Non Destructive Analysis of Fsw Welds using Ultrasonic Signal Analysis

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Abstract. Friction Stir Welding is an evolving metal joining technique and is mostly used in joining materials which cannot be easily joined by other available welding techniques. It is a technique which can be used for welding dissimilar materials also. The strength of the weld joint is determined by the way in which these material are mixing with each other, since we are not using any filler material for the welding process the intermixing has a significant importance. The complication with the friction stir welding process is that there are many process parameters which effect this intermixing process such as tool geometry, rotating speed of the tool, transverse speed etc.,

In this study an attempt is made to compare the material flow and weld quality of various weldments by changing the parameters. Ultrasonic signal Analysis is used to characterize the microstructure of the weldments. use of ultrasonic waves is a non destructive, accurate and fast way of characterization of microstructure. In this method the relationship between the ultrasonic measured parameters and microstructures are evaluated using background echo and backscattered signal process techniques. The ultrasonic velocity and attenuation measurements are dependent on the elastic modulus and any change in the microstructure is reflected in the ultrasonic velocity.

An insight into material flow is essential to determine the quality of the weld. Hence an attempt is made in this study to know the relationship between tool geometry and the pattern of material flow and resulting weld quality the experiments are conducted to weld dissimilar aluminum alloys and the weldments are characterized using and ultra Sonic signal processing. Characterization is also done using Scanning Electron Microscopy. It is observed that there is a good correlation between the ultrasonic signal processing results and Scanning Electron Microscopy on the observed precipitates. Tensile tests and hardness tests are conducted on the weldments and compared for determining the weld quality.

1. Introduction

Friction Stir welding process is a significant metal joining process since its invention by The Welding Institute(TWI) in 1991[1].Friction Stir welding process is a joining process which employs a tool which rotates and travels along the joining surfaces which are clamped together. The tool is non-consumable and many types of tool profiles are employed for the welding purpose. Tool geometry is defined by the shoulder diameter, pin diameter, profile of pin and the pin length. The pin length is usually shorter than then the thickness of the plates. The pin is penetrated into the work pieces and the tool rotates and transverses along the centreline. The interaction that takes place between the tool & work piece gives rise to friction generating heat which in turn creates plastic deformation and the flow
takes place in plasticized state as the tool traverses forward [2], the process is illustrated in the Fig. The material flow in friction stir welding is complex in nature and mainly depends on the tool geometry and other process parameters viz. tool rotation speed, traverse speed of welding, tilt angle of the tool, axial force applied and properties of the material to be welded. The weld formation depends on the material flow behavior of the materials to be welded. As friction stir welding is a fusion welding process the welding takes place due to the intermixing of the materials for which material flow is the primary criteria.

Fig. 1  Friction Stir Welding Process

Understanding of the material flow pattern and flow characteristics during the friction stir is very much essential for proper selection of the process parameters and the tool geometry [3]. Few attempts are made by the researchers to describe the material flow characteristics. Material flow during the friction stir welding process is illustrated experimentally by employing marker insert technique which partially described the material flow in the weld zone [4]. Some attempts are made to describe the material flow using two-dimensional flow modelling around the tool pin [5-6]. CFD was used by some researchers to describe the 3D model flow [7]. Tool geometry plays an important role and influences material flow in friction stir welding process [8]. The advantage of the friction stir welding process is that it reduces various metallurgical problems like porosity, spatter etc., and also it is an environmental friendly process. As friction stir welding is a hybrid thermo mechanical process the weld zone is near the joint and is divided into different zones Base Metal zone (BMZ), Heat affected ZONE (HAZ) and thermo mechanically affected zone (TMAZ). BMZ has no microstructural changes, no plastic deformation occurs in the HAZ but due to the heat generated microstructural changes occur in HAZ. Drastic microstructural changes are observed in TMAZ [9-12]. The properties of the welded joint are mostly influenced by the temperatures due to the heat generated due to the friction between the tool and the work piece. The present work is to study the influence of tool geometry on material flow during friction stir welding in two dissimilar Aluminium Alloys. Various types of tool geometries used for the process are triangular, square, pentagon and hexagon. The Tool is made of H-13 tool steel. Experiments are planned with different tool geometries. A fixture is designed for firmly clamping the work pieces with a provision of thermocouples for measuring the temperatures at various locations using thermocouples and thermography is also employed using fluke thermal camera which records the temperature at various locations during the friction stir welding process. A correlation between the temperature distribution and resulting material flow pattern is studied by analyzing the microstructural properties of the various locations using both metallurgical microscope and Scanning Electron microscope (SEM). EDX studies are also carried out.
2. Experimental Procedure

2.1. Equipment and Materials used: The welding process is carried out on 8mm thick plates having single plate size of 100mmX200mmX8mm. FSW is carried on a modified vertical milling machine with arrangement to record temperatures at various locations using thermocouples and arrangement to measure the forces acting during welding. Various types of tool geometries have been used in the present work such as triangle, square, pentagon and hexagon, made of high carbon high chromium steel for the welding process. The FSW process is used to join two plates of materials AA 6061 and AA6082 whose material properties are shown in the Table 1 and Table 2 below.

| TABLE 1 Composition of AA 6061 |
|--------------------------------|
| Element | Al | Mg | Si | Cu | Cr |
| Amount (wt %) | Bal. | 1.0 | 0.6 | 0.3 | 0.2 |

| TABLE 2 Composition of AA 6082 |
|--------------------------------|
| Element | Al | Mg | Si | Cu | Cr | Zn |
| Amount (wt %) | Bal. | 0.87 | 0.9 | 0.08 | 0.09 | 0.03 |

The experimental setup including the fixture and the tools used for the FSW process are shown in the fig.2. The Experiments are conducted by placing the plate made of AA6082 on the RS(retreating side) and the plate made of AA6061 on the AS(Advancing side). The tool geometry of the different tools used in the FSW process is shown in the Table 3 below.

Fig. 2. Experimental Setup
TABLE 3 Description of the tools used in the FSW process

| Tool number | tool profile | Pun Length(mm) | Pin Diameter(mm) | Shoulder diameter (mm) |
|-------------|--------------|----------------|------------------|------------------------|
| 1           | Triangle     | 7.8            | 4                | 12                     |
| 2           | square       | 7.8            | 4                | 12                     |
| 3           | pentagon     | 7.8            | 4                | 12                     |
| 4           | hexagon      | 7.8            | 4                | 12                     |

The experiments are conducted at a constant tool rotational speed of 1400rpm and a welding speed of 20mm/min. Temperatures are recorded using thermography and analysed using fluke smartview thermal imaging software. The experimental setup with arrangement of thermocouples to measure temperatures is shown in the Fig 2.

Mechanism of Friction stir Welding Process

The friction stir welding process generally involves three stages plunging of the tool, tool traverse and retraction of the tool from the work piece. Initially the tool is plunged in to the work piece till the surface of the shoulder of the tool touches the surface of the work piece. Once the preheating time is elapsed the tool slowly traverses forward till the end of the work piece is reached and tool is retracted from the work piece leaving a hole at the end of the weld. All the three phases of the mechanism have physical significance as they influence the temperature distribution which in turn affects the material flow pattern and resulting microstructure.

Correlation between the thermal histories and Mechanical and micro structural properties of the weldments

Temperatures at various locations along the weld line at an interval of 35mm at points A, B, C, D, and E at a distance of 35mm, 70mm, 105mm, 140mm & 175mm from the initial point of the weld along the traverse direction of the tool are recorded and tabulated in TABLE 4. Both the methods of recording of the thermal histories are correlated and found correct. The Images obtained at point C are selected and analysed and the corresponding temperature distribution profiles using fluke smart view thermal image software are given below.

TABLE 4 Temperatures Recorded using Thermocouples at different points for different tool profiles

| S.No. | Tool Geometry | A  | B  | C  | D  | E  |
|-------|---------------|----|----|----|----|----|
| 1     | Triangle      | 68 | 124| 220| 246| 280|
| 2     | Square        | 97 | 146| 272| 282| 296|
| 3     | Pentagon      | 98 | 210| 320| 328| 364|
| 4     | Hexagon       | 112| 226| 420| 436| 454|
The weldments obtained from the friction stir welding process using different tool profiles triangle, square, pentagon and hexagon shaped tool profiles are subjected to mechanical and microstructural tests to correlate with thermal histories. For this purpose tensile tests are conducted on the specimens as per ASTM standards. For this purpose the specimens are sectioned longitudinally as per ASTM standards and tested on a universal testing machine and corresponding stress – strain curves are obtained. Similarly micrographs are obtained by means of optical and scanning electron micrography (SEM) to correlate the material flow pattern with the thermal distribution.

![Fig. 3. Tensile Specimens after Tensile Test](image1)
![Fig. 4. Tensile Specimens after Tensile Test](image2)

1. Specimen corresponding to Triangle Tool
2. Specimen corresponding to Square Tool
3. Specimen corresponding to Pentagonal tool
4. Specimen corresponding to hexagonal tool

| S.No. | Tool Geometry | Tensile Strength(MPa) |
|-------|---------------|-----------------------|
| 1     | Triangle      | 67.6                  |
| 2     | Square        | 82.4                  |
| 3     | Pentagon      | 91.2                  |
| 4     | Hexagon       | 102.4                 |

The necking zone generally occurs at the HAZ because of dynamic recrystallization occurs at the HAZ. Hardness tests are also conducted using Brinell hardness testing machine along the transverse direction of the weld on either side of the centerline i.e advancing side as well as the retreating side and are tabulated below.
TABLE 6 Hardness test results corresponding to different tool profiles

| S.No. | Tool Geometry | Brinell HB |
|-------|---------------|------------|
|       |               | AS  | RS  |
| 1     | Triangle      | 81  | 82  |
| 2     | Square        | 86  | 85  |
| 3     | Pentagon      | 91  | 92  |
| 4     | Hexagon       | 100 | 98  |

There is no difference in hardness on advancing side (AS) and retreating side (RS).

Fig. 5. Digital image of the welded Plate

Characterization of weld quality using ultrasonic signal analysis

Ultrasonic signal Analysis is used to characterize the microstructure of the weldments. Use of ultrasonic waves is a non-destructive, accurate and fast way of characterization of microstructure. In this method the relationship between the ultrasonic measured parameters and microstructures are evaluated using background echo and backscattered signal process techniques. The ultrasonic velocity and attenuation measurements are dependent on the elastic modulus and any change in the microstructure is reflected in the ultrasonic velocity.

Fig. 6. Ultrasonic Signal corresponding to specimens
During the welding process the AA6061 plate is positioned on the retreating side and AA6052 plate is positioned on the advancing side. The micrographs obtained at the fracture surfaces of the specimens obtained with various tool profiles are shown in the Fig7, Fig.8, Fig9, and Fig.10 for the tool profiles triangle, square, pentagon, and hexagon respectively. Similarly, EDX studies are also carried out. EDX results for the specimen welded using hexagonal tool is shown in the Fig.11.

The observations of the micrographs which suggested low mechanical strength and failure through the stir zone is due to inadequate material intermixing. The micrograph corresponding to triangle tool features vortex structures of material corresponding to both base materials. By observing the micrographs it is observed that spacing between the material bands along the longitudinal sections decreased with increase in the number of sides of the tool pin which is in correlation with the temperature distribution and mechanical properties. As the material mixing increases the joint strength increases. EDS studies revealed the presence of oxide layer which may result in enhancing corrosion properties.
3. Results and Conclusions

The friction stir welding process is studied by conducting experiments with different tool profiles: triangle, square, pentagon, and hexagon for joining dissimilar aluminium alloys AA6061 and AA6082 by placing AA6061 on the retreating side and AA6082 on the advancing side with constant tool rotation speed and welding speed for all the experiments. Temperature distributions are obtained using thermocouples and it is observed that the hexagonal tool generated maximum temperature of 452.24°C and minimum temperature of 108.3°C, and the triangle tool generated maximum temperature of 220.52°C and minimum temperature of 52.1°C. It is observed that as the number of sides of the tool is increased, there is more frictional heat resulting in increasing in the maximum and minimum temperatures and the corresponding range in the thermal histories. Similarly, tensile test results and hardness test results are in correlation with the temperature distributions. The temperature distribution in the case of the hexagonal tool showing high average temperatures of 300°C to 350°C reveals that adequate frictional heat is generated which results consistent material flow and allow proper intermixing of the welding materials resulting in a good weld formation which resulted in good mechanical properties of the welding joints. The tensile test and hardness test results which are obtained and tabulated above justify this as the welded joint obtained using hexagonal tool exhibited tensile strength of 102.4MPa and that with triangle tool exhibited tensile strength of 67.6MPa. Similar results are obtained in the case of hardness test with the specimen obtained with hexagonal tool has 100 Brinell HB while that with triangle tool is 81 brinell HB. A successive progression in tensile stress and brinell HB is observed with successive increase in the number of sides of the tool pin. Finally, the micrographs obtained at the fracture surfaces are studied which revealed that the fracture is caused due to the lack of proper intermixing of the materials which is direct consequence of improper material flow. It is seen that the tool pin shape affects the frictional heat generation which in turn affects the temperature distribution which causes improper material flow which results in improper intermixing of the materials leading to the failure of the joints. Hence it can be concluded that the tool pin profile is an important process parameter and its design is crucial in deciding the material flow pattern. The results present a comparative study of the temperature distribution, tensile strength behaviour, resulting hardness and formation of microstructures with various tool pin profiles and it is observed that hexagonal tool shows good results compared to other tool profiles keeping other process parameters constant.

Fig. 11. EDS Studies of the specimen-hexagonal Tool
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