Experimental Investigations and Prediction on MRR and SR of Some Non Ferrous Alloys in AWJM Using ANFIS

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Abstract

Background/Objectives: Last decades have witnessed a rapid growth in the development of harder, difficult and complexity to machine metals and alloys. Abrasive Water Jet Machining (AWJM) is one of the recently developed nontraditional mechanical type hybrid machining processes in processing various kinds of hard-to-cut materials. It is an economical method for heat sensitive materials that cannot be machined by processes that produce heat while machining. Machining parameters play the lead role in determining the machine economics and quality of machining. This paper investigates the prediction of MRR and SR on Aluminum, Copper and Lead alloys using the combination of Artificial Neural Network (ANN) and Fuzzy Logic (FL).

Methods/Statistical Analysis: In this study, the consequence of different AWJM process parameters on Material Removal Rate (MRR) and Surface Roughness (SR) of three nonferrous alloys namely Aluminum, Copper and Lead which are machined by AWJM was experimentally performed and analyzed. According to Response Surface Methodology (RSM) design, different experiments were conducted with the combination of input parameters on these alloys.

Findings: A combinational method called as Adaptive Neuro Fuzzy Inference System provides effective knowledge based training to process parameters, to make its enhancement of process performance.

Keywords: Abrasive Water Jet Machining, Adaptive Neuro Fuzzy Inference System, Material Removal Rate, Response Surface Methodology, Surface Roughness

1. Introduction and Review of Literature

AWJM is the recently developed hybrid processes. This technique is suitable for machining of brittle materials similar to glass, ceramics and stones as well as for composite materials, ferrous and non-ferrous materials. From the literature review of Adel¹ in 2011 an elastic-plastic erosion model was implemented to build up an Abrasive Water Jet (AWJ) model for machining brittle materials. C. Ma, R.T. Deam² in 2006 investigated that kerf geometry have been measured by the use of an optical microscope. With these measurements, an empirical correlation for kerf profile shape under various traverse speed have been developed that fits the kerf shape well³. Computational Fluid Dynamics (CFD) models for ultrahigh velocity water jets and AWJs are established by the use of Fluent6 flow solver⁴. Performed micro-EDM and hybrid process of micro-wire electrical discharge grinding to assess the inaccuracies while machining. They examined the MRR, SR and TWR results by ANN and ANFIS and showed that the ANFIS model is better when compared with ANN⁵. Performed ANFIS model for SR on D5 tool steel in WEDM process and examined the metallographic properties⁶. Jang observed from that Artificial Intelligence (AI) techniques comprising of ANN, FL and Taguchi based fuzzy systems have wide applications in modeling of WEDM process parameters. In this modeled the process parameters with ANFIS which combines the ANN adaptive capability and FL qualitative

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2. Experimental Work

2.1 Material

The three materials chosen for this study are Aluminium6061 alloy, Copper Iron alloy and Lead Tin alloy. Aluminium 6061 alloy is a precipitation hardening Aluminium alloy which is available in several forms such as tube, ingot, ribbon, wire, foil, bar, pipe and rod. The important factor in selecting Aluminum 6061 alloy is their high strength to weight ratio, appearance, and their nonmagnetic properties. Some of the applications of Aluminium 6061 alloy include marine fittings, aerospace maintenance, transport, bicycle frames, brake components, valves couplings etc.

Copper and its alloys was used as a building material, a conductor of heat and electricity, and as a component of various metal alloys. Because of its high electrical conductivity, huge quantity of Copper are applied in electrical industry for wire. As Copper was resistant to corrosion due to moisture, it's widely used and applied in jewelry, coins, and pipes. As Copper is too soft for applications, it is integrated in various alloys. This alloy is available as wire, sheet, shot, bar, ingot, ribbon, and foil. It has superb corrosion resistance for atmospheric conditions.

Lead Tin alloy, an American element is available in several forms such as tube, ingot, ribbon, wire, foil, bar, pipe and rod. The important factor in selecting Lead Tin alloy is their high strength to weight ratio, their resistance to corrosion by many chemicals, their high thermal and electrical conductivity, non-toxicity, reflectivity, and appearance, and their ease of formability and machinability and nonmagnetic properties. Some of the applications of Lead Tin alloy include marine fittings, aerospace maintenance, transport, bicycle frames, brake components, valves couplings etc. The dimension of these alloys used for this study is 150mm x 50mm x 50mm. shown in Figure 1.

![Figure 1. Non Ferrous Alloys. (a) Aluminium 6061Alloy. (b) Copper Iron. (c) Lead Tin Alloy.](a) (b) (c)

2.2 Response Surface Methodology

RSM is a set of mathematical and statistical techniques which are useful for modeling and investigation of problems. In the present study five process parameters are chosen and varied in three levels as shown in Table 1.

![Figure 1. Non Ferrous Alloys. (a) Aluminium 6061Alloy. (b) Copper Iron. (c) Lead Tin Alloy.](a) (b) (c)

Based on response surface methodology, Box-Behnken design 46 sets of experimental design were selected.
2.3 Experimentation

The machine used to cut all the three nonferrous alloys was the AWJM machine is set with KMT Ultrahigh Pressure Pump with the designed pressure of 4000bar; gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a work piece table. The controller fixed in the control stand is used to adjust the SOD for different experiments. The abrasive water jet machine is programmed using numerical control code is to change the transverse speed and manage the supplement of abrasives. After the water is pumped at very high pressures resulting in high velocity of water jet of 1000m/s as it comes out of focusing nozzle cuts the materials of the desired size and shape. The KMT abrasive water jet cutting machine is shown in Figure 2.

For performing the experiments it has to design the combination of input parameters for each experiment and how many experiments has to be done. For this purpose using Minitab software according to the Box-Behnken design of RSM, with five input parameters, 46 experimental designs is selected and performed experimentally and machining time is observed for all experiments as shown in Table 2. The MRR is calculated by the formula;

\[ MRR = (m_f - m_i)/t \]

Where, \( m_f \) = mass of the material after machining, \( m_i \) = mass of the material before machining and \( t \) = machining Time.

The SR for the machined Alloys is measured using portable surface roughness tester.

The mathematical model for the experimental data by cutting all the three nonferrous alloys using AWJM for MRR and SR is developed using linear regression analysis through Minitab software. The developed regression equations are given below.

For Aluminium:

\[
MRR = 195.719 - 0.360226A + 99.1877B + 1516.21C + 364.430D - 6.05121E + 0.0019673A^2 - 1.34839B^2 - 802.864C^2 - 82.6080D^2 - 0.410467E^2 + 0.000769113A*B - 0.102446A*C + 0.000769113A*E - 300.422B*C + 15.6465B*D - 438.266C*D - 18.4785C*E + 10.3697D*E
\]

\[
SR = 179.473 - 0.0589755A + 6.28678B - 132.385C - 94.7475D - 0.00175000A*B + 0.00161011A*C - 0.00528029A*D - 3.55958B*D - 0.216667B*E + 113.234C*D - 0.0302120C*E + 1.16942D*E
\]

For Copper:

\[
MRR = 3807.07 - 0.865684A - 1541.90B - 13291.1C - 620.554D + 717.689E + 0.000235908D - 678.682B*E + 16370.4C*G + 619.730D*E + 26.3263E*F + 0.482583A*B + 2.17099A*C + 0.222252A*D - 0.219850A*E - 954.417B*C + 572.784B*D + 174.917B*E - 5426.25C*D + 110.636C*E + 171.187D*E
\]

\[
SR = 31.3516 + 0.00233958A - 31.1430B - 137.754C - 6.56011D + 7.28615E + 5.14367e^{07}A*D - 1.21594B*E + 220.213C*C + 9.75236D*D + 0.0385801E*E + 0.00484167A*B - 0.00887783A*C - 0.00505543A*D
\]
Table 2. Scheduling Matrix of the Experiments with the Optimal Model Data

| Pressure (Bar) | Abrasive Flow Rate (Kg/min) | Orifice Diameter (mm) | Focusing Tube Diameter (mm) | Stand Off Distance (mm) | MRR mm3/min Al | SR µm Al | MRR mm3/min Cu | SR µm Cu | MRR mm3/min Pb | SR µm Pb |
|---------------|-----------------------------|----------------------|-----------------------------|-------------------------|----------------|----------|----------------|----------|----------------|----------|
| 3400          | 0.55                        | 0.3                  | 0.9                         | 0.9                     | 48.6111        | 3.57     | 897.80         | 3.62     | 1709.00        | 2.450    |
| 3600          | 0.55                        | 0.3                  | 0.9                         | 1                       | 53.6399        | 2.08     | 1000.03        | 1.63     | 2014.86        | 1.415    |
| 3800          | 0.55                        | 0.3                  | 0.9                         | 2                       | 62.2222        | 1.90     | 1043.96        | 1.767    | 2182.26        | 0.788    |
| 4000          | 0.55                        | 0.3                  | 0.9                         | 3                       | 61.2423        | 2.07     | 987.80         | 1.901    | 2085.98        | 1.201    |
| 4200          | 0.55                        | 0.3                  | 0.9                         | 1                       | 50.1792        | 1.99     | 920.30         | 1.989    | 1943.11        | 1.887    |
| 4400          | 0.55                        | 0.3                  | 0.9                         | 2                       | 52.9101        | 2.17     | 922.40         | 2.224    | 2009.16        | 1.571    |
| 4600          | 0.55                        | 0.3                  | 0.9                         | 3                       | 51.1696        | 2.54     | 950.62         | 2.32     | 2004.80        | 1.709    |
| 4800          | 0.55                        | 0.3                  | 1.05                        | 2                       | 47.7164        | 3.08     | 800.02         | 2.991    | 1746.88        | 1.905    |
| 5000          | 0.55                        | 0.3                  | 0.9                         | 1                       | 50.1792        | 1.99     | 920.30         | 1.989    | 1943.11        | 1.887    |
| 5200          | 0.55                        | 0.3                  | 0.9                         | 2                       | 52.9101        | 2.17     | 922.40         | 2.224    | 2009.16        | 1.571    |
| 5400          | 0.55                        | 0.3                  | 0.9                         | 3                       | 51.1696        | 2.54     | 950.62         | 2.32     | 2004.80        | 1.709    |
| 5600          | 0.55                        | 0.3                  | 1.05                        | 2                       | 47.7164        | 3.08     | 800.02         | 2.991    | 1746.88        | 1.905    |
| 5800          | 0.55                        | 0.3                  | 0.9                         | 2                       | 52.9101        | 2.17     | 922.40         | 2.224    | 2009.16        | 1.571    |
| 6000          | 0.55                        | 0.3                  | 0.9                         | 3                       | 51.1696        | 2.54     | 950.62         | 2.32     | 2004.80        | 1.709    |
| 6200          | 0.55                        | 0.3                  | 1.05                        | 2                       | 47.7164        | 3.08     | 800.02         | 2.991    | 1746.88        | 1.905    |
| 6400          | 0.55                        | 0.3                  | 0.9                         | 1                       | 56.3607        | 1.68     | 987.80         | 1.50     | 2055.75        | 1.431    |
| 6600          | 0.55                        | 0.3                  | 0.9                         | 2                       | 49.2264        | 2.29     | 846.98         | 2.70     | 1866.40        | 2.013    |
| 6800          | 0.55                        | 0.3                  | 0.9                         | 3                       | 51.1696        | 2.50     | 928.76         | 3.03     | 1916.85        | 2.008    |
| 7000          | 0.55                        | 0.3                  | 1.05                        | 2                       | 49.2264        | 2.29     | 846.98         | 2.70     | 1866.40        | 2.013    |
| 7200          | 0.55                        | 0.3                  | 0.9                         | 2                       | 55.9552        | 2.14     | 973.52         | 1.85     | 1970.09        | 1.500    |
| 7400          | 0.55                        | 0.3                  | 0.9                         | 1                       | 56.7721        | 2.18     | 973.52         | 1.734    | 1937.80        | 1.699    |
| 7600          | 0.55                        | 0.3                  | 1.05                        | 1                       | 50.8352        | 1.90     | 957.37         | 2.00     | 2049.81        | 1.707    |
| 7800          | 0.55                        | 0.3                  | 0.9                         | 1                       | 51.8519        | 1.99     | 990.22         | 1.66     | 2009.16        | 1.500    |
| 8000          | 0.55                        | 0.3                  | 1.05                        | 2                       | 64.8148        | 1.70     | 1100.85        | 1.407    | 2142.69        | 0.620    |
| 8200          | 0.55                        | 0.3                  | 0.9                         | 2                       | 52.9101        | 2.20     | 922.40         | 2.201    | 2014.86        | 1.597    |
| 8400          | 0.55                        | 0.3                  | 1.05                        | 2                       | 59.8291        | 1.99     | 1035.93        | 1.564    | 2162.30        | 0.800    |
Table 2. Scheduling Matrix of the Experiments with the Optimal Model Data

| Pressure (Bar) | Abrasive Flow Rate (Kg/min) | Orifice Diameter (mm) | Focusing Tube Diameter (mm) | Stand Off Distance (mm) | MRR mm3/min | SR μm | MRR mm3/min | SR μm |
|---------------|-----------------------------|-----------------------|-----------------------------|-------------------------|-------------|-------|-------------|-------|
| 3400          | 0.7                         | 0.33                  | 0.99                        | 2                       | 51.8519     | 2.80  | 831.30      | 2.456 |
| 3600          | 0.55                        | 0.35                  | 1.05                        | 2                       | 51.1696     | 2.34  | 907.89      | 2.56  |
| 3400          | 0.55                        | 0.3                  | 0.99                        | 2                       | 48.9168     | 3.23  | 833.01      | 2.80  |
| 3600          | 0.4                         | 0.33                  | 0.99                        | 3                       | 48.3092     | 2.69  | 824.51      | 3.01  |
| 3600          | 0.55                        | 0.33                  | 0.99                        | 2                       | 53.2725     | 2.18  | 928.76      | 2.23  |
| 3600          | 0.55                        | 0.35                  | 0.99                        | 1                       | 52.5526     | 1.80  | 968.85      | 2.00  |
| 3800          | 0.55                        | 0.35                  | 0.99                        | 2                       | 59.3724     | 1.82  | 1049.38     | 1.863 |
| 3600          | 0.7                         | 0.33                  | 1.05                        | 2                       | 56.7721     | 2.03  | 961.93      | 1.99  |
| 3600          | 0.55                        | 0.33                  | 1.05                        | 3                       | 51.1696     | 2.73  | 922.40      | 2.65  |
| 3800          | 0.55                        | 0.33                  | 0.99                        | 1                       | 61.2423     | 1.72  | 1138.06     | 1.35  |

- 0.00203625A*E + 24.5694B*C + 11.5488B*D - 0.373333B*E + 25.1778C*D -1.32747C*E - 2.58095D*E
- 0.00203625A*E + 24.5694B*C + 11.5488B*D - 0.373333B*E + 25.1778C*D -1.32747C*E - 2.58095D*E

For Lead:
MRR = -13961.9 + 5.73727A + 6875.08B - 2320.47C + 3365.86D + 607.050E - 5.96565e^-04A*A - 2790.52B*B - 25643.8C*C - 3056.18D*D - 16.5610E*E - 0.874956A*B + 1.62406A*C -0.373333B*E + 24.5694B*C + 11.5488B*D - 0.373333B*E + 25.1778C*D -1.32747C*E - 2.58095D*E

SR = - 45.9273 + 0.0396519A + 9.14096B - 120.471C - 10.1247D + 3.53665E - 6.23825e^-6A*A + 5.22830B*B + 86.1907C*C + 1.20020D*D + 0.212358E*E - 0.00318333A*B + 0.0145270A*C + 9.23203e^-5A*D - 3.25000e^-4A*E - 19.2841B*C + 1.24719B*D + 0.183333B*E + 30.9078C*C - 4.44447C*E - 1.60457D*E

2.4 Prediction of MRR and SR Using ANFIS

The prediction of MRR and SR for all the three alloys using ANFIS is done by means of the Matlab software. The command used for ANFIS is ANFIS edit which displays a window as shown in Figure 3. Click the Load Date box in the window to enter the training data to display the training data plot in the ANFIS window as shown in Figure 4 and Figure 5 for MRR and SR respectively. After loading the training data, the user has to select the type of membership function and number of membership functions for each input. To generate (Fuzzy Inference System) FIS portion from ANFIS window, click on generate FIS. Now it is displayed to another window as shown in Figure 6. Select gauss2mf membership function from MF type to input and linear membership function to output. Assign three member ship functions for each input as shown in number of MFs. Close the window by selecting ok. Now select method and number of epochs from train FIS portion of ANFIS window. Then click on train now to train ANFIS with training data. After training was completed for 50 epochs, training curve will display as shown in Figure 7 and Figure 8 for MRR and SR respectively. This curve shows the reduction of error for each epoch, and it was observed in Figure 7 and 8. The curve reached the minimum error target and there was no further reduction of error possible. Now load the test data to ANFIS as a testing data, and select the testing data in test FIS portion of ANFIS window and click test now. Then two different types of points, square points (in blue color) which represents the experimental results and points (in red color) which represents the predicted outputs for given training data as shown in Figure 9 and Figure 10 for MRR and SR respectively. It can be observed from these Figures that all predicted outputs for testing data are very close to the experimental outputs of testing data. The predicted MRR and SR values are found in Ruler Viewer of ANFIS as shown in the Figures 11 and 12. The ANFIS model structure for five inputs and one output is shown

| Pressure (Bar) | Abrasive Flow Rate (Kg/min) | Orifice Diameter (mm) | Focusing Tube Diameter (mm) | Stand Off Distance (mm) | MRR mm3/min | SR μm | MRR mm3/min | SR μm |
|---------------|-----------------------------|-----------------------|-----------------------------|-------------------------|-------------|-------|-------------|-------|
| 3400          | 0.7                         | 0.33                  | 0.99                        | 2                       | 51.8519     | 2.80  | 831.30      | 2.456 |
| 3600          | 0.55                        | 0.35                  | 1.05                        | 2                       | 51.1696     | 2.34  | 907.89      | 2.56  |
| 3400          | 0.55                        | 0.3                  | 0.99                        | 2                       | 48.9168     | 3.23  | 833.01      | 2.80  |
| 3600          | 0.4                         | 0.33                  | 0.99                        | 3                       | 48.3092     | 2.69  | 824.51      | 3.01  |
| 3600          | 0.55                        | 0.33                  | 0.99                        | 2                       | 53.2725     | 2.18  | 928.76      | 2.23  |
| 3600          | 0.55                        | 0.35                  | 0.99                        | 1                       | 52.5526     | 1.80  | 968.85      | 2.00  |
| 3800          | 0.55                        | 0.35                  | 0.99                        | 2                       | 59.3724     | 1.82  | 1049.38     | 1.863 |
| 3600          | 0.7                         | 0.33                  | 1.05                        | 2                       | 56.7721     | 2.03  | 961.93      | 1.99  |
| 3600          | 0.55                        | 0.33                  | 1.05                        | 3                       | 51.1696     | 2.73  | 922.40      | 2.65  |
| 3800          | 0.55                        | 0.33                  | 0.99                        | 1                       | 61.2423     | 1.72  | 1138.06     | 1.35  |
in Figure 13. This is the complete training and testing procedure of ANFIS for prediction of material removal rate and surface roughness. Figures 3 to 13 show all the steps in ANFIS for Copper Iron alloy. Similarly all the similar steps for Aluminium 6061 alloy and Lead tin alloy is done separately.

The comparison between predicted and experimental values of MRR and SR using ANFIS for Aluminium alloy is depicted in Figures 14 and 15. Table 3 shows that the predicted values are found very closer to the experimental values. It also shows the comparison of error...
values for RSM and ANFIS and comparison of RSM and ANFIS Least Mean Square Error Values for MRR and SR which shows that the Error values and Least Mean Square Error for ANFIS is very less while compared to RSM for Aluminium alloy.

The comparison between predicted and experimental values of MRR and SR using ANFIS for copper alloy is depicted in Figures 16 and 17. Table 4 shows that the predicted values are found very closer to the experimental values. It also shows the comparison of error values for RSM and ANFIS and comparison of RSM and ANFIS Least Mean Square Error Values for MRR and SR which shows that the Error values and Least Mean Square Error for ANFIS is very less while compared to RSM for copper alloy.

The comparison between predicted and experimental values of MRR and SR using ANFIS for lead alloy is depicted in Figures 18 and 19. Table 5 shows that the predicted values are found very closer to the experimental values. It also shows the comparison of error values for RSM and ANFIS and comparison of RSM and ANFIS Least Mean Square Error Values for MRR and SR which shows that the Error values and Least Mean Square Error for ANFIS is very less while compared to RSM for lead alloy.

3. Results and Discussion

3.1 Effect of Process Parameters on Material Removal Rate for Aluminium 6061 Alloy

Figures 20 to 29 show the effects of input process parameters used in this study such as waterjet pressure, rate of abrasive flow, diameter of the orifice, diameter of the nozzle and stand of distance on the response MRR for cutting
### Table 3. Comparison between the Error and Least Mean Square Error of RSM and ANFIS for MRR and SR for Aluminium 6061 Alloy

| Sl. No. | Predicted MRR (mm³/min) Using ANFIS | Error MRR Using ANFIS | Error MRR Using RSM | Predicted SR (µm) Using ANFIS | Error SR Using ANFIS | Error SR Using RSM |
|---------|-----------------------------------|-----------------------|---------------------|-------------------------------|---------------------|-------------------|
| 1       | 48.1                              | 1.051406              | 1.443585            | 3.56                          | 0.28011             | 0.15964           |
| 2       | 53.4                              | 0.447242              | 0.609506            | 2.08                          | 0                   | 1.72271           |
| 3       | 52.0                              | 0.285621              | 1.113345            | 2.21                          | 0                   | 0.38539           |
| 4       | 51.1                              | 0.520899              | 0.53218             | 2.54                          | 0.39216             | 0.68585           |
| 5       | 61.9                              | 0.517822              | 0.11579             | 1.89                          | 0.52632             | 0.23761           |
| 6       | 52.8                              | 1.828477              | 1.651953            | 2.19                          | 0                   | 0.20923           |
| 7       | 45.6                              | 0.331355              | 0.139565            | 3.21                          | 0.3125              | 0.65087           |
| 8       | 53.6                              | 0.074385              | 1.410356            | 1.81                          | 0.05556             | 1.38293           |
| 9       | 61.3                              | 0.094216              | 0.918782            | 2.07                          | 0                   | 0.62955           |
| 10      | 62.1                              | 0.196393              | 0.546128            | 2.05                          | 0                   | 1.98682           |
| 11      | 51.2                              | 0.05941               | 1.233395            | 2.53                          | 0.3937              | 0.08124           |
| 12      | 47.6                              | 0.243941              | 1.4064              | 3.08                          | 0                   | 0.28142           |
| 13      | 50.4                              | 0.440023              | 1.306339            | 2.00                          | 0.50251             | 1.98073           |
| 14      | 52.8                              | 0.208089              | 0.381082            | 2.19                          | 0.92166             | 0.7105            |
| 15      | 54.3                              | 0.165655              | 2.476147            | 2.08                          | 0                   | 1.69355           |
| 16      | 51.7                              | 0.29295               | 0.490423            | 2.79                          | 0                   | 0.64989           |
| 17      | 48.7                              | 0.18288               | 0.246409            | 3.30                          | 0                   | 0.27654           |
| 18      | 52.8                              | 0.208089              | 0.381082            | 2.19                          | 0                   | 0.20923           |
| 19      | 47.9                              | 0.384773              | 0.276932            | 2.36                          | 0                   | 0.46431           |
| 20      | 48.8                              | 1.015956              | 0.784941            | 2.96                          | 0.33898             | 1.39724           |
| 21      | 58.5                              | 0.036766              | 0.762979            | 1.90                          | 0.5291              | 1.56395           |
| 22      | 54.5                              | 0.498602              | 0.693319            | 2.26                          | 0.44444             | 1.16724           |
| 23      | 56.3                              | 0.107699              | 0.628993            | 1.69                          | 0.59524             | 0.05293           |
| 24      | 49.4                              | 0.352656              | 0.708614            | 2.29                          | 0                   | 0.40076           |
| 25      | 48.9                              | 0.034344              | 1.837778            | 2.36                          | 0                   | 0.47499           |
| 26      | 51.3                              | 0.254839              | 0.841824            | 2.50                          | 0                   | 1.04148           |
| 27      | 55.9                              | 0.09865               | 0.11053             | 2.14                          | 0                   | 0.42778           |
| 28      | 48.9                              | 0.663059              | 0.030145            | 2.65                          | 0                   | 1.23968           |
| 29      | 56.6                              | 0.303142              | 0.711547            | 2.18                          | 0                   | 0.53922           |
| 30      | 50.6                              | 0.462672              | 0.856829            | 1.90                          | 0                   | 0.17781           |
| 31      | 51.9                              | 0.092764              | 0.430451            | 2.00                          | 0.50251             | 1.96228           |
| 32      | 64.9                              | 0.131451              | 0.062823            | 1.70                          | 0                   | 0.70083           |
| 33      | 48.5                              | 0.228549              | 0.592409            | 2.41                          | 0.41667             | 0.3126            |
| 34      | 52.3                              | 0.191763              | 0.020404            | 2.69                          | 0.37313             | 0.48561           |
| 35      | 52.8                              | 0.208089              | 0.381082            | 2.19                          | 0.45455             | 0.66282           |
| 36      | 59.5                              | 0.550067              | 0.640535            | 1.99                          | 0                   | 1.4636            |
Table 3. Comparison between the Error and Least Mean Square Error of RSM and ANFIS for MRR and SR for Aluminium 6061 Alloy

| Sl. No. | Predicted MRR (mm³/min) Using ANFIS | Error MRR Using ANFIS | Error MRR Using RSM | Predicted SR (µm) Using ANFIS | Error SR Using ANFIS | Error SR Using RSM |
|--------|-----------------------------------|-----------------------|---------------------|-------------------------------|---------------------|------------------|
| 37     | 51.9                              | 0.092764              | 0.65866             | 2.81                          | 0.35714             | 0.73733          |
| 38     | 51.6                              | 0.841124              | 1.136787            | 2.34                          | 0                   | 0.02899          |
| 39     | 49.4                              | 0.9878                | 1.484928            | 3.23                          | 0                   | 0.15912          |
| 40     | 48.3                              | 0.019044              | 0.162944            | 2.68                          | 0.37175             | 0.45591          |
| 41     | 52.8                              | 0.886949              | 1.058765            | 2.19                          | 0.45872             | 0.24853          |
| 42     | 52.9                              | 0.661052              | 0.152343            | 1.81                          | 0.55556             | 0.72328          |
| 43     | 59.5                              | 0.214915              | 1.615305            | 1.81                          | 0.54945             | 0.66866          |
| 44     | 56.7                              | 0.126999              | 2.718975            | 2.03                          | 0                   | 1.13511          |
| 45     | 51.0                              | 0.331447              | 0.685909            | 2.74                          | 0.3663              | 1.1317           |
| 46     | 61.0                              | 0.395642              | 0.202849            | 1.72                          | 0                   | 0.82097          |

Least Mean Square Error MRR for RSM: 0.148249
Least Mean Square Error MRR for ANFIS: 0.075355
Least Mean Square Error SR for RSM: 0.137694
Least Mean Square Error SR for ANFIS: 0.047660

Table 4. Comparison between the Error and Least Mean Square Error of RSM and ANFIS for MRR and SR for Copper Iron Alloy

| Sl. No. | Predicted MRR (mm³/min) Using ANFIS | Error MRR Using ANFIS | Error MRR Using RSM | Predicted SR (µm) Using ANFIS | Error SR Using ANFIS | Error SR Using RSM |
|--------|-----------------------------------|-----------------------|---------------------|-------------------------------|---------------------|------------------|
| 1      | 903                               | 0.579193584           | 1.878906            | 3.62                          | 0                   | 0.18998          |
| 2      | 1000                              | 0.002999910           | 0.291186            | 1.63                          | 0                   | 2.01916          |
| 3      | 963                               | 0.111234705           | 2.467892            | 2.25                          | 0.44643             | 1.80644          |
| 4      | 920                               | 0.194944512           | 0.599156            | 3.08                          | 0.32362             | 0.69508          |
| 5      | 1040                              | 0.379324878           | 0.495263            | 1.77                          | 0.16978             | 1.54915          |
| 6      | 921                               | 0.835522632           | 1.116426            | 2.23                          | 0.08977             | 0.35086          |
| 7      | 762                               | 0.038043264           | 1.375882            | 3.29                          | 0.57419             | 0.41846          |
| 8      | 987                               | 0.163387085           | 1.718834            | 2.19                          | 0.08977             | 0.76341          |
| 9      | 990                               | 0.222717149           | 0.931024            | 1.91                          | 0.47344             | 1.66912          |
| 10     | 1020                              | 0.527593841           | 1.163409            | 1.65                          | 0.60241             | 0.9634           |
| 11     | 911                               | 0.342552512           | 1.810896            | 2.77                          | 0                   | 0.40329          |
| 12     | 808                               | 0.997475063           | 0.654059            | 3.01                          | 0.63524             | 0.71371          |
| 13     | 925                               | 0.510703032           | 0.380924            | 1.98                          | 0.45249             | 1.16909          |

(Continued)
Table 4. Comparison between the Error and Least Mean Square Error of RSM and ANFIS for MRR and SR for Copper Iron Alloy (Continue)

| Sl. No. | Predicted MRR (mm3/min) Using ANFIS | Error MRR Using ANFIS | Error MRR Using RSM | Predicted SR (µm) Using ANFIS | Error SR Using ANFIS | Error SR Using RSM |
|---------|-------------------------------------|-----------------------|---------------------|-------------------------------|---------------------|------------------|
| 14      | 921                                 | 0.151777971           | 0.434618            | 2.23                          | 0.26978             | 0.53135          |
| 15      | 946                                 | 0.250954259           | 0.136459            | 2.44                          | 0.41152             | 2.87254          |
| 16      | 951                                 | 0.039973912           | 1.87803             | 2.31                          | 0.43103             | 0.97746          |
| 17      | 819                                 | 0.141837034           | 1.232423            | 2.84                          | 0.35336             | 0.91963          |
| 18      | 921                                 | 2.584094453           | 2.293505            | 2.23                          | 2.62009             | 2.36606          |
| 19      | 829                                 | 0.134075783           | 2.87923             | 2.59                          | 0.03862             | 0.15216          |
| 20      | 814                                 | 0.066295087           | 0.710342            | 3.19                          | 0                 | 0.35031          |
| 21      | 961                                 | 0.096680632           | 2.024162            | 1.78                          | 1.05614             | 0.7779           |
| 22      | 999                                 | 0.144352219           | 0.073196            | 2.36                          | 0.12728             | 0.77744          |
| 23      | 986                                 | 0.182223122           | 0.098441            | 1.5                           | 0                 | 2.10261          |
| 24      | 846                                 | 0.115705211           | 0.519132            | 2.72                          | 0.74074             | 0.32983          |
| 25      | 858                                 | 0.610469494           | 0.0973683           | 2.46                          | 0                 | 2.15337          |
| 26      | 927                                 | 0.189499978           | 0.497468            | 1.03                          | 0                 | 1.88193          |
| 27      | 974                                 | 0.049305613           | 0.209475            | 1.85                          | 0                 | 1.65886          |
| 28      | 976                                 | 0.482213638           | 0.45243             | 2.23                          | 0.44643             | 0.73598          |
| 29      | 970                                 | 0.361574493           | 0.987546            | 0.73                          | 0.23068             | 1.21237          |
| 30      | 964                                 | 0.692522222           | 0.499189            | 2.01                          | 0.5                | 1.30556          |
| 31      | 997                                 | 0.68469633            | 0.548861            | 1.67                          | 0.60241             | 2.10325          |
| 32      | 1100                                | 0.077213063           | 0.057019            | 1.4                           | 0.49751             | 1.22861          |
| 33      | 821                                 | 0.42570739            | 0.938293            | 2.47                          | 0                 | 0.11208          |
| 34      | 937                                 | 0.272467964           | 0.4519113           | 2.82                          | 0.71429             | 1.09195          |
| 35      | 921                                 | 0.151777971           | 0.434618            | 2.23                          | 1.31758             | 1.58188          |
| 36      | 1040                                | 0.392883689           | 0.205726            | 1.57                          | 0.38363             | 1.4942           |
| 37      | 828                                 | 0.396986803           | 1.005071            | 2.45                          | 0.2443              | 0.69785          |
| 38      | 909                                 | 0.122261507           | 0.716311            | 2.57                          | 0.39062             | 0.27364          |
| 39      | 828                                 | 0.601433356           | 0.716609            | 2.79                          | 0.35714             | 0.18289          |
| 40      | 826                                 | 0.180713393           | 0.395826            | 3                             | 0                 | 0.33223          |
| 41      | 921                                 | 0.835522632           | 1.116423            | 2.23                          | 0                 | 0.26086          |
| 42      | 969                                 | 0.015482273           | 0.292896            | 2                             | 0                 | 2.06066          |
| 43      | 1050                                | 0.059082506           | 0.300565            | 1.87                          | 0.37574             | 2.29979          |
| 44      | 965                                 | 0.319150042           | 0.3552              | 1.99                          | 0                 | 2.07628          |
| 45      | 922                                 | 0.043365134           | 0.850008            | 2.66                          | 0.37736             | 0.33818          |
| 46      | 1140                                | 0.170465529           | 0.989072            | 1.35                          | 0                 | 0.61975          |

Least Mean Square Error MRR for RSM 0.161162
Least Mean Square Error MRR for ANFIS 0.066068
Least Mean Square Error SR for RSM 0.201764
Least Mean Square Error SR for ANFIS 0.084770
Figure 16. Comparisons of Predicted MRR and Experimental MRR (Cu).

Figure 17. Comparisons of Predicted SR and Experimental SR (Cu).

Table 5. Comparison between the Error and Least Mean Square Error of RSM and ANFIS for MRR and SR for Lead Tin alloy

| Sl. No | Predicted MRR (mm³/min) Using ANFIS | Error MRR Using ANFIS | Error MRR Using RSM | Predicted SR (µm) Using ANFIS | Error SR Using ANFIS | Error SR Using RSM |
|-------|-------------------------------------|-----------------------|---------------------|--------------------------------|----------------------|-------------------|
| 1     | 1700                                | 0.0266238             | 0.140804            | 2.44                           | 0.40816              | 0.22129            |
| 2     | 2010                                | 0.2412078             | 0.22388             | 1.41                           | 0.35336              | 1.64361            |
| 3     | 1970                                | 0.0045683             | 1.455883            | 1.63                           | 0.36946              | 1.3945             |
| 4     | 1910                                | 0.3573571             | 0.255508            | 2.2                            | 0                    | 0.18168            |
| 5     | 2190                                | 0.3546782             | 0.698198            | 0.786                          | 0.25381              | 1.20364            |
| 6     | 2010                                | 0.6086574             | 0.419778            | 1.6                            | 0.55935              | 0.60723            |
| 7     | 1690                                | 0.0799455             | 2.564097            | 2.1                            | 0.42674              | 0.86209            |
| 8     | 2000                                | 0.1081168             | 0.50632             | 1.52                           | 0                    | 1.95643            |
| 9     | 2090                                | 0.1927152             | 0.293584            | 1.2                            | 0.08326              | 0.16391            |
| 10    | 2140                                | 0.427603              | 0.120616            | 0.805                          | 0.49938              | 1.39366            |
| 11    | 1890                                | 0.3343282             | 1.543912            | 2.1                            | 0                    | 1.27126            |
| 12    | 1750                                | 0.1786041             | 1.521448            | 1.9                            | 0.26247              | 1.01542            |
| 13    | 1940                                | 0.1600527             | 0.727295            | 1.88                           | 0.37096              | 0.40004            |
| 14    | 2010                                | 0.0418085             | 0.146007            | 1.6                            | 1.84596              | 1.79693            |
| 15    | 1940                                | 0.4331671             | 0.070388            | 1.54                           | 0.65359              | 2.00431            |
| 16    | 2010                                | 0.3254338             | 0.554358            | 1.71                           | 0.05851              | 2.52001            |
| 17    | 1740                                | 0.0389941             | 0.085287            | 1.9                            | 0                    | 0.34481            |
| 18    | 2010                                | 0.3254338             | 0.137086            | 1.6                            | 2.17114              | 2.12195            |
| 19    | 1840                                | 0.1172537             | 1.907532            | 1.91                           | 0                    | 0.14304            |
| 20    | 1760                                | 0.5030865             | 0.899159            | 1.89                           | 0.47393              | 1.09612            |
| 21    | 2130                                | 0.2925688             | 1.619043            | 1.2                            | 0.90834              | 0.36569            |
| 22    | 1900                                | 0.4605322             | 0.091595            | 1.98                           | 0.95048              | 0.9955             |
| 23    | 2070                                | 0.6931777             | 0.139848            | 1.42                           | 0.76869              | 0.66169            |

(Continued)
Table 5. Comparison between the Error and Least Mean Square Error of RSM and ANFIS for MRR and SR for Lead Tin alloy

| Sl. No. | Predicted MRR (mm³/min) Using ANFIS | Error MRR Using ANFIS | Predicted MRR (mm³/min) Using RSM | Error MRR Using RSM | Predicted SR (µm) Using ANFIS | Error SR Using ANFIS | Error SR Using RSM |
|---------|-------------------------------------|-----------------------|-----------------------------------|---------------------|--------------------------------|---------------------|-------------------|
| 24      | 1860                                | 0.3429061             | 1.002258                          | 2.01                | 0.14903                        | 0.39509            |
| 25      | 1840                                | 0.1172537             | 1.166095                          | 1.94                | 0.25707                        | 1.30973            |
| 26      | 1920                                | 0.1643321             | 0.62                              | 2.01                | 0.0996                         | 0.35867            |
| 27      | 1970                                | 0.0045683             | 0.260923                          | 1.5                 | 0                               | 0.88189            |
| 28      | 1790                                | 0.0599751             | 0.905793                          | 1.78                | 0.50307                        | 0.1                 |
| 29      | 1940                                | 0.1135308             | 0.82164                           | 1.7                 | 0.05886                        | 0.69401            |
| 30      | 2040                                | 0.4785809             | 0.03452                           | 1.71                | 0.17575                        | 2.39642            |
| 31      | 2010                                | 0.0418085             | 0.190011                          | 1.5                 | 0                               | 0.02388            |
| 32      | 2140                                | 0.1255431             | 0.064608                          | 0.615               | 0.80645                        | 0.56586            |
| 33      | 1860                                | 0.3429061             | 1.390375                          | 1.94                | 0.31024                        | 0.4587             |
| 34      | 1910                                | 0.3568373             | 0.067327                          | 2.31                | 0.04331                        | 0.83406            |
| 35      | 2010                                | 0.2412078             | 0.428492                          | 1.6                 | 0.18785                        | 0.13962            |
| 36      | 2170                                | 0.0561023             | 0.275813                          | 0.798               | 0.25                            | 1.86871            |
| 37      | 1800                                | 0.0044443             | 0.56061                           | 1.89                | 0.52632                        | 1.00533            |
| 38      | 2020                                | 0.0296942             | 0.790682                          | 1.71                | 0.35211                        | 0.99448            |
| 39      | 1770                                | 0.0757636             | 0.361177                          | 2.09                | 0.57088                        | 1.24783            |
| 40      | 1840                                | 0.1172537             | 0.516789                          | 2.36                | 0.63966                        | 0.76675            |
| 41      | 2010                                | 0.5245967             | 0.711348                          | 1.6                 | 2.43902                        | 2.48599            |
| 42      | 2080                                | 0.067312             | 0.939652                          | 1.64                | 0.3672                         | 2.17561            |
| 43      | 2170                                | 0.3561023             | 0.991671                          | 0.878               | 0.34052                        | 0.20328            |
| 44      | 1970                                | 0.0045683             | 0.072697                          | 1.54                | 0.06498                        | 0.61716            |
| 45      | 1920                                | 0.1061372             | 0.770923                          | 2                   | 0.15023                        | 0.00119            |
| 46      | 2220                                | 0.148428             | 0.900289                          | 0.801               | 0.125                           | 1.19214            |

Least Mean Square Error MRR for RSM 0.12714
Least Mean Square Error MRR for ANFIS 0.041937
Least Mean Square Error SR for RSM 0.178674
Least Mean Square Error SR for ANFIS 0.099991

Figure 18. Comparisons of Predicted MRR and Experimental MRR (Pb).

Figure 19. Comparisons of Predicted SR and Experimental SR (Pb).
Aluminium 6061 alloy using AWJM. Figures 20–23 illustrate that as the pressure of the abrasive water jet increases, rate of abrasive flow increases, diameter of the orifice decreases, diameter of the nozzle decreases and standoff distance decreases, MRR increases due to the high pressure, minor diameter of orifice and nozzle increases the velocity of water jet when impinged on the work surface with low standoff distance. Figures 24–26 illustrate that as the abrasive flow rate increases the MRR also increases due to the rate of flow of the abrasives and water increases. Figures 27–29 illustrate as the diameter of orifice and nozzle decreases produce high MRR with low stand of distance. Thus when the pressure is 3800 bar, abrasive flow rate is 0.7Kg/min, Orifice diameter is 0.3mm, nozzle diameter is 0.9mm and standoff distance is 1mm, the MRR is high.

3.2 Effect of Process Parameters on Surface Roughness for Aluminium 6061 Alloy

Figures 30 to 39 show the effects of input process parameters used in this study such as abrasive water jet pressure, rate of abrasive flow, diameter of orifice, diameter of nozzle and stand of distance on the response SR for cutting Aluminium 6061 alloy using AWJM. Figures 30–33 illustrate that as the pressure of the abrasive water jet increases, rate of abrasive flow increases, diameter of orifice decreases, diameter of nozzle decreases and standoff distance decreases produce good SR due to the high pressure, minor diameter of orifice and nozzle increases the velocity of water jet when impinged on the work surface.
with low standoff distance. Figures 34-36 illustrate that as the abrasive flow rate decreases the SR value i.e., good surface finish also increases due to the rate of flow of the abrasives and water increases. Figures 37-39 illustrate as the diameter of orifice and nozzle decreases; it produces good SR with low stand of distance. Thus when the pressure is 3800 bar, abrasive flow rate is 0.7Kg/min, Orifice diameter is 0.3mm, nozzle diameter is 0.9mm and stand-off distance is 1mm, the SR obtained is very good.

### 3.3 Effect of Process Parameters on Material
Removal Rate for Copper Iron Alloy

From Figures 40 to 49 the effects of input process parameters used in this study such as water jet pressure, rate of abrasive flow, diameter of orifice, diameter of nozzle and stand of distance on the response Material removal rate for cutting Copper iron alloy using AWJM is shown. The Figures 40-43 illustrates that as the pressure of the abrasive water jet increases, rate of abrasive flow increases, diameter of orifice decreases, diameter of nozzle decreases and standoff distance decreases the MRR increases due to the high pressure, minor diameter of orifice and nozzle increases the velocity of water jet when impinged on the work surface with low standoff distance. The Figures 44-46 illustrates that as the abrasive flow rate increases the MRR also increases due to the rate of flow of the abrasives and water increases. Figures 47-49 illustrates as the diameter of orifice and nozzle decreases produce high MRR with low stand of distance. Thus when the pressure is 3800 bar, abrasive flow rate is 0.7 Kg/min, Orifice diameter is 0.3mm, nozzle diameter is 0.9mm and standoff distance is 1mm, the MRR is high.

3.4 Effect of Process Parameters on SR for Copper Iron Alloy

Figures 50 to 59 show the effects of input process parameters used in this study such as water jet pressure, rate of abrasive flow, diameter of orifice, diameter of nozzle and stand of distance on the response Surface Roughness for cutting Copper Iron alloy using AWJM. The Figures 50-53 illustrate that as the pressure of the abrasive water jet increases, rate of abrasive flow increases, diameter of
Figure 40. MRR vs. Pressure and Abrasive Flow Rate.

Figure 41. MRR vs. Pressure and Orifice Diameter.

Figure 42. MRR vs. Pressure and Nozzle Diameter.

Figure 43. MRR vs. Pressure and Stand Off Distance.

Figure 44. MRR vs. Abrasive Flow Rate and Orifice Diameter.

Figure 45. MRR vs. Abrasive Flow Rate and Nozzle Diameter.

Figure 46. MRR vs. Abrasive Flow Rate and Stand Off Distance.

Figure 47. MRR vs. Orifice Diameter and Nozzle Diameter.

orifice decreases, diameter of nozzle decreases and stand-off distance decreases produce good SR due to the high pressure, minor diameter of orifice and nozzle increases the velocity of water jet when impinged on the work surface with low standoff distance. The Figures 54-56 illustrate that as the abrasive flow rate decreases the SR value i.e., good surface finish also increases due to the rate of flow of the abrasives and water increases. Figures 57-59 illustrate as the diameter of orifice and nozzle decreases produce good SR with low stand of distance. Thus when
the pressure is 3800 bar, abrasive flow rate is 0.7Kg/min, Orifice diameter is 0.3mm, nozzle diameter is 0.9mm and standoff distance is 1mm, the SR obtained is good.

3.5 Effect of Process Parameters on Material
Removal Rate for Lead Tin Alloy

Figures 60 to 69 show the effects of input process parameters used in this study such as abrasive water jet pressure, rate of abrasive flow, diameter of orifice, diameter of nozzle and stand of distance on the response MRR for cutting Lead Tin alloy using AWJM. Figures 60-63 illustrate that as the pressure of the abrasive water jet increases, rate of abrasive flow increases, diameter of orifice decreases, diameter of nozzle decreases and standoff distance decreases the MRR increases due to the high pressure, minor diameter of orifice and nozzle increases the velocity of water jet when impinged on the work surface with low standoff distance. Figures 64-66 illustrate that as the abrasive flow rate increases the MRR also increases due to the rate of flow of the abrasives and water increases. Figures 67-69 illustrate as the diameter of orifice and nozzle decreases produce high MRR with low stand of distance. Thus when the pressure is 3800 bar, abrasive flow rate is 0.7 Kg/min, Orifice diameter is 0.3mm, noz-

Figure 57. SR vs. Orifice Diameter and Nozzle Diameter.

Figure 58. SR vs. Orifice Diameter and Stand Off Distance.

Figure 59. SR vs. Nozzle Diameter and Stand Off Distance.

Figure 60. MRR vs. Pressure and Abrasive Flow Rate.

Figure 61. MRR vs. Pressure and Orifice Diameter.

Figure 62. MRR vs. Pressure and Nozzle Diameter.

Figure 63. MRR vs. Pressure and Stand Off Distance.

Figure 64. MRR vs. Abrasive Flow Rate and Orifice Diameter.
zzle diameter is 0.9mm and standoff distance is 1mm, the MRR is high.

3.6 Effect of Process Parameters on Surface Roughness for Lead Tin Alloy

From Figures 70 to 79 the effects of input process parameters used in this study such as abrasive water jet pressure, rate of abrasive flow, diameter of orifice, diameter of nozzle and stand of distance on the response Surface Roughness for cutting Lead Tin alloy using AWJM is shown. The Figures 70-73 illustrates that as the pressure of the abrasive water jet increases, rate of abrasive flow increases, diameter of orifice decreases, diameter of nozzle decreases and standoff distance decreases produce good surface roughness due to the high pressure, minor diameter of orifice and nozzle increases the velocity of water jet when impinged on the work surface with low standoff distance. Figures 74-76 illustrate that as the abrasive flow pressure increases, rate of abrasive flow increases, diameter of orifice decreases, diameter of nozzle decreases and standoff distance decreases produce good surface roughness due to the high pressure, minor diameter of orifice and nozzle increases the velocity of water jet when impinged on the work surface with low standoff distance. Figures 74-76 illustrate that as the abrasive flow
rate decreases the SR value i.e., good surface finish also increases due to the rate of flow of the abrasives and water increases. Figures 77-79 illustrate as the diameter of orifice and nozzle decreases produce good SR with low stand of distance. Thus when the pressure is 3800 bar, abrasive flow rate is 0.7 Kg/min, Orifice diameter is 0.3mm, nozzle diameter is 0.9mm and standoff distance is 1mm, the SR obtained is high.
4. Conclusion

In this paper, using linear regression analysis a mathematical model is developed for three nonferrous alloys through AWJM process by Minitab software is done. Then the prediction of MRR and SR for Aluminium 6061 alloy, Copper Iron alloy and Lead Tin alloy by cutting through AWJM process by the tool named ANFIS is done which illustrates that the experimental values are closer to the predicted values for all the three materials. The error comparison between RSM and ANFIS is also studied which shows the percentage of error is very less in ANFIS while compared with RSM. More over the effect of abrasive water jet pressure, rate of abrasive flow, diameter of orifice, diameter of focusing nozzle and standoff distance on MRR and SR is studied through this intelligent tool.

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