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Effect of Tool Pin Profile on Mechanical Strength on Friction Stir Welded AA 6063 Joint

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Abstract: AA-6063 T5 aluminum alloy (Al-Mg-Si alloy) is widely used in the fabrication of light weight structures requiring a high strength-to-weight ratio and good corrosion resistance. Friction stir welded joints of aluminum alloys are extensively employed in marine frames, pipelines, storage tanks and aircraft applications. In this research work an attempt has been made to understand the effect of tool profiles, tool dimensions and process parameters on mechanical properties and microstructure of friction stir welded AA6063 T5 joints. Square tool profile with shoulder diameter to pin diameter ratio 3: 1 found best for higher tensile and impact strength. Rotation per minute (rpm) found the most significant parameter for welding followed by welding speed, shoulder-diameter, pin-diameter and tool geometry. Beyond 1000 rpm, strength of joint start decreasing due to stresses and higher heat generation.

Keywords: friction stir welding, aluminium alloy, tool design, parametric optimization, tool shape

I. INTRODUCTION

Friction stir welding (FSW) is latest development in solid state joining processes and extensively used for welding aluminum alloys. FSW becomes more popular due to its energy efficiency, environmental friendly nature and versatility[1]. FSW tool heat the work piece and stir/intermix the material for joining metals together. Friction stir welding tool is critical component for successful welding. Rotating round shoulder and cylindrical pin of FSW tool heat the work piece by frictional heat and moves the soften alloy to produce sound weld. Tool shape and material is critically important due to stress and higher temperature faced by it[2]. Tool should be designed for higher strength and longer life span.

Recently many researcher worked on parametric optimization and tool design of friction stir welding [3-10]. Combination of tool design and parametric optimization for higher mechanical strength was not found in literature for AA 6063 T5 alloy joints. This paper provides detailed study of optimization and effect of various parameters (rpm, pin diameter, shoulder diameter, welding speed) along with tool profile for friction stir welding of aluminum alloy.

II. EXPERIMENTATION

A. Consumables

The rolled plates of 6 mm thickness, AA6063 T5 aluminum alloy, have been cut into required size (300 mm x 100 mm) by power hacksaw cutting and milling. Butt joint configuration has been prepared to fabricate FSW joints. The initial joint configuration is obtained by securing the plates in position by clamping in the fixture. The direction of welding is normal to the rolling direction. Single pass welding procedure has been used to fabricate the joints. The chemical composition and mechanical properties of base metal are presented in Table 1 and Table 2.

TABLE I ALLOYING ELEMENT IN THE BASE METAL OBTAINED BY OPTICAL EMISSION SPECTROSCOPY

| Element | Weight % |
|---------|----------|
| Mg | 0.65 |
| Cr | 0.053 |
| Cu | 0.043 |
| Fe | 0.254 |
| Mn | 0.042 |
| Si | 0.35 |
| Zn | 0.0257 |
| Al | Balance |

TABLE 2 MECHANICAL PROPERTIES OF BASE METAL

| Mechanical Properties | Values Tested |
|--------------------------------------|---------------|
| Tensile Strength. UTS (MPa) | 140 |
| % Elongation | 18% @ 24°C |
| Vicker hardness (HV ₁₀₀) | 73 |

B. Equipment

Vertical milling machine (VMM: model VF-3.5, Bharat Fritz Werner Limited make with 11 kW main spindle power, 1.3 kW power feed and digital position display along three axes) available in the machine shop of central workshop, IIT-Delhi, was used for the experimentation. Pre-weld cleaning was done in two steps: oil/grease removal and oxide removal. Oils and greases were removed first, then removed the oxide.

C. Tool material and tool geometry

The primary function of the non-consumable rotating tool pin is to stir the plasticized metal and move the same behind it to have good joint. Pin profile plays a crucial role in material flow and in turn regulates the soundness of the welded joint produced. Pin profiles with flat faces (square and triangular) are associated with eccentricity. This eccentricity allows incompressible material to pass around the pin profile [11,12]. Thus, in the present study three different tool pin profiles viz., (a) threaded cylindrical, (b) triangular, and (c) square are used to examine the effect of pin profile on the welded joint. Non-consumable tool made of high speed steel(H-13) has been used to fabricate the joints. Three different tool pin profiles as shown in Fig. 2 have been used to fabricate the joints.

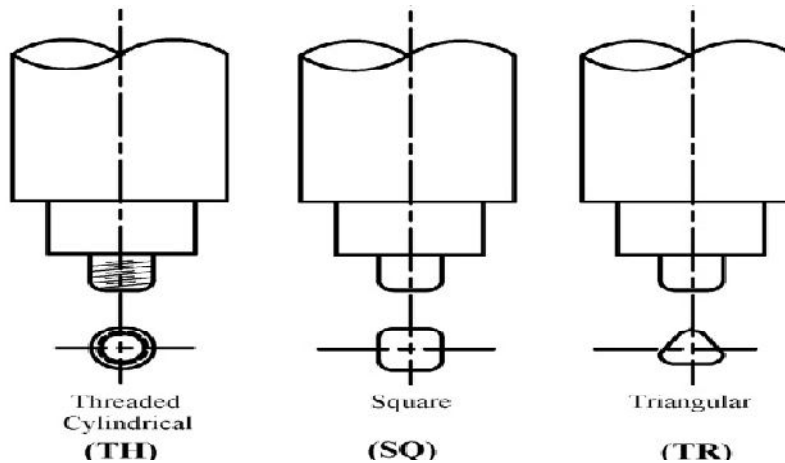


Figure 1 FSW tool pin profiles

D. Process Parameters and their ranges

It was observed during trial runs that mechanical strength of joint has been increasing continuously till 1000 rpm and beyond that it starts decreasing. High stresses and temperatures may be the reason for this decrement. Hence to observe the effect of process parameters accurately, experiments were performed in two sets (SET-I and SET-II) as shown in Table 3 and Table 4. Taguchi Design L9 was selected for the study. To observe the effect of variable accurately experiments were performed in random manner. Set-up for friction stir welding is shown in Figure 2. Welded plates are shown in Figure 3.

TABLE 3 PARAMETERS FOR SET-I

| Input parameters | Levels | | |
|------------------------|------------|--------|----------|
| | 1 | 2 | 3 |
| Tool geometry | Triangular | Square | Cylinder |
| RPM | 500 | 750 | 1000 |
| Welding speed (m/min) | 50 | 75 | 100 |
| Shoulder diameter (mm) | 14 | 16 | 18 |

TABLE 4 PARAMETERS SET-II

| Input parameters | Type of parameter | Levels | | |
|-----------------------|-------------------|------------|--------|----------|
| | | 1 | 2 | 3 |
| Atmosphere | Categorical | Air | Water | – |
| Tool geometry | Categorical | Triangular | Square | Cylinder |
| RPM | Numerical | 1000 | 1500 | 2000 |
| Welding speed (m/min) | Numerical | 100 | 125 | 150 |
| Shoulder dia (mm) | Numerical | 18 | 20 | 22 |



Figure 2 Setup for underwater friction stir welding



Figure 3 Welded specimen

III. RESULTS AND DISCUSSION

A. Mechanical Testing of the Weld specimens

American Society for Testing of Materials (ASTM E8M) guidelines are followed for preparing test specimens. Tensile test has been carried out in 100 KN, electro-mechanical controlled Universal Testing Machine[13]. The specimen was loaded at the rate of 1.5 KN/min as per ASTM E8M specifications, so that tensile specimen undergoes deformation. The specimen finally fails after necking and load versus displacement has been recorded.

Impact tests were performed on standard notched test specimens (ASTM E 23-04) machined on wire-EDM. The impact energy absorbed by each sample was calculated and analyzed for effect of process parameters and their interactions. Impact testing was conducted at room temperature using a pendulum-type impact testing machine (ENKAY, India) with a maximum capacity of 300 J.

The amount of energy absorbed in fracture was recorded, and the absorbed energy is defined as the impact toughness of the material. ASTM E23-04 specifications were followed for preparing and testing the impact specimens [14]. Three specimens are tested at each condition for tensile and impact test and average of the results of three specimens is presented in Table 5 and Table 6.

TABLE 5 WELDING RUNS AND THEIR DETAILS FOR SET-I.

| Run No. | Tool Pin Profile | RPM | Welding Speed(m/min) | Shoulder dia (mm) | Pin dia (mm) | Impact Strength (J) | Tensile Strength (MPa) |
|---------|------------------|------|----------------------|-------------------|--------------|---------------------|------------------------|
| 1 | Trinagular | 500 | 50 | 14 | 4 | 30 | 120 |
| 2 | Trinagular | 750 | 75 | 16 | 5 | 48 | 146 |
| 3 | Trinagular | 1000 | 100 | 18 | 6 | 70 | 165 |
| 4 | Square | 500 | 50 | 16 | 5 | 37 | 131 |
| 5 | Square | 750 | 75 | 18 | 6 | 58 | 156 |
| 6 | Square | 1000 | 100 | 14 | 4 | 54 | 155 |
| 7 | T.Cylinder | 500 | 75 | 14 | 6 | 32 | 130 |
| 8 | T.Cylinder | 750 | 100 | 16 | 4 | 44 | 138 |
| 9 | T.Cylinder | 1000 | 50 | 18 | 5 | 51 | 146 |

T Cylinder = Threaded Cylinder

TABLE 5 WELDING RUNS AND THEIR DETAILS FOR SET-II.

| RunNo. | Tool Pin Profile | RPM | Welding Speed(m/min) | Shoulder dia (mm) | Pin dia (mm) | Impact Strength (J) | Tensile Strength (MPa) |
|--------|------------------|------|----------------------|-------------------|--------------|---------------------|------------------------|
| 1 | Trinagular | 1000 | 100 | 18 | 6 | 70 | 165 |
| 2 | Trinagular | 1500 | 125 | 20 | 7 | 49 | 143 |
| 3 | Trinagular | 2000 | 150 | 22 | 8 | 30 | 124 |
| 4 | Square | 1000 | 100 | 20 | 7 | 64 | 160 |
| 5 | Square | 1500 | 125 | 22 | 8 | 44 | 139 |
| 6 | Square | 2000 | 150 | 18 | 6 | 42 | 137 |
| 7 | T.Cylinder | 1000 | 125 | 18 | 8 | 50 | 146 |
| 8 | T.Cylinder | 1500 | 150 | 20 | 6 | 46 | 141 |
| 9 | T.Cylinder | 2000 | 100 | 22 | 7 | 44 | 135 |
| 10 | Trinagular | 1000 | 150 | 22 | 7 | 51 | 146 |
| 11 | Trinagular | 1500 | 100 | 18 | 8 | 61 | 153 |
| 12 | Trinagular | 2000 | 125 | 20 | 6 | 47 | 143 |
| 13 | Square | 1000 | 125 | 22 | 6 | 61 | 158 |
| 14 | Square | 1500 | 150 | 18 | 7 | 53 | 146 |
| 15 | Square | 2000 | 100 | 20 | 8 | 51 | 144 |
| 16 | T.Cylinder | 1000 | 150 | 20 | 8 | 47 | 145 |
| 17 | T.Cylinder | 1500 | 100 | 22 | 6 | 51 | 152 |
| 18 | T.Cylinder | 2000 | 125 | 18 | 7 | 43 | 138 |

T Cylinder = Threaded Cylinder

B. Effect of tool pin profile

The primary function of the non-consumable rotating tool pin is to stir the plasticized metal and move the same behind it to have a good joint. Pin profile plays a crucial role in material flow of the FSW process. The details of static area and dynamic area for each tool pin profile is presented in the following Table 7. The relationship between the static volume and dynamic volume decides the flow of plasticized material from the leading edge to the trailing edge of the rotating tool. This ratio is equal to 1.35 for triangular, 1.57 for square and 1.01 for threaded cylindrical pin profiles. In addition, the triangular and square pin profiles produce a pulsating

action in the flowing material due to flat surfaces. Figure 4 and Figure 5 shows that maximum tensile strength and impact strength observed with square tool due to highest static to dynamic volume ratio with optimum shoulder diameter to pin diameter (D/d) ratio.

TABLE 7 STATIC AND DYNAMIC AREA FOR DIFFERENT TOOL PROFILES.

| Pin Profile | Static Area (mm ²) | Pin Diameter | Dynamic Area (mm ²) | Dynamic Vol/Static Vol |
|-------------|--------------------------------|--------------|---------------------------------|------------------------|
| Triangular | 20.78 | 6 | 28.26 | 1.35 |
| Triangular | 28.29 | 7 | 38.465 | 1.35 |
| Triangular | 36.95 | 8 | 50.24 | 1.35 |
| Square | 18.00 | 6 | 28.26 | 1.57 |
| Square | 24.50 | 7 | 38.465 | 1.57 |
| Square | 32.00 | 8 | 50.24 | 1.57 |
| T.Cylinder | 27.88 | 6 | 28.26 | 1.01 |
| T.Cylinder | 38.03 | 7 | 38.465 | 1.01 |
| T.Cylinder | 49.74 | 8 | 50.24 | 1.01 |

Note: The static and dynamic volume is calculated for the pin height of 5.7 mm.

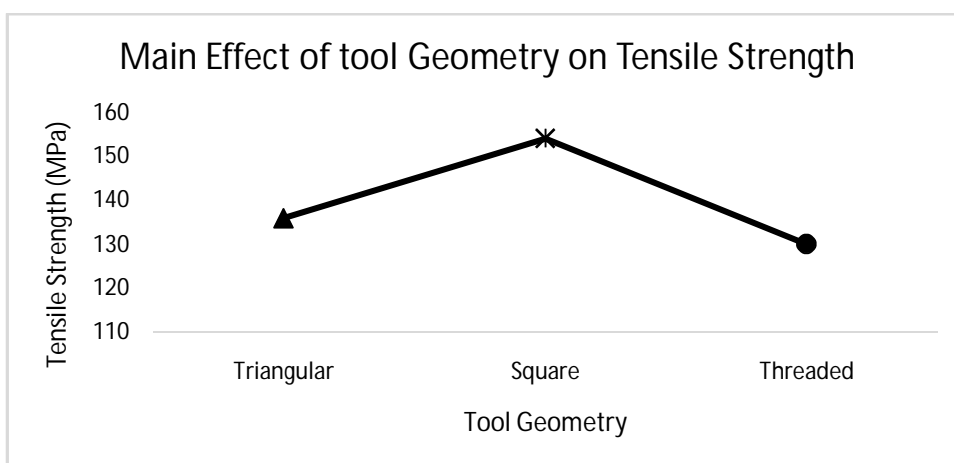


Figure 4 Main Effect of tool Geometry on Tensile Strength

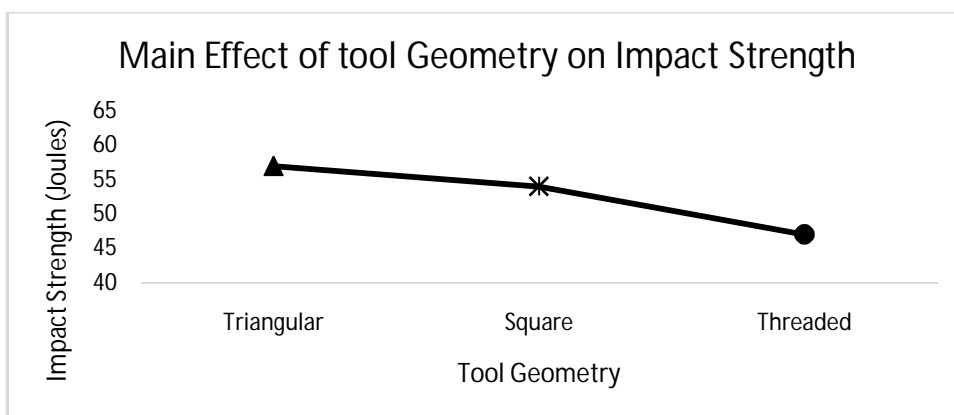


Figure 5 Main Effect of tool Geometry on Impact Strength

C. Effect of Process parameters on Mechanical properties

The joints fabricated by square pin profiled tool exhibited superior tensile properties compared to the other joints irrespective of other parameters. Figure 6 and Figure 10 shows that the joints fabricated at 1000 rpm have shown higher tensile and impact strength compared to joints fabricated at 500 rpm and 2000 rpm and this trend is common for all tool profiles. Figure 7 and Figure 11 shows the joints fabricated at a welding speed of 100 mm/min have also shown higher tensile and impact strength compared to joints

fabricated at a welding speed of 50 mm/min and 150 mm/min. The joints fabricated by the tools with shoulder diameter 18 mm and tool pin diameter 6 mm ($D/d=3$) have shown higher tensile strength and elongation compared to joints fabricated by the tools with shoulder diameter 20 mm and 22 mm and this trend is common for all the tool profiles and shown by Figure 8. The interaction effect of welding and tool pin profile is shown in Fig 9. Welds produced using square tool pin profile at welding speed of 100 mm/min exhibit higher tensile strength than the other counterparts. It can be concluded that the joints fabricated by square pin profiled tool exhibited superior Tensile and impact properties compared to the other joints irrespective of other parameters.

The rotation per minute (rpm) has been found most significant parameter followed by welding speed, shoulder-diameter, pin-diameter and tool geometry. The maximum Tensile and impact strength is obtained at 1000 rpm, 100 m/min of welding speed and square tool with 18 mm of shoulder diameter and 6 mm of pin diameter.

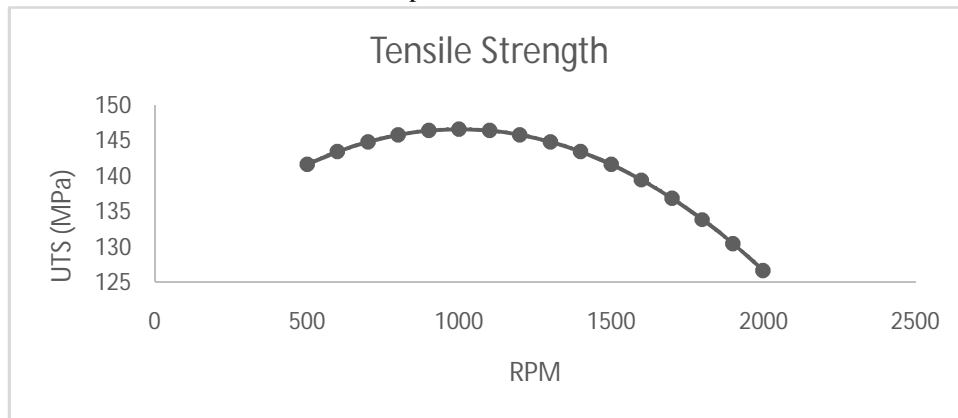


Figure 6 Main Effect of rpm on Tensile Strength

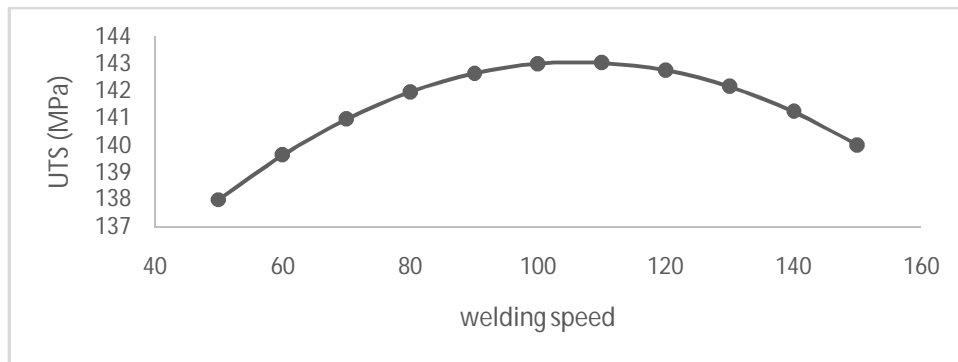


Figure 7 Main effect of welding Speed on Tensile Strength

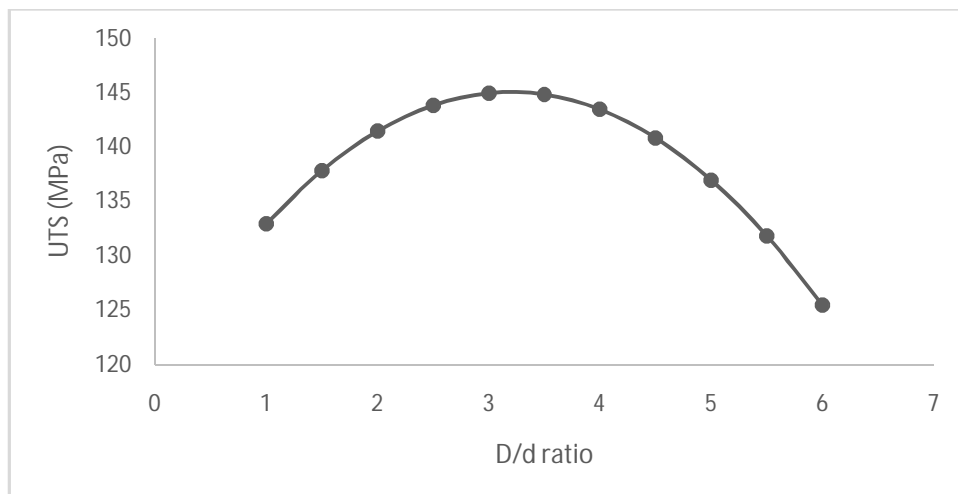


Figure 8 Main effect of (D/d) ratio on tensile strength

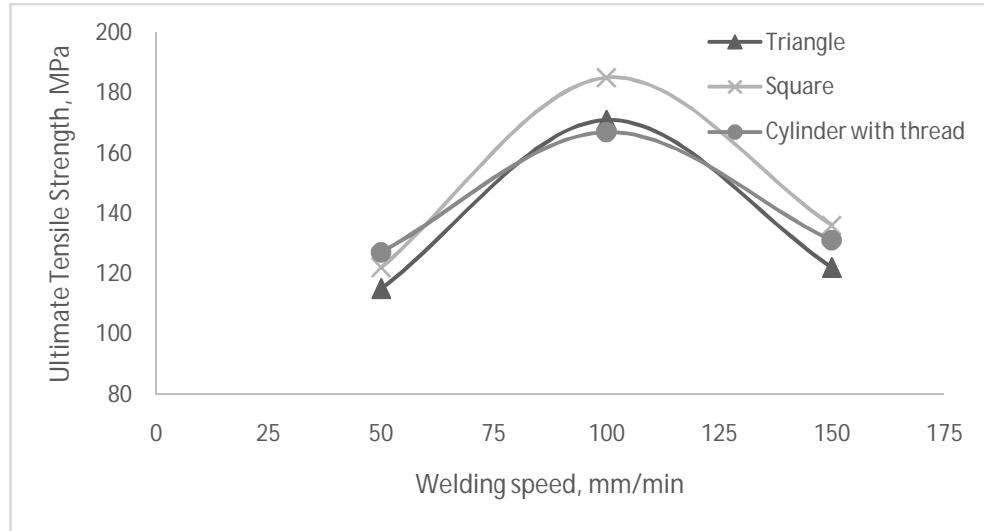


Figure 9 Interaction effect of welding speed and tool pin profile on UTS

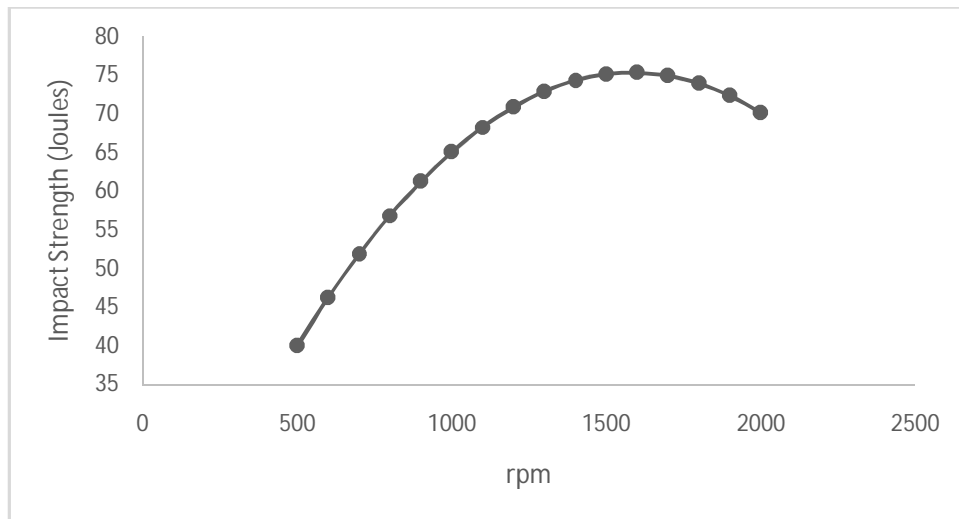


Figure 10 Main Effect of RPM on Impact Strength

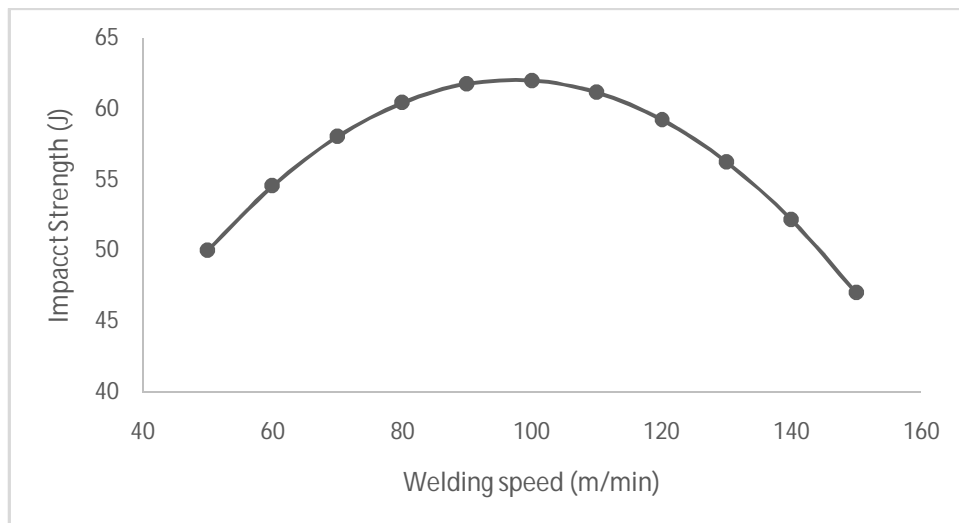


Figure 11 Main effect of welding speed on Impact Strength

IV. CONCLUSION

Friction stir welding was successfully performed on 6 mm thick AA-6063 T5 Aluminum alloy. A new fixture was designed and fabricated for friction stir welding of aluminum alloy. Following specific conclusions may be drawn from this research:

- 1) Process Parameters were optimized for welding of AA-6063 T5 alloy friction stir welding. Optimum process parameters were proposed for sound weld.
- 2) The effect of process parameters along with tool geometry represented. Beyond 1000 rpm, due to high temperature generated mechanical properties start decreasing.
- 3) Best welds found with square tool pin and 1000 rpm, 100 m/min welding speed, 18 mm shoulder diameter and pin diameter of 6 mm. Square tool pin provides maximum swirl of weld metal which is necessary for sound weld.
- 4) The rotation per minute (rpm) has been found most significant parameter followed by welding speed, shoulder-diameter, pin-diameter and tool geometry.
- 5) Shoulder diameter to pin diameter ratio is equal to 1.35 for triangular, 1.57 for square and 1.01 for threaded cylindrical pin profiles. Triangular and square pin profiles produce a pulsating action in the flowing material due to flat surfaces.

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