An experimental analysis and process parameter optimization on AA7075 T6-AA6061 T6 alloy using friction stir welding

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Abstract
Friction stir welding is a non consumable concrete condition welding course for joining aluminum alloys and is engaged in aerospace, rail, automotive and marine industries. The weld quality of this type depends upon the process parameters such as the rotational speed of the tool, the welding speed and the axial force. In this paper, friction stir welding was used to weld two dissimilar aluminium alloys AA7075 T6 & AA6061 T6 by varying the input parameter namely the rotational speed and maintaining the welding speed, load as constants. Morphological characterization is done using Scanning Electron Microscope while the mechanical properties of the welded specimens are characterized by conducting smooth tensile and hardness test and the values are reported.

Keywords: Dissimilar aluminum alloys, Friction stir welding, Scanning electron microscope, Tensile test, Hardness test

1. Introduction

Friction-stir welding is a non-consumable hard state welding joint methods in which a rotating tool with a shoulder and contained by a tool pin profile moves along the butting surfaces of two tightly clamped plates placed on a backing plate. The shoulder makes rigid contact with the top surface of the work-piece. Heat generated by friction at the shoulder and to a lesser level at the pin surface, softens the material being welded. Severe plastic deformation and flow of this plasticized metal occurs as the tool is translated along the welding direction. The tool placed to in front of welding materials and the trailing edge where it is forged interested in a welded joint (Dawes and Thomas 1996). The plate where the advancing side known as direction of rotation is the similar as that of welding joint, while the supplementary side is called as the retreating side. This difference can lead to asymmetry in heat transfer (Cho et al. 2005). The material flow and the properties of the two sides of the weld. For example, the hardness of particular age-hardened aluminum alloys tends to be lower in the heat-affected zone on the retreating side, which then becomes the location of tensile fracture in cross-weld tests (Liu et al., 2003) this is also the case for pure titanium.(Lee et al. 2005)

Due to their high strength-to-weight ratio, good machinability, and high resistance to corrosion, aluminum alloys are attractive light weight metals for structural applications in the aerospace, automotive and naval industry. However, joining of aluminum alloys by conventional fusion welding techniques is problematic because of the formation of secondary brittle phases, cracking during solidification, high distortion, and residual stresses. (Gibson et al. 2014). Among the available aluminum alloys, the heat treatable 6XXX Al–Mg–Si and 7XXX Al–Mg–Zn systems (Schweitzer et al., 2003) are some of the most widely used advanced alloys.
The AA6061 class has been extensively employed in marine frames, pipelines, storage tanks and aircrafts (Elangovan and Balasubramanian 2008). On the other hand, the AA7075 T6 alloy is widely used in the aerospace industry for its improved toughness and corrosion resistance when compared to other alloys from 7XXX series (Dursun and Soutis 2014). In this work, the two varieties of aluminium such as AA7075 T6 and AA6061 T6 alloys are selected for experimental studies and also for optimization of welding parameters.

Friction Stir Welding is a solid state joining process combination of deformation heating and mechanical work to obtain rich quality, defect free joints. Khwajamuzammil et al. (2017) have studied the effect of processing parameters on tensile properties of friction stir welding butt joint by considering various process parameters such as spindle speed, welding speed and plunge depth. Taguchi method orthogonal array is used to reduce the number of experiments, based on which the aluminium alloys are welded. Balaji et al. (2017) investigated the friction stir welding of aluminium alloys based on varying the welding process parameters such as rotation speed of the tool (RPM), welding speed, downward force and tool pin profile. The properties such as defects, microstructure, hardness, tensile and bend behavior on welded plates were studied and compared with the base metal. Based on the results the process parameters are optimized. Yan.Z et al. (2017) compared friction stir welding and Metal Inert Gas welding based on tensile strength and wear properties. The result shows that, friction stir welding is better than MIG for aluminium alloys. Sudhagar et al. (2017) have a comprehensive attempt to select the best probable development parameters for friction stir welding of aluminium 2024 alloy based on multiple criteria decision making approach. They have used orthogonal array to categorize the input parameters.

Verma et al. (2015) have selected the process parameters at low, medium and high setting for the feed rates. Optical microscope and scanning electron microscopy techniques are used to study the particle distribution of the welded samples. Homogenous mixture of the materials is achieved at high rotational speed of about 2000 rpm. Khourshid and Sabry et al. (2013). An investigation of tried to find the feasibility to weld two pieces of aluminium pipes by friction stir welding and investigation of effect on the mechanical properties of welding samples in visual inspection and destructive test (tensile test, hardness and microstructure) are studied. The friction stir welding experiments conducted by aluminum alloy pipes AA 6061 can be welded, there by the results show that 78.7% Using parameter 1400rpm rotational speed and 4 mm/min traveling speed the ultimate tensile strength obtained Doos and Wahab et al. (2012). The feasibility to weld both pieces of a aluminum alloy pipes by friction stir welding have made an attempt to find mechanical properties of welding are studied using visual inspection techniques, X-ray, tensile test, micro-hardness and by observing microstructure. Arora et al. (2011) have tried torque for using different shoulder diameter welded and found optimum tool geometries the result shows main factor that affect the experimental value of the sticking torque change due to the strength of the material decreases with growing temperature due to an increase in the shoulder diameter. And other factor of area over which the torque is applied increases with shoulder diameter. Pasha et al. (2014) addressed the crisis of high tool cost with low tool life during welding of harder alloys. They also discussed heat generation rate and plastic flow in the work piece. They are affected by the size and shape of the tool shoulder and pin. Rao et al. (2017). Investigated the effects of friction stir welding on the microstructure and hardness of rolled pure aluminium 6061. The weld is obtained by varying its tilt angle 2° and pin diameter 6mm. Tensile strength and % elongation is carried out to evaluate the strength of the weld. Optical microscopic study is carried out to study the uniform stirring of materials. Hardness test indicated that the minimum and maximum hardness values are obtained in the HAZ and BM, respectively.

Patil et al. (2016) reported the hardness testing conducted on welded butt joints by friction stir welding and TIG welding process on similar and dissimilar aluminium alloys. Friction stir welding joints are produced for similar alloys of AA7075 T6 and dissimilar alloys of AA7075 T6- AA6061T6. The Friction stir welds of AA7075 T6 and AA6061T6 aluminium alloy are produced at different tool rotational speeds of 650,700, 800, 900, 1000 mm/min and transverse speed of 30, 35, 40 mm/min. The Brinell hardness testing techniques are employed to ascertain the joint integrity before characterization in order to justify the quality of the welds.

Chauhan et al. (2016) have made an effort to develop a model to predict ultimate tensile strength and hardness of weld zone with and without tool shoulder geometry using friction stir welded AA6082 aluminium alloy by response
surface methodology (RSM). Non destructive testing has been carried on FS welded area. Liquid penetrate testing method is chosen for NDT. (Bhattacharya et al., 2016) investigated the properties of welded Al alloys. Material flow behavior and identification of intermetallic have been exclusively characterized by energy-dispersive X-ray spectroscopy, mapping and X-ray diffraction. Experimentally measured thermal cycles are found to be in a good agreement with those numerically calculated. The maximum joint strength achieved for 1000 rpm and travel speed of 20 mm min\(^{-1}\), 86.5 % of aluminium base metal is the optimized parameter with intermetallic thickness of 3.6 \(\mu\)m for the present study. Singh et al. (2016) discussed the experimental investigation for mechanical properties of aluminium alloy Al 6061 by considering different parameters of friction stir welding. Two different types of tool shapes and shoulder surfaces for single weld configurations were used in experiments. Tensile test indicated that welding speed is the main parameter which affects the tensile strength followed by feed rate and tool shape as the second and third parameters respectively.

From the literature available, it can be noticed that most of the studies on Friction stir welding have been concerned on changing the process parameters such as rotational speed, welding speed and axial load for welding dissimilar aluminium alloys. Another proven technique that is gaining importance in this domain is the influence of the tool profile for producing good weldments. Moreover, works related to the welding of dissimilar aluminium alloys AA AA7075 T6 and AA6061 T6is not extensively available. Hence the focus of the current research is to perform welding by joining the dissimilar aluminium alloys AA6061 T6 and AA6061 T6 and then to conduct mechanical characterization studies such as tensile test and hardness test on the welded zone. In this work, the cylinder pin profile tool geometry is used to prepare the welding specimen and the welding speed, load as maintained as constant.

2. Materials and Methods

The raw materials used for specimens in this study are dissimilar aluminium alloys namely AA 6061 T6 and AA7075 T6. AA 6061 T6 major alloying elements contains magnesium and silicon produce by precipitation-hardened process. Originally called ‘Alloy 61S’, it is one of the most commonly used alloy of aluminium. Another Aluminium alloy used in the present study is AA7075 T6 which contains zinc as the primary alloying element. This alloy is strong and its strength is comparable to many steels. The material properties of this alloy include good fatigue strength, average machinability and less resistance to corrosion than other aluminium alloys. This alloy is expensive and it can be put into use for applications where other alloys are not suitable. These two aluminium alloys are used as the preparation of the work samples. The chemical compositions of the aluminium alloy are analyzed using a vacuum spectrometer is shown in Table 1

| CONSTITUENTS  | AA7075 T6 | AA6061 T6 |
|---------------|-----------|-----------|
| Aluminium     | 97.766    | 90.311    |
| Chromium      | 0.064     | 0.2       |
| Copper        | 0.19      | 1.31      |
| Iron          | 0.25      | 0.17      |
| Magnesium     | 0.8       | 2.28      |
| Manganese     | 0.12      | 0.019     |
| Zinc          | 0.11      | 5.61      |
| Silicon       | 0.7       | 0.1       |

2.2 Tool material

The tool material used in this present investigation is High Carbon High Chromium steel (HC-HCr) whose chemical composition is given in Table 3. This material is noted for its high dimensional stability in addition to good wear resistance and excellent edge holding capabilities. The chemical composition of the tool materials used in the present study is shown in Table 2
Table 2 Chemical composition HC-HCr

| Components | C   | Si  | Mn  | P   | S   | Cr   | Mo  | V   |
|------------|-----|-----|-----|-----|-----|------|-----|-----|
| Wt.%       | 1.40| MAX | MAX | MAX | MAX | 11.00| 0.80| 0.20|
| 1.60       | 0.40| 0.40| 0.030| 0.030| 0.030| 13.00| 1.20| 0.50|

High Carbon High Chromium steels that used as tool material is the commonly used material in the manufacture of die, cutters, measuring tools and finishing rolls for tyre mill sand punches. The density of the material is 7.7-8.03 g/m³ and possesses a melting point temperature of 1426°C with an elastic modulus of 190-210GPa. This tool material is preheated very slowly up to 815°C (1500°F), and then temperature is increased to 1009°C (1850°F) and held for 30 minutes in the same temperature, after which they are air quenched. This is done to harden the material so that it can withstand high temperature in the stir zone that is generated during friction stirring. The raw materials in the form of plates of 50 mm wide and 100 mm long and 6mm thick are taken and they are machined using milling machine to make them parallel. The aim for making them parallel is to enable friction stir welding machine clamping system leading to uniformity in welding the gaps between the plates. The experiments are carried out on friction stir welding machine capable of welding plates of thickness ranging from 0.5 mm to 10 mm.

3. Experimental Setup

One of the most important aspects of friction stir welding is the utilization of readily available vertical milling machine and an inexpensive tool for producing welded joints that uses a vertical head attachment to accommodate high spindle speeds that vary between 200 and 4000 rpm, powered by a 22kW AC motor and with axis stroke length movement of 600, 200 and 300 mm along x, y and z axis respectively. Automatic feed system in the milling machine is used to control the traverse feed rate of the work table. Since the friction stir welding involves large forces of about 2500kgf, fixture with proper clamps is designed to prevent movement specimens during The friction stir welding machine has the capability of welding plate thickness of from 0.5 mm to 10 mm with ease. Friction stir welding process a data acquisition system with suitable instrumentation is integrated for acquiring relevant parameters to monitor the process. Fig 1 shows the experiment setup for conducting friction stir welding process.

During the friction stir welding process, large forces that develop when friction stir welding tool plunges into the work pieces to be welded directly act on the base plate and cause the plates to drift apart. Hence, a rigid clamping fixture is essential to withstand the forces and to prevent the extrusion of plasticized material from the joint interface to the bottom of the joint. The thermal expanding and buckling behavior that the plates encounter during normal friction stir welding conditions too can be restrained by the clamping. In the present work, fixture components are fabricated from mild steel plates. The base plate is made using mild steel plates of size 200x160x 10mm and is machined precisely to hold the clamping plates and stopper plate for the aluminum alloy AA7075 T6 and AA6061 work pieces with 6mm thickness. The friction stir welding tools and backing plates are generally made up of HC-HCr steel to weld aluminum alloys.

Two clamping plates are used to align and stabilize the plates during friction stir welding. The clamping screws are used to hold the work piece rigidly on its top surface to prevent the lateral movement of work plates during the friction stir welding process. The Fig 5 shows the photographic view of the fabricated friction stir welding fixture for the experimental work. The fixture is aligned to the T-slots of machine table. Hexagonal socket screws are used to assemble the fixture components and clamping work plates. The sockets screws are tightened with uniform torque level to prevent the movement and bending of the aluminum alloy work plates during friction stir welding process. The Fig 1 shows photocopy of friction stir welding tool and fixture setup.
3.1 Selection of experimental parameters

Friction stir welding involves complex material movement and plastic deformation. Welding parameters play a vital role in the determination of the weld characteristics. In this section, tool rotational speed, welding speed and axial force are considered for experimentation that are major factors affecting friction stir welding process. Based on the various trails, the various parameters along with their range are selected and presented in the table 4. The final experiments were conducted as per the design matrix.

All welding joints are prepared using Computer Numerical Control (CNC) program to maintain consistency and reliability of the experimental runs. The friction stir weld is initiated by positioning the friction stir welding tool in such a position that the tip of the pin just touches the upper surfaces of the abutted work pieces. Welds were made by joining of two pieces of (100 x 50 x 6) mm plates to prepare a weld joint of size 100 mm wide and 100 mm long. Work pieces are clamped firmly on the machine table a backward tool tilt angle of 0° is used throughout the length of the weld. The selected rotational speed, welding speed and axial force is listed in Table 3

| Experiment no | Rotational speed (rpm) | Welding speed (mm/min) | Axial force (KN) |
|---------------|------------------------|------------------------|-----------------|
| 1             | 900                    | 20                     | 4               |
| 2             | 1000                   | 20                     | 4               |
| 3             | 1100                   | 20                     | 4               |
The table 3 is common optimizing parameter of friction stir welding process (experiment array)

| Experiments | Rotational speed | Welding speed | Axial forces |
|-------------|------------------|---------------|-------------|
| 1           | 1                | 1             | 1           |
| 2           | 2                | 1             | 3           |
| 3           | 3                | 1             | 1           |
| 4           | 1                | 2             | 3           |
| 5           | 2                | 2             | 1           |
| 6           | 3                | 2             | 3           |
| 7           | 1                | 3             | 2           |
| 8           | 2                | 3             | 3           |
| 9           | 3                | 3             | 2           |

3.2 Tension Test

Tensile test is performed on the welded samples with universal testing machine having of 100 KN capacity according to IS 1608:2005 specifications as shown in Fig 2. The centre of the weld is identified and a two inch mark is made to facilitate the measurement of elongation after the test sample breaks under tension. Three tensile test pieces are prepared and tested from each weld joint to ensure consistency and the data obtained from the three welded specimens is averaged to give single value of tensile strength.

![Fig. 2 Tensile test specimens](image)

3.3 Hardness test

The hardness of the welded specimen is found by Rockwell hardness in the present study. Hardness may be defined as fight of metal to plastic buckle by indentation. In the present investigation, an indentation force of 100 kg is used along with an indentation time of 10 seconds in steps of 0.3 mm as per ASTM E18 (2016) standards. Hardness tests are conducted in the two base plates AA7075 T6, AA6061 T6 and also at the stir zone. Change in hardness at the stir zone is studied to determine the effect of temperature on the friction stir welding.
4. Results and discussion

The welding is done by maintaining both the welding speed and axial force as constant and by varying the rotational speed. The scanning Electron Microscope is used to analyze the micro structure of prepared. This joint is tested mechanically by conducting tensile test and hardness test. It is used for identifying the best parameters for joining two dissimilar aluminum alloys namely AA7075 T6 and AA6061 T6.

4.1 Microstructure observations of friction stir zone

The microstructure of the welded aluminum alloys shown in Fig 3. It shows proper and uniform fusion of materials as a result of high temperature that exists at the heated zone. The welding surface of the welded area is proper welding that may be due to the presence of uniform grains. The dark region shows the deposition of the carbon content at the weld zone. It is reason for the improved hardness at the junction. The hardness value of the welded sample is very high at the stir zone. As seen in the image, uneven surfaces could not be noticed proving that the welding process is uniform and controllable. The small weld burrs could be noticed on the sample and is due to the result of welding process. At high magnification, small micro cracks could be observed and it may be due to the temperature gradient that exists at the welded zone. In 900 rpm rotational speed there is no crack and grains which is shown in the figure 3.a. In 1000 rpm rotational speed there is burr and grains produced on welding joint which is shown in the figure 3.b. In 1100 rpm rotational speed there is burr, grains and micro crack produced on welding joint which is shown in the figure 3.c. Due to this result may always prefer the 900 rpm rotational speed, 20 welding speed and 4 axial load optimization parameter is satisfied.

![Microstructure observations of friction stir zone](image)

4.2 Tensile test

The tensile tests conducted on the welded samples by varying the rotational speed and maintaining the welding speed and axial load as constant is shown below.

| Experiment No | Rotational Speed (rpm) | Welding speed (mm/min) | Axial force (KN) | UTS (MPa) |
|---------------|------------------------|------------------------|-----------------|-----------|
| 1             | 900                    | 20                     | 4               | 72.3      |
| 2             | 1000                   | 20                     | 4               | 159.8     |
| 3             | 1100                   | 20                     | 4               | 236.9     |
Experiments | Rotational speed | Welding speed | Axial forces |
--- | --- | --- | --- |
1 | 900 | 20 | 4 |
2 | 1000 | 20 | 4 |
3 | 1100 | 20 | 4 |
4 | 900 | 20 | 4 |
5 | 1000 | 20 | 4 |
6 | 1100 | 20 | 4 |
7 | 900 | 20 | 4 |
8 | 1000 | 20 | 4 |
9 | 1100 | 20 | 4 |

Tensile test conducted at nine different experiments and the results are tabulated in Table 4. In which three was best from the parameters using L9 orthogonal array method in the my journal paper, the tensile test optimizing parameter showed in only best three experimental values but hardness test showed nine experiment values. These information was given considering the data will be sufficient, it can be seen that there is an increase in the tensile strength when the rotational speed increases. When the rotational speed is 900rpm the corresponding tensile strength is 72.3MPa. The rotational speed is increased to 1000rpm the tensile strength increases to 159.8 MPa which is more than twice the tensile strength obtained for 900 rpm and increase in rotational speed to 1100 rpm, a 49% increase in the tensile strength is achieved. This shows that increase in rotational speed is in linear relationship with tensile strength of the weld samples. The tensile strength of welded aluminium AA7075 T6 and AA6061 T6 alloys using non-threaded cylindrical tool is reported as 229MPa for non-threaded cylindrical Hasan et al. (2017). This agrees with the values obtained in the present study. The welding parameter such as 100mm/min feed and rotational speed of 1400rpm tensile strength values obtained is 198.98MPa for friction stir welded aluminium alloys AA7075 T6 and AA6061 T6. Sameer and Schneider et al. (2016) Researches conclude that 6065-T6 Aluminum. 6065-T6 aluminum is 6065 aluminum in the T6 temper. To achieve this temper, the metal is solution heat-treated and artificially aged until it meets standard mechanical property 7075-T6 Aluminum. 7075-T6 aluminum is 7075 aluminum in the T6 temper. To achieve this temper .The Metal is 450 °C for several hours, quenching, and then aging at 120 °C for 24 hours. This yields the peak strength of the 7075 alloy for a speed change from 900 to 1000 rpm, the UTS value increases from 72.3 MPa to 159.8MPa, almost increase. From the Tensile strength test result 900 rpm rotational speed, 20 welding speed 4 axial load optimization parameter is satisfied.

### 4.3 Hardness test

The hardness of the welded specimen is found by Rockwell hardness and is reported in the present research. When the rotational speed is 900rpm, and the load applied is 60kg, the Rockwell hardness values obtained are 48, 51 and 54 respectively from three trials and averaging to Rockwell hardness value of 51. The rotational speed is 1000rpm, and the load applied is 60kg, the Rockwell hardness values obtained are 45, 42 and 46 respectively from three trials and averaging to Rockwell hardness value of 44. Similarly The rotational speed is 1100rpm, and the load applied is 60kg, the Rockwell hardness values obtained are 38, 47 and 46 respectively from three trials and averaging to Rockwell hardness value of 43. From the above information, it can be noticed that the increase in rotational speed causes increase in hardness value. It could be due to the hardenability characteristic imparted of the welded samples as a result of friction and high temperature. The rotational speed is increased to 900 rpm. The average hardness value obtained is 51 with only a slight variation range unlike the values obtained at lower rotational speeds. This shows that the rotational speed of 900 rpm is good and consistent in producing a hard surface at the welded zone when compared with other
speeds. This may be considered as the optimum speed for producing good welded samples with high hardness. The hardness value for stirred zone is shown in Table 5. Higher hardness 51 is obtained for high rotational speed. In hardness test conducted sameer and birru et al. (2014) using AA7075 T6 and AA6061 T6. The hardness values reported lie between 52 and 63 with maximum value at the stir zone which is due to the formation of hard surface as a result of high temperature Schneider et al. (2016).

| Sl.no | Rotational speed (rpm) | Load (kg) | Rockwell hardness value (RHB) | Average hardness value (RHB) |
|------|------------------------|-----------|--------------------------------|-----------------------------|
| 1    | 900                    | 60        | 48                             | 51                          |
| 2    | 1000                   | 60        | 45                             | 44                          |
| 3    | 1100                   | 60        | 46                             | 43                          |

5. Conclusion

In this study, the AA7075 T6 & AA6061 T6 alloys by friction stir welding process. The butt joints are prepared by maintaining the welding speed, axial force as constant and by increasing the rotational speed of the tool. The SEM, tensile test and hardness test are used to justify the optimized process parameters. From this experimental result, it is concluded that may always prefer the 900 rpm rotational speed, 20 welding speed and 4 axial load optimization parameter is satisfied. The mechanical properties such as tensile strength and hardness at the stir zone of the welded joint strength increases with increase in the rotational speed can be used to obtain the best welding parameters as an extension of this work.

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