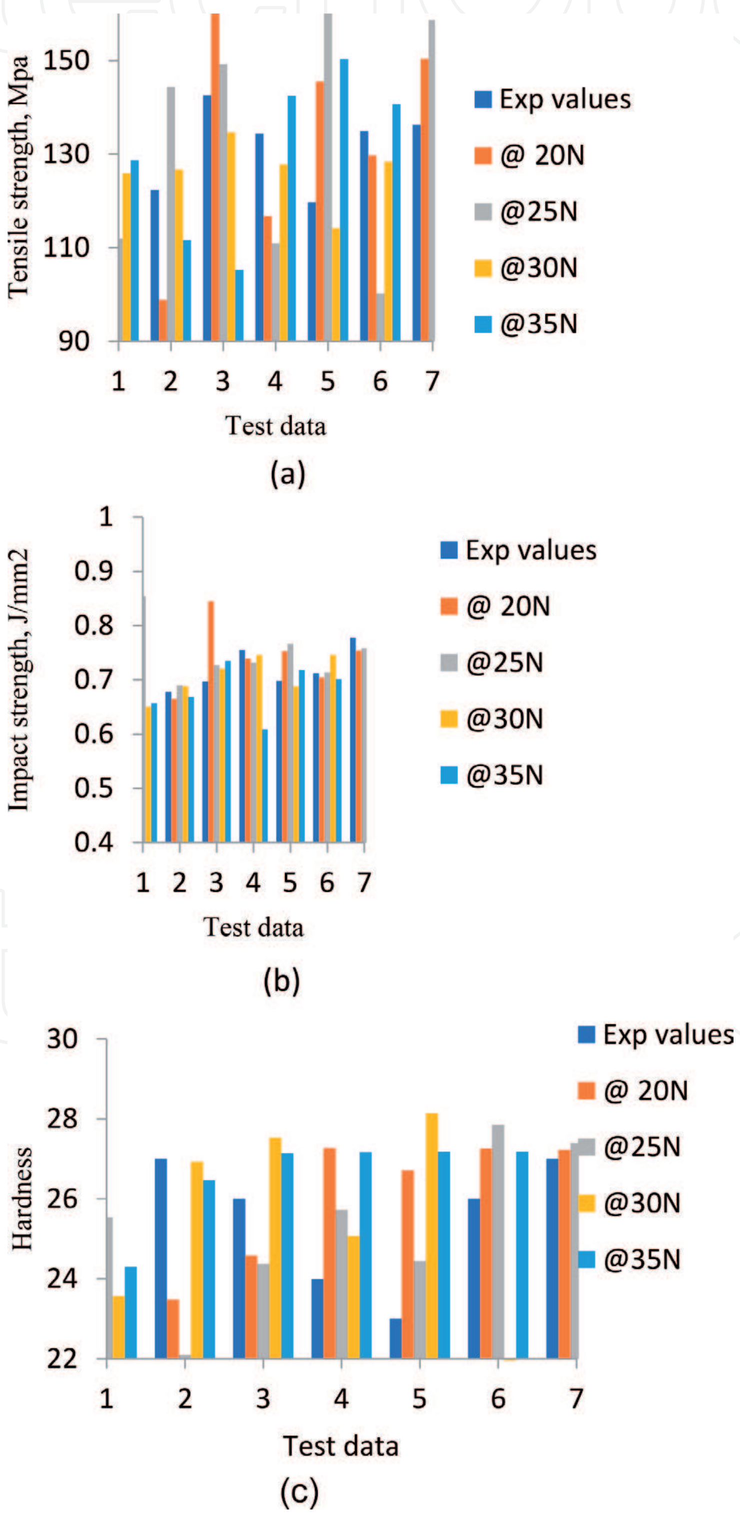

Figure 10.
Predicted mechanical properties of conical pin profile using ANN.

to each response. To find the finest network architecture, differently hidden layer networks were created and tested with distinct numbers of hidden layers and neurons; various algorithms is used for practice; the hidden layer and output layer transfer functions are altered and the generalization ability of the various networks is noted. Finally, the ideal network is chosen to forecast the strengths. Twenty-five concealed neurons are trained for the ideal architecture of the network. The ANN network is run on MATLAB software. The data set with 27 models is randomly split into two classifications: The training dataset consists of 75% of information and

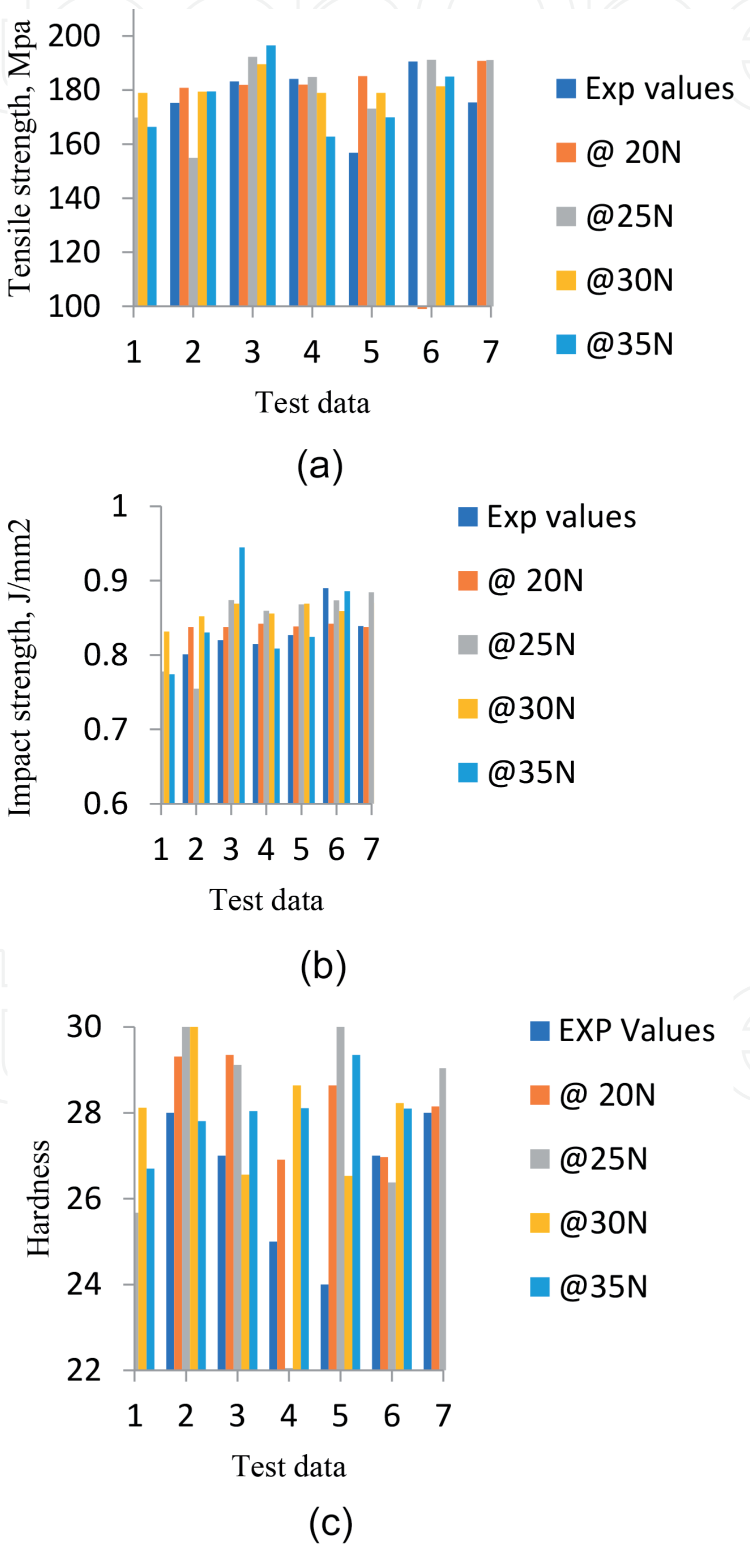

Figure 11.
Predicted mechanical properties of triangular pin profile using ANN.

25% of information in test information set. 20 training models for ANN strength modelling are considered. The weights are frozen after the training and the model is checked for experimental findings.

Figures 10(a), **11(a)** and **12(a)** show the experimental and ANN computed tensile strength values for AA6061 materials with a conical pin tool, triangular pin tool and threaded pin tool, and it is clear that the values predicted by ANN are very close to the experimental values. **Figures 10–12** show the ANN prediction values and experimental values for the different mechanical properties. The experimental investigation it is proved that the triangular pin profiles yield better results.

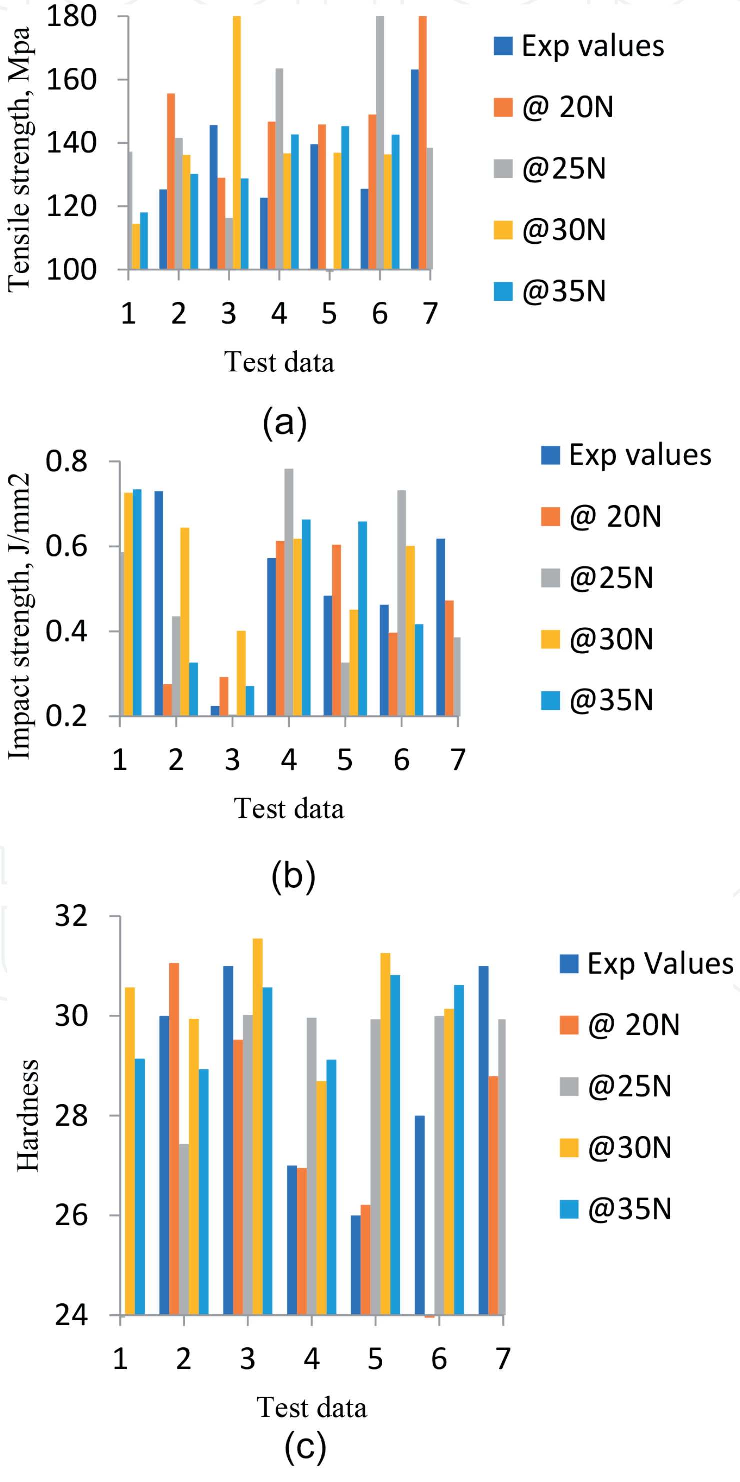

Figure 12.
Predicted mechanical properties of threaded pin profile using ANN.

9. SEM analysis

SEM assessments are completed utilizing a Scanning Electronic Microscope for 6061 aluminum alloy to dissect the weld testimony on weld chunk surface. The SEM photos of the joints at different procedure parameters are appeared

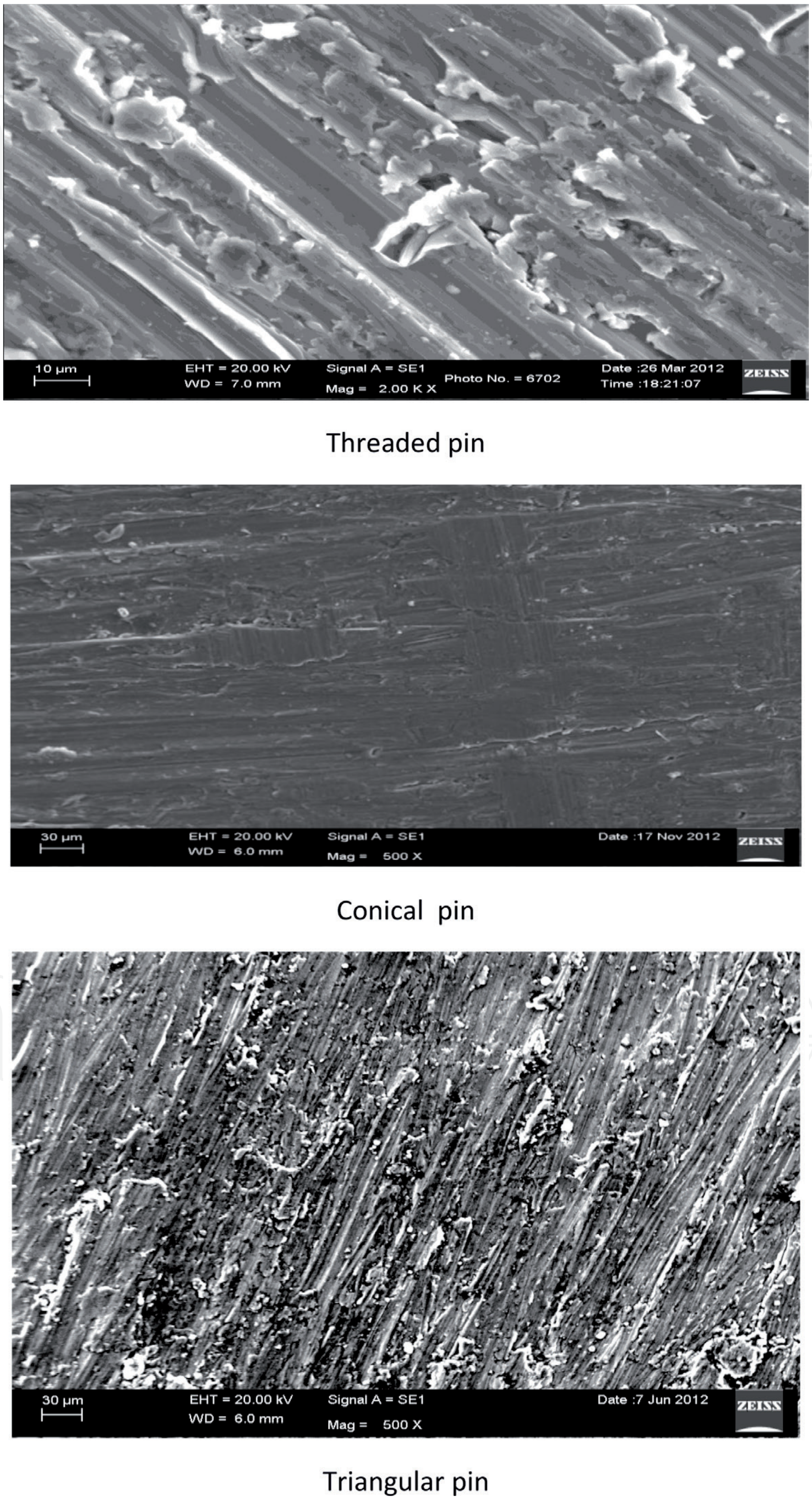

Figure 13.
SEM images of different tool pin profiles of FSW joints of AA 6061.

in **Figure 13**. The SEM analysis has been conducted at three different levels of magnification to analyse the weld defects. It is observed that no micro or microscopic voids and cracks observed in the FSP region. The thermal flow of material is being viewed clearly across the FSP zone.

10. Conclusions

- The attempt made in the present work for joining of age hardenable aluminum alloy AA6061 (medium strength) by FSW using Vertimach V-350 Vertical Machining Centre and the attempt was effective and proved to be consistent with the expected values with their mechanical properties of the joints.
- The tool with triangulated pin profiles produced mechanically sound and non-metallurgically deficient joints for both AA6061 aluminum alloys, regardless of welding parameters, among the three tool pin profiles for this study.
- The macrostructure, tensile strengths, hardness, microstructure and SEM analysis have been evaluated in detail for the effect of rotational speed, welding speed and axial force on the formation of a defeat free FSP zone. The welding conditions for producing defect-free joints have been established for AA6061 aluminum alloy.
- An ANN modelling is developed to obtain the theoretical results and compared with the experimental results among all three different pin profiles, the triangular pin profile found to be closer value to the experimental strength of the weld joint at 30 neurons and validated at 95% confidence level.
- The SEM images clearly show the metal flow across the joints for three different pin profiles. It is also evident from SEM analysis that the triangular pin profile exhibits better stirring action than compared to a threaded pin profile.

11. Limitations of the present work

- The FSW joints are susceptible to defects such as pinhole, defects in the tunnel, piping failures, kissing attachment, cracks and so on due to poor metal flow and lack of metal build-up in the FSP area, although they are free from cracks of solidification.

Acknowledgements

The author is grateful to M/s. Bindu Tools India Pvt. Ltd. for supplying necessary tools and also to the department of mechanical engineering, S.V. University College of Engineering, Tirupati, for providing necessary facilities to carry out the work.

Author details

Pothur Hema
Department of Mechanical Engineering, SVU College of Engineering, Tirupati, Andhra Pradesh, India

*Address all correspondence to: hemasvumech@gmail.com

References

[1] Thomas WM, Nicholas ED, Needham JC, Murch MG, Temple Smith P, Dawes CJ. Friction-stir butt welding. GB Patent No: 9125978.8, International Patent No: PCT/GB92/02203. 1991

[2] Krishnan KN. On the formation of onion rings in friction stir welds. Materials Science and Engineering. 2002;**327**:246-251

[3] Thomas WM, Johnson KI, Wiesner CS. Friction stir welding—Recent developments in tool and process technologies. Advanced Engineering Materials. 2003;**5**(7):485-490. DOI: 10.1002/adem.200300355

[4] Colegrove PA, Shercliff HR. 3-Dimensional CFD modeling of flow around a threaded friction stir welding tool profile. Journal of Materials Processing Technology. 2005;**169**:320-327

[5] Ouyang J, Yarrapareddy E, Kovacevic R. Microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper. Journal of Materials Processing Technology. 2006;**172**:110-122

[6] Elangovan K, Balasubramanian V. Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminum alloy. Journals of Materials and Design. 2008;**29**(2):362-373. DOI: 10.1016/j.matdes.2007.01.030

[7] Iordachescu M, Vilaca P, Iordachescu D, Porro JA. Aluminium friction stir processing of AA 6061 alloys. IIW Doc III-1433-07. 2007

[8] Sakthivel T, Sengar GS, Mukhopadhyay J. Effect of welding speed on microstructure and mechanical properties of friction-stir-welded aluminum. International Journal of Advanced Manufacturing Technology. 2009;**43**:468-473. DOI: 10.1007/s00170-008-1727-7

[9] Jayaraman M, Sivasubramanian R, Balasubramanian V, Lakshminarayanan AK.Optimization of process parameters for friction stir welding of cast aluminum alloy A319 by Taguchi method. Journal of Scientific & Industrial Research. 2009;**68**:36-43

[10] Rajakumar S, Muralidharan C, Balasubramanian V. Sensitivity analysis on friction stir welding process and tool parameters for joining AA6061-T6 aluminium alloy joints. Indian Welding Journal. 2010;**43**(3):32-42

[11] Yokoyama T, Nakai K, Sukedai E. Tensile properties and constitutive modeling of friction stir welded AA6061-T6 butt joints. Journal of Solid Mechanics and Materials Engineering. 2011;**5**(12):780-792

[12] Chang W-S, Rajesh SR, Chun C-K, Kim H-J. Microstructure and mechanical properties of hybrid laser-friction stir welding between AA6061-T6 Al alloy and AZ31 Mg alloy. JMST. 2011;**27**(3):199-204

[13] Dinaharan I, Murugan N. Influence of friction stir welding parameters on sliding wear behavior of AA6061/0-10 wt.% ZrB2 in-situ composite butt joints. Journal of Minerals & Materials Characterization & Engineering. 2011;**10**:1359-1377

[14] Nourani M, Milani AS, Yannacopoulos S. Taguchi optimization of process parameters in friction stir welding of 6061 aluminum alloy: A review and case study. Scientific Research. 2011;**3**:144-155