Impact resistance and hardness modelling of Aluminium alloy welds using square-headed friction-stir welding tool

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Abstract: This paper proposes modelling and optimization issues relating to friction-stir welding process of aluminium alloys. A specially prepared SS tool of square headed pin profile with cylindrical shoulder is used with a vertical milling machine. Effects of process variables including tool rotation and tool velocity on the weld performance are studied in terms of impact strength and hardness. Three different rotational motions and three welding speeds (feeds) of tool are considered at constant axial load (depth of cut) condition and altogether nine experiments are conducted on a vertical milling machine with specially prepared fixture. Each weld sample is then tested for its impact strength (IS) and hardness independently. A model is developed to correlate the relations between the hardness/impact strength with tool rotation and weld speed using neural networks. The optimized process conditions are predicted to improvise the impact strength and hardness of the weld. Further, the morphology of the weld is studied using SEM to know the material flow characteristics.

Keywords: Friction-stir welding, Joint toughness, impact strength, hardness, neural network model.

1 Introduction

Recently, several cost-effective and eco-friendly joining techniques have been evolved in material industries. Solid-state joining techniques like laser-welding, friction-welding, friction-cladding and friction-stir welding have replaced the conventional fusion welding processes for Aluminium alloys. Friction-stir welding (FSW) was invented in 1991 by welding institute in UK for welding dissimilar materials. It results in excellent weld strength, ductility and toughness. Here, a rotating tool with a specially designed shoulder and probe is pressed over the workpiece surface at the junction and traversed along the interface with a weld-speed. Due to friction between the rotating tool and work piece, the plastic deformation occurs and temperature rises. The generated heat softens the work piece and yield strength of base materials reduces. As tool is moved from one location to other, the momentary softening at each instant of time will form the weld. Main advantage of the process is that it is free from oxide formation and welding cracks as well as it results in low residual stresses due to relatively small input energy. During FSW, the weld quality is affected by various process and tool parameters. It results in changes of different mechanical properties of work-material.
There are several studies in the literature concerning mechanical characterization of friction stir welded joints. The effect of tool rotational and traverse speed on friction stir weld characteristics of AISI 430 ferritic stainless steels were studied by Bilgin and Mera [1]. Ahn et al. [2] examined the mechanical properties of friction stir welded 409L stainless steel. Heidarzadeh et al. [3] used a mathematical model for predicting the tensile properties of friction stir welded aluminum alloy joints. Rajakumar et al. [4] illustrated the response surface methodology to develop empirical relationship to predict grain size and hardness of weld nugget of AA6061 alloy weld as function of process parameters. Shojaee et al. [5] investigated the Artificial Neural Network (ANN) model for the mechanical properties of friction stir welded aluminum alloys butt joints. The ultimate tensile strength of joint of aluminum alloys were predicted using Artificial Neural Network model. Elatharasan and Kumar [6] investigated the experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy. They modeled the ultimate tensile strength (UTS), yield-strength (YS), and percentage elongation in FSW process and analyzed through response surface methodology. Silva et al. [7] investigated the friction stir weld Joint optimization using Taguchi method. They suggested that the tool rotational speed was the most influencing factor in joint mechanical properties. Sivamani and Palanikumar [8] investigated optimizing the friction welding parameters to attain maximum tensile strength in AISI 1035 grade carbon steel rods. Birol and Kasman [9] studied effect of tool tilt angle and rotation on the ultimate strength and micro hardness of the friction stir welding of twin roll cast EN AW Al-Mn1Cu plates. Liu et al. [10] carried out FSW of aluminum alloy 6061-T6 alloy sheets with high strength steel and computed the effects of various process parameters on the ultimate strength of the weld. More recently Wang et al. [11] studied the microstructure and texture evaluations of weld formed by dissimilar aluminum alloys. Use of soft computing tools in modelling of friction-stir welding is another concept. Okuyucu et al. [12] showed the neural network application for friction-stir welding of Aluminium plates. Fratini et al. [13] presented the procedure of predicting the average grain size in friction-stir welding process using neural networks. BoldSaikhan et al. [14] used neural networks and Fourier transforms for real time evaluation of friction-stir welding. Bakara et al. [15] illustrated quality monitoring frame work for steel friction-stir welding using computational intelligence. Modelling and optimization of mechanical properties from experimental studies is very much required to minimize the time-consuming experiments. Present paper deals with development of a process-model based on experimental data and further this model is employed for process optimization simultaneously to obtain better hardness and impact strength of the joint. Effects of the operating variables on impact strength and hardness of aluminium weld samples is initially studied. A neural network model is employed to obtain relationship between the input and output parameters, whose weight structure is adopted later in optimizing the process parameters. Results of the analysis are shown in the form graphs and tables.

2. Experimental work

This section describes the experimental work carried out on AA3003 alloy strips for welding along with description of the material characterization using impact testing machine and hardness tester.

2.1 Weld Preparation

The rolled plates of aluminium alloy AA3003 of 5 mm thick are cut in to required sizes (100 mm × 30 mm) by power hacksaw machine and square butt configuration is prepared. Initial joint configuration was obtained by securing plates in position using mechanical clamps. Non-consumable tool made of high speed steel was used in the weld joint preparation. To carry out the FSW process, a Column & Knee type Universal Milling Machine as shown in Fig.1 is employed. The cutting tools are initially fabricated on a lathe machine using stainless steel material. The work holding fixture was designed and tested before the experiments. The FSW tool consists of a 9mm diameter shoulder and square cross-section of side 4mm tool pin of thickness 3mm is considered as shown in Fig.2.
It is made of stainless steel. All the experimental analysis is carried out at workshops of Mechanical Engineering with courtesy of GITAM University. The FSW tool was plunged into the pilot hole of size 3mm machined already in the work piece. The tool initially removes some material, and subsequently started to generate heat when the required plunge is provided. The tool was traversed through the length of the plate. The schematic diagram of the friction stir welding process is shown in Fig. 3.

Welding was carried out with various tool rotations and weld speeds using full factorial experimental designs. Depth of cut was set at 3.5mm during welding. Standard test pieces were made for impact and hardness tests by cutting along the transverse direction. In this study, a total of nine experiments were carried out by varying two input variables in three levels. Table-1 shows the input variables considered.
2.2 Impact strength and hardness measurements

For impact and hardness tests, the samples were cut from weld specimens in cross direction. From each welded sample, two test specimens were prepared. Fig.4 shows the samples for impact test. The Charpy impact test was carried-out to find the impact strain energy and hence the strength. Fig.5 shows the variation of impact strength of the joints welded at different weld speeds and tool rotational speeds. In welding, the heat input plays an important role on the mechanical properties of the weldments. Vickers hardness was recorded by using a tester employing 100Kgf load. The measurements were made at weld nugget zone. Fig.6 shows the variation of hardness for the various tool rotations and weld speeds. It was observed that the hardness decreases with increase in heat input. For instance, at tool rotation of 560 rpm at 45 mm/min weld-speed, the hardness value is low due to maximum heat input. For the same tool rotation, the weld hardness value is high at 22.4 mm/min because of lower heat input.

| Designation | Tool rotational Speed (TRS) RPM | Weld speed (mm/min) |
|-------------|-------------------------------|---------------------|
| A1          | 560                           | 22.4                |
| A2          | 560                           | 31.5                |
| A3          | 560                           | 45.0                |
| B1          | 900                           | 22.4                |
| B2          | 900                           | 31.5                |
| B3          | 900                           | 45.0                |
| C1          | 1400                          | 22.4                |
| C2          | 1400                          | 31.5                |
| C3          | 1400                          | 45.0                |

3. Analysis and Modelling

The statistical analysis of the data was made in two phases. The first phase was concerned with the analysis of variance with the effect of process parameters and their interactions. The second phase was concerned with correlation of input parameters and properties of friction stir-weld. The simplest way to determine the most influencing parameters on impact strength and hardness is to obtain the idea from the
Main Effect plots as shown in Fig.7. The S/N response data are calculated using Minitab16 software (trail). The largest S/N response reflects the best response resulting in the lowest noise for impact strength and hardness. The lowest tool rotational speed (560 rpm) with lowest weld-speed (22.4 mm/min) is determined to be the best choices for obtaining highest impact strength and hardness. The plots also show that the tool rotation speed is most influential parameter on the impact strength and hardness.

![Main Effect plots for SN ratios](image)

(a) Impact strength  
(b) Hardness

Figure 7. Main effect plots of (a) Impact strength and (b) Hardness

The SEM micrographs of surface generated after the welding operation is shown in Fig.8. They indicate the weld uniformity at lower speed and feeds. The aluminium particles dispersion is found to be uniform in the alloy. More number of surface studies are required.

![SEM micrograph at the weld zone](image)

(a) At weld centre  
(b) At weld corners

Figure 8. SEM micrograph at the weld zone

3.1 Modeling data with network

Artificial neural networks are the computational models, which replicate the function of a biological network, composed of neurons and are used to approximate complex functions in various applications. The present system considered has three layers, which are input, hidden and output layers. The input layer consists of all the input factors including tool rotation and weld speed. Information from the input layer is then processed to hidden layer followed by the output, where the output vector is computed. A schematic
description of the layers is given in Fig.9. In this work, supervised learning, in which the network is presented with inputs along with the target outputs together with adjusted weighting, are employed. One of the most popular learning-algorithms is the back-propagation algorithm. With a single hidden layer, Levenberg-Marquardt scheme is employed to minimize the square error between the data points obtained from experiments.

![Neural network diagram](image)

**Figure9.** Neural network employed in present task

Inputs and outputs have been normalized in the range of 0–1. Neurons in the input layer do not have transfer function, while in the other layers a logistic sigmoid (logsig) transfer function has been used. Both a built-in code and MATLAB toolbox are employed for modeling. After training the network successfully, it has been tested by using the known test data. Fig.10 shows the error convergence trend for various number of hidden-layer neurons.
Figure 10. Mean-square error convergence

It is seen that 4 hidden layer architecture is best one and employed further. The mechanical properties of friction-stir welding of Al plates with tool rotation and weld speed as well as predicted new data obtained from the network after the training stage are compared and it is found that measured and predicted output values were very close to each other. Fig.11 shows the process optimization module which uses the neural network weights for obtaining the impact strength and hardness.

Figure 11. Process of estimation of optimum welding parameters

4. Conclusion

This work presented the outcomes of friction-stir welding of aluminum alloy plates using a tool with square headed pin profile. Nine welding conditions were considered by varying the tool rotation speed and weld speed using the vertical milling machine set-up. In all the cases, impact strength and hardness were predicted independently. The morphology was studied at the weld zone to understand the mixing ability of phases and weld defects including burrs. The optimum cutting states were predicted from analysis of variance test using Minitab software. Finally, the relation between the weld parameters and mechanical characteristics of weld was obtained using a three layer back propagation model. Use of this model towards prediction of optimal process parameters was briefed-out and can be treated as future scope of the work.

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