

Chapter 27

Optimization of Friction Stir Welding Parameters Using Taguchi Method for Aerospace Applications



K. Ramesha, P. D. Sudersanan, N. Santhosh, G. Ravichandran and N. Manjunath

Abstract The current research work investigated the optimization of the input parameters for the friction stir welding of AA3103 and AA7075 aluminum alloys for its applications in aerospace components. Friction stir welding is rapidly growing welding process which is being widely used in aerospace industries due to the added advantage of strong strengths without any residual stresses and minimal weld defects, in addition to its flexibility with respect to the position and direction of welding. Thus, the demand for this type of welding is very high; however, the welding of aluminum alloys is a key aspect for its use in aircraft components, particularly with respect to bracket mounting frames, braces and wing components. Henceforth in the current work, research is focused on optimization of welding of aluminum alloys, viz. AA 3103 and AA 7075; AA 3103 is a non-heat treatable alloy which is having good weldability, while AA 7075 is having higher strength. Therefore, the welding of these aluminum alloys will produce superior mechanical properties. The optimization of input parameters was accomplished in this work based on L9 orthogonal array designed in accordance with Taguchi method—using which the friction stir welding experiment was conducted. There were nine experimental runs in total after formulating the L9 orthogonal array table in Minitab software. The input parameters which were selected for optimization were—tool rotation speed, feed rate, tool pin profile. The output parameters which were optimized were hardness, tensile strength and impact strength. In addition, the microstructure of the fractured surfaces of the friction stir welded joint was analyzed. It was found from the optimization of the process parameters that strong friction stir welded joints for aerospace applications can

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be produced at an optimized set of parameters of tool rotational speed of 1100 rpm, traverse speed of 15 mm/min with a FSW tool of triangular pin profile of H13 tool steel material.

Keywords AA3103 · AA7075 · Friction stir welding · H13 tool steel · Taguchi orthogonal array · Minitab · Aerospace · Components

27.1 Introduction

Friction stir welding is type of welding in which a non-consumable tool is being used in order to weld two workpieces. The welding of the workpiece occurs heating the working piece at its line of joint. The heat is generated due to the friction between the rotating tool and the workpiece, and as the tool is rotating, it intermixes both the workpiece materials. The mechanical intermixing of the workpiece material will be accomplished as the tool moves along the line of the joint, and subsequently the forging of hot and soft material is made by the means of mechanical pressure. The FSW tool serves two primary functions:

- Heating of the workpiece material.
- Mixing of two materials in a mushy state to produce the joint.

Friction stir welded aluminum alloys are widely used in aeronautical and aerospace industries for manufacturing airplanes both commercial and defense type, spacecraft, helicopters, etc. Among the different types of aluminum alloys, AA3103 is a non-heat treatable alloy and having superior strength, whereas the AA7075 is having higher strength. Thus, the weld obtained from these two alloys will be of superior quality. But AA7075 aluminum weld is quite expensive. In order to reduce the expense, the AA7075 aluminum alloy is welded with other grades of aluminum alloys. The AA3103 aluminum alloy has good weldability and is less expensive. Therefore, a weld produced from these two alloys will be showing the properties of both these alloys. For the weldment between AA2024-T365 and AA5083-H111, heat-treated H13 steel is used as the tool material; the tool is having a concave shoulder of 20 mm diameter and a pin diameter of 5 mm, and the height of pin is 4.7 mm.

The tool pin profiles used for welding are square, triangular and stepped. The welding parameters used for the experimentation are 900, 1120 and 1400 rpm for tool rotational speed and 16, 40 and 80 mm/min for feed rate [1]. The friction stir welding is conducted between two grades of aluminum alloys 5086 H116 and 5083 H321. Each workpiece plate is having a thickness of 6 mm, the AA 5086 is having dimensions of 100 * 95 * 6 mm, and the AA 5083 is of 100 * 70 * 6 mm dimensions. During the welding process, AA 5086 is taken as the advancing side (AS), while AA 5083 is the retracting side (RS), and this is because the advanced side material should be always a hard material. The tool used for welding is a chromium–molybdenum

tool which is made of H13 steel. The five different pin profiles used for the welding experiments are threaded, square, cylindrical, tapered and triangular [2]. The metallurgical characterization is carried out by SEM and EDS, and the mechanical properties are developed by tensile and hardness test. From this paper, they come out with the most efficient result that is of 710 rpm and 28 mm/min, and the tool design is cylindrical pin [3]. Fatigue behavior of friction stir welded Al–Mg joints exhibited wide scatter. The Al–Mg joints exhibited two distinct failure modes: kink crack and interfacial. Intermetallic compounds outside the weld likely led to fretting initiated fatigue. Insufficient material mixing resulted in underperforming joints [4]. The tool profiles are as follows: The shoulder shape is concave, pin shape is triangular, shoulder diameter is 12 mm, and pin diameter is 5.4 mm [5].

The tool used for friction stir welding is made up of carbon steel of diameter 20 mm with shoulder diameter 12 mm and with a cylindrical pin of diameter 5 mm. Eight joints were fabricated as per the design plan from the Taguchi method [6]. Microstructural suggested that there was no rigorous mixing, and there was a small change in the microhardness across the surface. The microelectron analysis test shows that there is a bonding at the atomic scale due to interdiffusion of the alloys in the nugget. Thus, the interdiffusion of alloying elements and attaining of similar orientation in the nugget have contributed good mechanical properties [7]. It is concluded that for AA5083–AA5083 similar material welding, the welding efficiency is 77% from base metal AA5083, and for the AA6061–AA5083 dissimilar material welding, the welding efficiency was 34 and 93% compared to AA5083 and AA6061 [8]. The tool used in this experiment is EN-31 with a shoulder diameter of 20 mm and pin diameter of 5 mm at the root and 5.75 mm pin length. The weld joints are cut as per ASTM dimensions for impact test [9, 10]. L8 orthogonal array is used by taking three process parameters and two levels for optimizing the process parameters for obtaining higher hardness and tensile strength of the welded region [11, 12].

From the literature review, it is seen that the friction stir welding of aluminum components has great scope, and studies can be carried out on the process since friction stir welding depends on the parameters selected, which facilitates the need to optimize these input parameters so that we could find out how it affects the resulting weld and the output parameters like strength and quality of weld. To do so, there are many input parameters, so by going through the findings, it is finalized that three parameters which are speed, feed rate and tool profile are considered, and each parameter has to be selected. These values will be then optimized in order to obtain the perfect combination of the input parameter value so that high quality weld will be obtained.

27.2 Materials and Methods

The current section gives an overview of the materials used for fabrication of the plates that are friction stir welded by optimizing the parameters.

27.2.1 Selection of Materials

AA 7075 and AA 3103 are the aluminum alloys which are chosen as the two work-piece materials having dimensions of 103 * 50 * 6 mm, for friction stir welding in this experiment. The chemical composition of the workpiece is presented in Tables 27.1 and 27.2.

27.2.2 Selection of Tool

The welding tool is made up of H13 tool steel. The weld tool is manufactured by casting process and then heat treated. Right after the heat treatment, the tool is kept in oil bath (for three days). This is done in order to improve the strength of the weld tool.

27.2.3 Selection of Welding Parameters and Levels

The three main parameters selected for this welding operation are tool rotational speed, feed rate of tool and tool pin profile. The selection of the welding parameter values was based on the knowledge obtained from the literature survey. Table 27.3 gives the values selected for the welding parameters and their levels.

27.2.4 Experimental Setup

The entire experiment is carried out in a vertical CNC machine. Both the workpieces are placed on a rig with AA3103 specimen placed on the advancing side. The rig for holding the workpiece rigidly is installed on the CNC worktable. The friction stir welding is carried out based on the combination of input parameter values, obtained using Minitab software. Computer numerical control (CNC) machining is a machining process in which the machining tools and traverse path of the cutting tool are controlled by means of a computer. In this machining process, pre-programmed computer software will control all the movements of the tool. When a CNC machine is activated, the desired operations required to be done will be programmed into the software in the form of G codes and M codes, and these programs shall then dictate the tool for the corresponding motions to perform the operations. The current experiment is carried out in a high quality CNC milling machine without using coolant and with a maximum speed of 1200 rpm. The maximum feed rate used in our project is 25 mm/min, and the electric drive used is a 25-kw drive motor. The fixture is used to hold the workpiece tight and in perfect position without any vibration while

Table 27.1 Chemical composition of AA 3103 (weight %)

Elements	Mn	Fe	Cu	Mg	Si	Zn	Cr	Ti + Zr	Al
Percentage composition	1.5	0.7	0.1	0.3	0.5	0.2	0.1	0.1	Balance

Table 27.2 Chemical composition of AA 7075 (weight %)

Elements	Al	Zn	Mg	Cu	Cr
Percentage composition	90	5.6	2.5	1.6	0.23

Table 27.3 Welding parameters and their levels

Parameters	Unit	Symbol	Level 1	Level 2	Level 3
Tool rotational speed	rpm	A	1000	1100	1200
Feed rate	mm/min	B	15	20	25
Tool pin profile	Shape	C	Square	Circle	Triangle

Table 27.4 Design of experiments matrix with input values

Experimental trial No.	Speed of rotation (rpm)	Feed rate (mm/min)	Tool pin profile
1	1000	15	Circular
2	1000	20	Square
3	1000	25	Triangle
4	1100	15	Square
5	1100	20	Triangle
6	1100	25	Circular
7	1200	15	Triangle
8	1200	20	Circular
9	1200	25	Square

welding. The fixture consists of a main plate and above that four supporting sides each containing a M12 hole, where the tightening screws are inserted to adjust the position of the workpiece. The experimental trails were carried out based on Taguchi’s L9 orthogonal array. The values of the input parameters were selected based on the literature survey. A nine run, three factors, three-level orthogonal array was designed by following Taguchi’s design of experiments, which is given in Table 27.4.

27.2.5 CNC Programming

Since the friction stir welding of the workpieces was carried out in a CNC machine, a program was required to run the welding experimentation. The CNC program used for the friction stir welding considered the various aspects of tool rotational speed, feed rate and depth with preparatory functions (G codes) and miscellaneous functions (M codes).

27.3 Results and Discussions

A nine trial run experiment was conducted in the vertical CNC milling machine by giving the input parameters varied at three levels of input parameters. The output parameters selected for the experiment are tensile strength, hardness and impact strength, and each of them determined using UTM, Brinell hardness testing machine and Charpy testing machine, respectively. Further, the microstructure of the fractured surfaces of the friction stir welded joints is **analyzed** using a Hitachi make SU 3500 scanning electron microscope. Initially, the specimens of 10 mm * 10 mm * 5 mm thickness from the fractured surfaces of the friction stir welded joints are cut and prepared suitably for microscopic observations in SEM at various resolutions and magnifications to analyze the fractography and evaluate the fracture mechanics behind the weld joints, which is presented in this section. Table 27.5 gives the values of the different properties characterized for the given set of parameters selected for the experimental trials carried out as per the design of experiments formulated in accordance with Taguchi's L9 orthogonal array.

The obtained results are the entered into the L9 orthogonal array with the input parameter values and analyzed in the Minitab software. As a result of the statistical approach, the software will optimize and compare both input and output parameters and provide combinations of input parameters which will produce the best and high quality weld.

Table 27.5 Resultant values from the experimental trials

Sl. No.	Speed (rpm)	Feed rate (mm/min)	Type of pin profile	Brinell hardness (HBW * 10/1000)	Tensile strength (N/mm ²)	Impact energy (J)
1	1000	15	Circular	90.7	89.9	4
2	1000	20	Square	92.3	96.1	2
3	1000	25	Triangle	96.7	81.2	4
4	1100	15	Square	90.2	97.1	10
5	1100	20	Triangle	98.3	95.4	6
6	1100	25	Circular	96.6	84.4	4
7	1200	15	Triangle	89.6	102.8	12
8	1200	20	Circular	92.3	98.7	4
9	1200	25	Square	92.8	87.7	4

27.3.1 Analysis of Tensile Strength

The tensile strength of the weldment characterized using an Intron make UTM of 1 k N capacity is tabulated and analyzed for the optimization of the values. Figures 27.1 and 27.2 show main effects plot for signal-to-noise (SN) ratios and for means. For the main effects plot for the SN ratios, the x-axis represents the input parameters, whereas the y-axis shows the SN ratios. For the main effects plot for means, the x-axis represents the input parameters, whereas the y-axis represents means. The Taguchi analysis has given validation for the SN ratio with the critical aspect considering the “larger is better” formulations that eventually gives the optimized values for the parameters; it is seen from the graph for SN ratio and main effects plot for means of tensile test results that the tensile strength of the weld joint will be maximum for a tool rotational speed of 1200 rpm, feed rate of 20 mm/min with a tool of square profile.

$$S/N = -10 * \log(\Sigma(1/Y^2)/n) \tag{27.1}$$

The empirical formula for “larger is better” is given in Eq. 27.1. The analysis of variance (ANOVA) was carried out in the Qualitek-4 software to find out the percentage influence of input parameters on the output parameters. The percentage influence of input parameters on tensile strength is given in Table 27.6. The feed rate of the tool is having more influence on tensile strength of the weld.

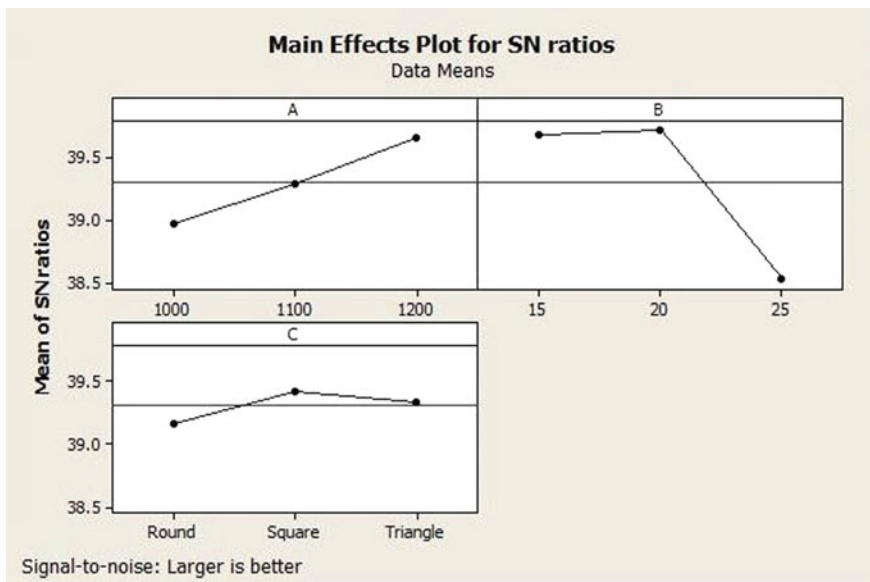


Fig. 27.1 Main effects plot for signal-to-noise ratios of tensile test results

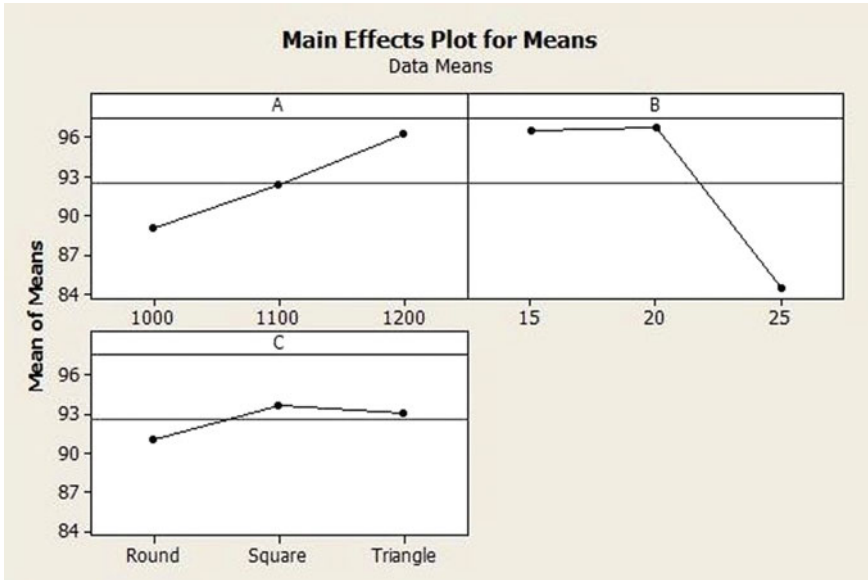


Fig. 27.2 Main effect plot for means of tensile test results

Table 27.6 Significant percentage of input parameters on tensile strength

Factor	Percentage P (%)
Speed	15.591
Feed	69.436
Profile	0
Other error	14.973
Total	100.00

27.3.2 Analysis of Hardness

The hardness of the weld was measured in Brinell hardness testing machine, and a load of 1000 kg was applied on the weld specimen while testing. Figs. 27.3 and 27.4 show main effects plot for SN ratios and for means. For the main effects plot for the SN ratios, the x-axis represents the input parameters, whereas the y-axis gives the SN ratios. For the main effects plot for means, the x-axis represents the input parameters, whereas the y-axis represents means.

The SN ratios are validated for “larger is better” condition, and it is herewith seen from the graph that the Brinell hardness of the weld joint is maximum for tool rotation speed of 1100 rpm, feed rate of 25 mm/min, friction stir welded with triangle tool insert. The percentage influence of input parameters on Brinell hardness is shown in Table 27.7. The table shows the feed rate of the tool is having more influence on

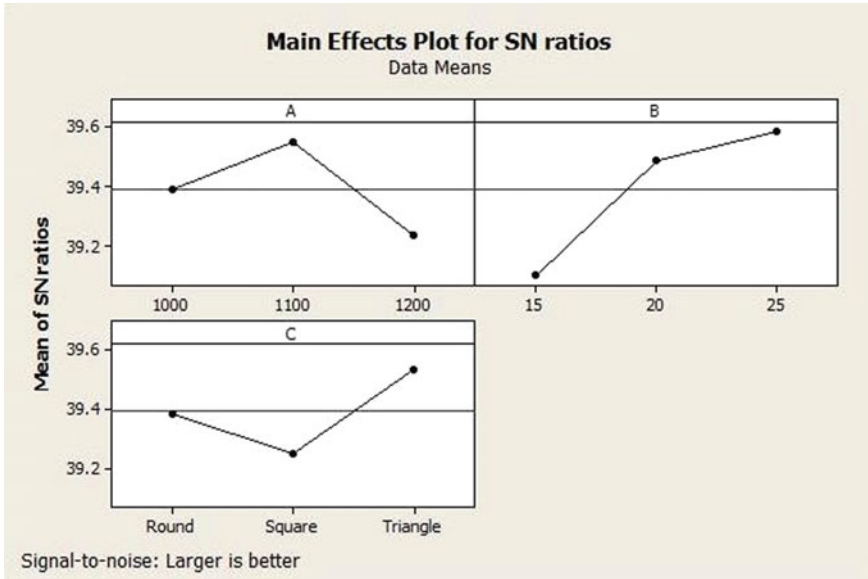


Fig. 27.3 Mean effect plot for signal-to-noise ratios of Brinell hardness test results

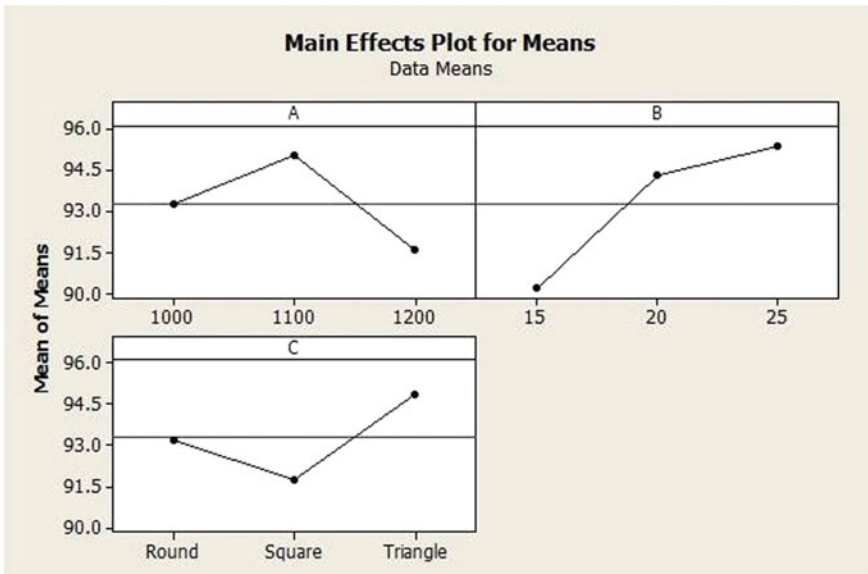


Fig. 27.4 Mean effect plot for means of Brinell hardness test results

Table 27.7 Significance percentage of input parameters on hardness

Factors	Percentage <i>P</i> (%)
Speed	20.093
Feed	54.225
Profile	15.572
Other error	10.11
Total	100.00

Brinell hardness of the weld.

27.3.3 Analysis of Impact Strength

The impact strength of the weld specimen was determined by a typical Charpy test. Figs. 27.5 and 27.6 show main effects plot for *SN* ratios and means, respectively. For the main effects plot for the *SN* ratios, the *x*-axis represents the input parameters, whereas the *y*-axis gives the *SN* ratios. For the main effects plot for means, the *x*-axis represents the input parameters, whereas the *y*-axis represents means. The main effects plot is analyzed for *SN* ratio considered to be better for larger values.

The percentage influence of input parameters on impact strength is given in Table 27.8. The table shows that the feed rate of the tool is having more influence on

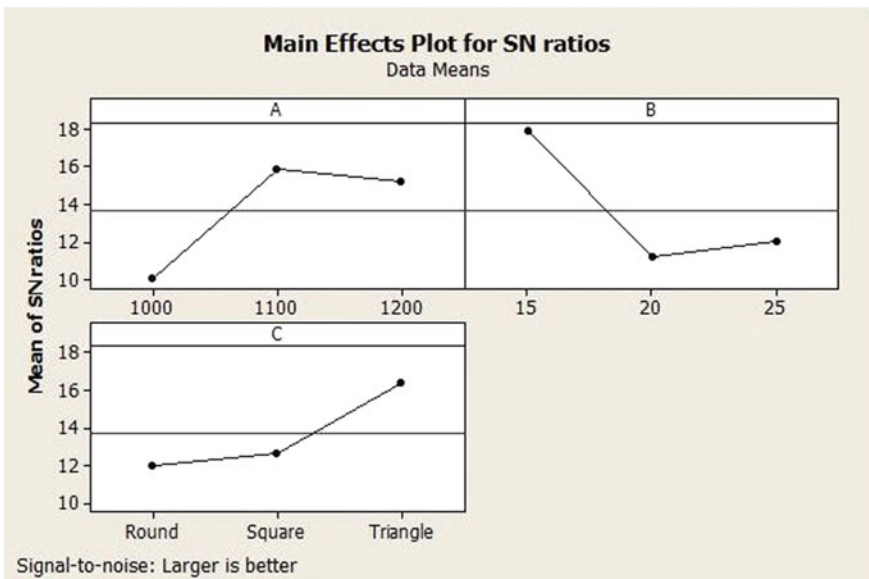


Fig. 27.5 Mean effect plot for signal-to-noise ratios of impact test results

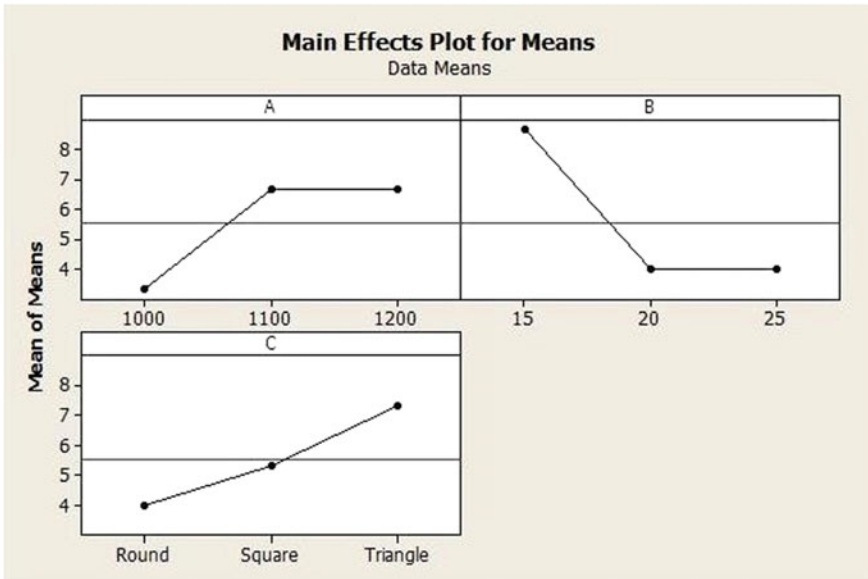


Fig. 27.6 Mean effect plot for means of impact test results

Table 27.8 Significance percentage of input parameters on impact strength

Factor	Percentage <i>P</i> (%)
Speed	21.649
Feed	46.391
Profile	15.463
Other error	16.497
Total	100.00

impact strength of the weld.

27.3.4 Fractography of the Weld Joint

The fractography of the weld joint of the aluminum AA 3103 and AA 7075 specimens is given in Fig. 27.7, and it is clearly evident that the fractured surfaces show a distinct coarse structure with twinned interfaces and striated surfaces rather than slip bands, thereby validating the fact that the residual stresses are minimal in friction stir weld joints; however, striations and luder bands can be observed, thus providing a proof for plastic deformation that has occurred under tensile loads before fracture. Further, the SEM image captured under a voltage of 20 k V at a magnification of 500× gives an account of the striated bands all around the periphery of the atoms inter-dwindled

LUDER BANDS

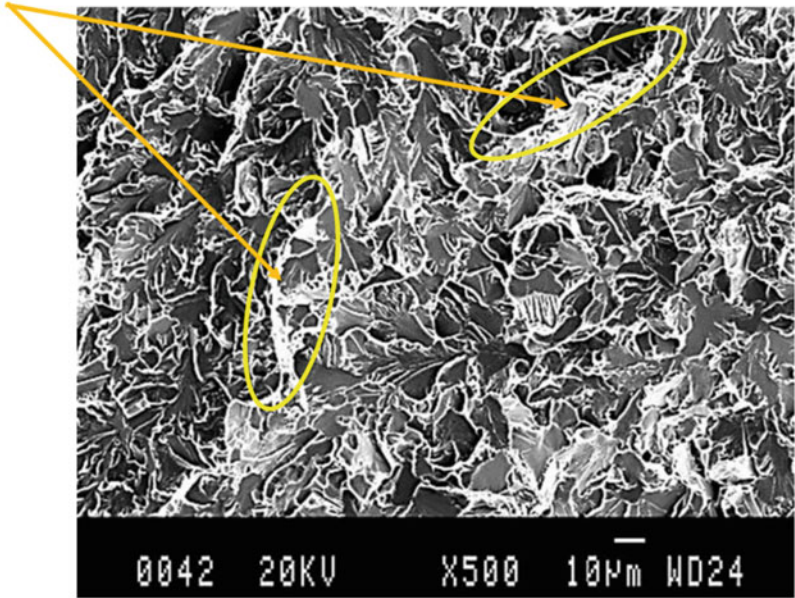


Fig. 27.7 Mean effect plot for means of impact test results

in the FSW weld structure due to the interatomic forces and coherent bonding that result in a strong joint.

27.4 Conclusions

After the analysis of the output parameters, it has been found out that if the friction stir welding is conducted at 1100 rpm tool rotational speed, 15 mm/min feed rate and using tool of triangular pin profile, an effective weld of AA3103 and AA7075 could be produced. Further, it has been observed that welds produced at higher tool rotational speed and lower feed rate give higher output values. Out of all the three types of tool profile, the weld produced by using triangular pin profile tool gave the best output. Also, the fractography of the friction stir welded specimens validates the fact that the friction stir welding of the aluminum alloys reduces the stress accumulation, distortions and other thermal effects as is evident in other welding processes. Hence, friction stir welding process can be employed for joints of aerospace components, in particular bracket mounting frames, braces and wing components, which require high degree of structural integrity.

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