A Study on Weld Quality and Tunnel Defect Characterization in Friction Stir Welding Using Acoustic Emission Techniques

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Abstract: ***Friction stir welding (FSW) is a solid-state welding process that joins two pieces of material together without melting them. It heats the metals using the heat produced by friction between the stir head and the base metal. A non-consumable tool with a shoulder and pin rotates and is inserted between the two pieces of material. The tool's friction with the material generates heat, which softens the material near the tool. The tool then moves along the joint line, mixing the softened material to create a solid weld. Friction stir welding is typically used in applications where conventional welding methods do not provide adequate mechanical properties or a cost-effective process. FSW is used in the manufacture of EV components like battery cases, motor cases, and inverter cases. It can also be used to join cooling parts for semiconductor equipment [1]. In the present work, assessment of weld quality and characterization of tunnel defect was done by using different tool shoulder parameters like flat, concentric, concave, scroll shoulders by keeping conical threaded pin constant for all tools with Acoustic Emission set up. The research work aim is , assessment of weld quality of friction stir welds produced by different tool shoulder parameters by Acoustic Emission technique by conducting characterisation tests like tensile test for each samples produced by all tools. Characterization of tunnel defect was done by considering the X Ray radiographic results and measurement of size of defects. This has been done by considering the AE parameters with the intention to use in on-line monitoring of process. The results of AE and radiographic test along with tensile test, defects measurement confirms that the Acoustic Emission technique found feasible method for online monitoring, assessment of weld quality and characterization of defects [2].***

Keywords: Friction Stir Welding, Wed Defects, Acoustic Emission

1. Introduction

Friction Stir Welding (FSW):

Friction Stir Welding is a solid-state joining process that bonds two pieces of material without melting them. The process relies on friction-generated heat between a non-consumable rotating tool (comprising a shoulder and a pin) and the base materials. The tool is inserted along the joint, where frictional heat softens the material. As the tool traverses the joint, it mechanically mixes the softened material, forming a strong, solid-state weld.

FSW is particularly advantageous for applications where conventional welding methods fall short in terms of mechanical properties or cost-effectiveness. While FSW is commonly used for materials like aluminium, welding high-melting-point materials such as steel, stainless steel, and nickel-based alloys requires advanced tool materials and precise process control. FSW is also effective for joining dissimilar materials, such as aluminium and steel, and for welding materials that are otherwise difficult to join.

One of the key benefits of FSW is its ability to produce robust joints with minimal deformation or distortion. This makes it an excellent choice for industries like electric vehicle (EV) manufacturing, where it is used for components such as battery cases, motor housings, and inverter enclosures. Additionally, FSW is employed in semiconductor equipment manufacturing, particularly for joining cooling components.

Figure 1.1: Schematic Diagram of FSW (Ref: megastir.com)

When the FSW tool is traversed along the weld seam, the tool shoulder and probe stir the material in the immediate area of the tool. In order for the FSW process to fuse the joint through the entire weld length, the FSW operation must maintain a high enough energy input per unit length travelled to drive the fusion process (Frigaard et al., 2001[5]; Friction stir welds have been produced in a wide variety of metals, all requiring different energy inputs and different types of tooling. The energy input per unit length in FSW is primarily a function of the variables of tool rotational speed and traverse speed, requiring that these welding parameters be modulated for each alloy to input sufficient energy to form a solid joint (Mishra & Ma, 2005[20]).

Defects and their causes in FSW:

Void Formation causes due to insufficient heat input, improper tool design, or low rotational/traverse speed, Tunnel Defects (Wormholes) formed due to inadequate material flow due to improper tool geometry or process settings, Root Flaws due to Insufficient tool penetration or misalignment, Surface Oxides Inclusion as a cause of inadequate cleaning of the workpiece surface before welding, Excessive Flash due to excessive heat input or high tool pressure, Lack of Fusion because of inadequate heat generation or insufficient mixing of materials, Tool Wear or Breakage because of high friction or welding of high-strength materials without suitable tool material, Poor Surface Finish since incorrect tool shoulder design or inappropriate process parameters.

Effects: The common effects of defects are Effect: Internal voids weaken the weld, compromising its mechanical properties.
Tunnel-like defects form along the weld, reducing strength and integrity, Unbonded regions at the weld root weaken the joint, especially under tensile or bending stress, Oxide layers trapped in the weld result in poor bonding and reduced ductility, excessive material is expelled from the weld zone, indicating inefficient material utilization and a weaker joint, the materials fail to bond properly, leading to weak joints, Produces rough or uneven weld surfaces that require additional machining. Weak intermetallic compounds or uneven mixing, compromising weld integrity.

Acoustic Emission (AE):

Acoustic Emission refers to the release of transient elastic waves caused by a sudden redistribution of stress within a material. When a structure undergoes external changes such as variations in pressure, load, or temperature, localized sources release energy in the form of stress waves. These waves travel to the surface, where they are detected and recorded by specialized sensors. AE monitoring is a valuable tool for assessing material integrity and identifying structural issues in real-time.

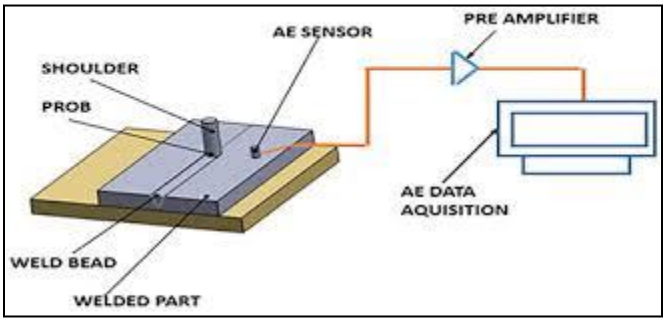

Figure 2: Schematic Diagram of FSW (Ref: www.tandfonline.com/)

Acoustic Emission (AE) is a non-destructive evaluation (NDE) technique that is highly effective in detecting and monitoring defects during and after the Friction Stir Welding (FSW) process. AE involves capturing transient elastic waves generated by stress redistribution within the material, which can indicate the presence of defects or anomalies.

Use of AE for Fault Detection in FSW:

Friction Stir Welding (FSW) is a robust and reliable joining process, but it is not without potential issues. Faults in FSW can arise due to improper process parameters, unsuitable tools, material properties, or environmental factors.

Advantages of Using AE in FSW:

- **Non-Destructive:** No damage to the weld or material.
- **Real-Time Monitoring:** Defects can be detected during the process, reducing downtime.
- **High Sensitivity:** Detects even minute defects or anomalies.
- **Cost-Effective:** Reduces the need for post-process destructive testing.

Experimentation:

The various test conducted for the characterisation and defect identification of friction stir welds produced by different shoulders geometry. The objective of the present experiment is to study the feasibility of using Acoustic Emission technique for online monitoring of the process to identify defects and for characterization of the weld. Friction stir welding with different types of tools and process parameters is done with AE system for online monitoring. Record the AE data and validate these data with the X-Ray Radiography and force graphs from FSW machine for presence of weld defects. Characterize the weld by comparing variation in AE signals with the ultimate tensile strength of the weld. Interest is focussed to study the influence of process parameters on weld defects and strength by correlating AE signals.

Aluminium alloy 6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys. Alloy 6082 is known as a structural alloy. In plate form, 6082 is the alloy most commonly used for machining.

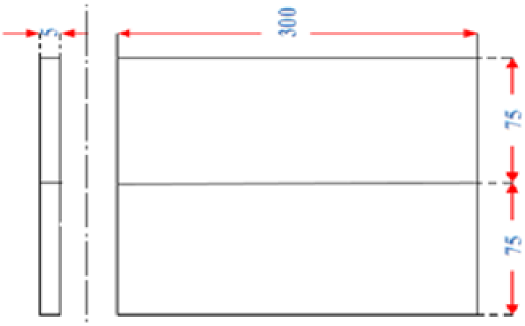

Figure 3: Flat Plate of Aluminium 6084

Four different pins with different Shoulder features and constant conical threaded pin features are used, they are:

1. Flat featured shoulder with conical threaded pin,
2. Concave featured shoulder with conical threaded pin,
3. Concentric featured shoulder with conical threaded pin and
4. Scroll featured shoulder with conical threaded pin.

The pin used for the experiment has a length of 4.70 mm, a pin diameter of 6.0 mm (major) and 4.0 mm (minor), a shoulder diameter of 20 mm, and a shoulder length of 24 mm as shown in Figure 2.

Figure 4: Pins used for experimentation

In the present experimental work, key process parameters considered for Friction Stir Welding (FSW) include transverse speed, plunge depth, and tilt angle. These parameters significantly influence weld quality, the formation of defect-free welds, and the mechanical characteristics of FSW joints. The selection of these parameters was guided by the Taguchi approach for optimizing FSW process parameters. For this study, the chosen process parameters were:

- Tool rotation speed: 1000 rpm
- Tool transverse speed: 100 mm/min
- Plunge depth: 4.83 mm
- Tilt angle: 20°

The computerised Horizontal Friction Stir Welding machine was used to create weld joints, carried out. The specification of machine is as follows in Table-1. The plates are butted and clamped properly; the process parameters were finalized. And next the welds were carried out by mounting the AE sensor on the advancing side plate and the AE data was recorded.

Table1: Specification of FSW Machine

Make	ETA Technology Pvt. Ltd., Bangalore
Type	Horizontal
Capacity	10 Tons
Traverse Speed	1 mm/min – 3000 mm/min
Plunge Speed	1mm/min- 2000mm/min
Tool Rotational Speed	1 rpm-3000 rpm

Figure 5: FSW Welding process

The FSW tool was securely mounted in the chuck of the horizontally traversing tool holder on the FSW machine. The tool rotation speed, transverse speed, weld length, and plunge depth were programmed into the machine's software. The plunge depth was calibrated and adjusted through preliminary plunge tests. Upon starting the machine, it automatically applied the required axial force, plunged the tool into the abutting joint, and initiated the welding process. As the tool rotated and traversed along the length of the joint, a weld was effectively produced.

Acquisition of AE data:

Acoustic Emission (AE) inspection was conducted during the welding process to capture AE signal data for subsequent analysis. AE sensors were positioned on the aluminium plates near the joint line, specifically on the advancing side, with a layer of coolant applied to ensure proper contact. The AE acquisition system was configured by setting up the channels, data parameters, graph displays, threshold voltage, and other necessary settings for signal acquisition.

Electrical signals generated by the transducer were amplified using a pre-amplifier with a 40 dB gain. Calibration of the AE system was performed using the pencil lead break test on the plate near the sensor to estimate the attenuation factor of the AE signal. The amplified and filtered signals were then recorded on a computer for further analysis. The nearly clustered dots observed on the AE graph indicated consistent and continuous interaction between the tool and the work piece during the welding process.

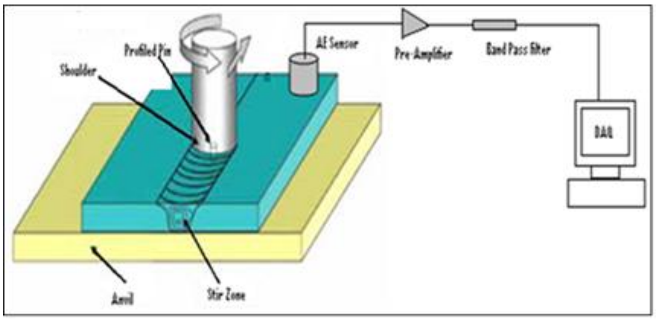

Figure 6: Experimental setup of AE

The breaking of the pencil lead generates an intense acoustic signal, quite similar to a natural AE source, which the sensors detect as a strong burst. The purpose of this test is twofold. First, it ensures that the transducers are in good acoustic contact with the part begins monitored. Generally, the lead break should register amplitudes of at least 80dB for a reference voltage of 1mV and a total system gain of 80dB. Second, it checks the accuracy of the source location setup.

The following steps were carried out acquire data during the AE test;

- Loading of the appropriate system layout (LAY) file in to system in order to setup the system desired operation and display conditions.
- Entering the acquire menu
- Selecting the data file to save to disc
- Starting data acquisition
- Ending of data acquisition

Electrical signals produced by the transducer were first amplified with a preamplifier of 40 dB gain. During AE data acquisition data was acquired in 2D scatter from which will be helpful for further analysis. The amplified signals were displayed for the set AE parameter like amplitude expressed in dB, energy voltage expressed without units, RMS voltage referred has RMS, counts expressed without units, duration expressed in seconds throughout the study.

Test specimen's extraction:

Samples for tests on weld response to tensile and bending, microstructure samples for imaging, and micro hardness profile samples were taken from multiple areas of a cohesive '4' welds produced by four different tool shoulder parameters. In all cases, samples were taken from locations of the weld that did not include transient zones surrounding entrance and exit moves. From each '4' weld, I have taken 4" specimens for tensile test, 1" for bending test and 2" specimens of 30*10mm, was used to create both microstructure and micro hardness.

These samples are taken according to good region, bad region and defected region from AE signal, axial force and x-ray radiographic image. Figure shows the locations from which welds were extracted.

Figure 7: Specimens are cut as per requirement by wire EDM

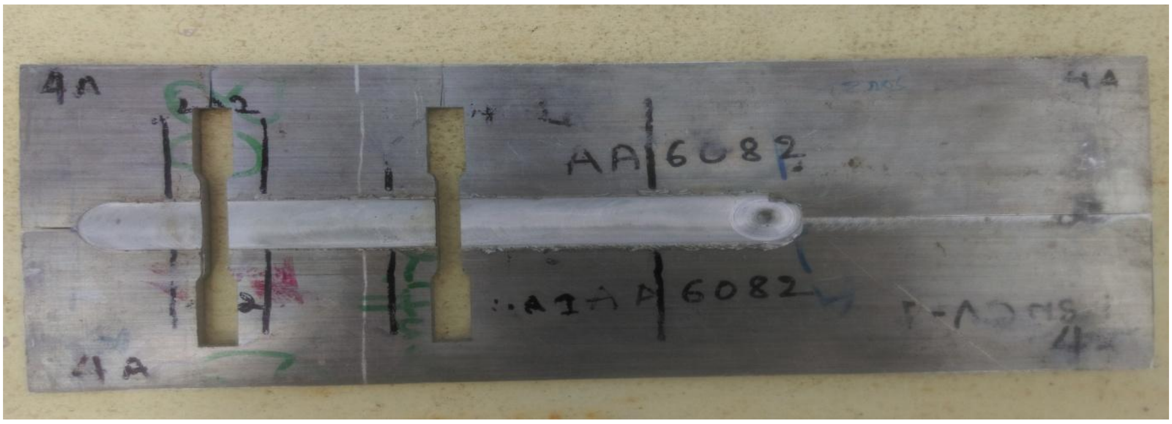

Figure 8: Specimens Extracted at AE signal variation regions from FSWCN Plate

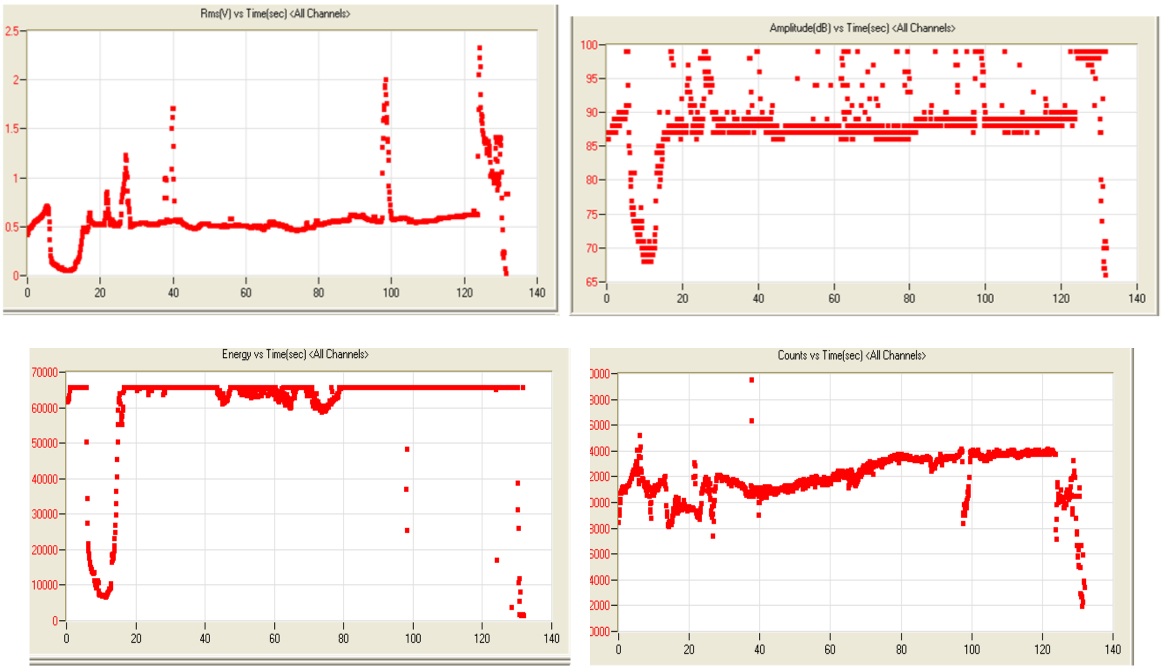

Figure 9: a) RMS v/s Time b) Energy vs Time c) Amplitude vs Time d) Counts vs time

2. Results

Tensile test results:

As per the ASTM standards the specimens were prepared and tensile tests followed by studying papers and thesis.

Table 2: Comparison table of Acoustic values compared with X-ray remarks

SL NO	SPECIMEN No.	UTS N/MM^2	JOINT η %	ACOUSTIC EMMISSION VALUES								X RAY REMARKS
				RMS		ENERGY		AMPLITUDE		COUNTS		
				LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	
1	4A1	183.8	59.75	0.45	0.47	49000	50000	95	96	24500	24500	ACCEPTABLE
2	4A2	189.8	61.7	0.35	0.35	40000	40000	83	85	26000	26500	ACCEPTABLE

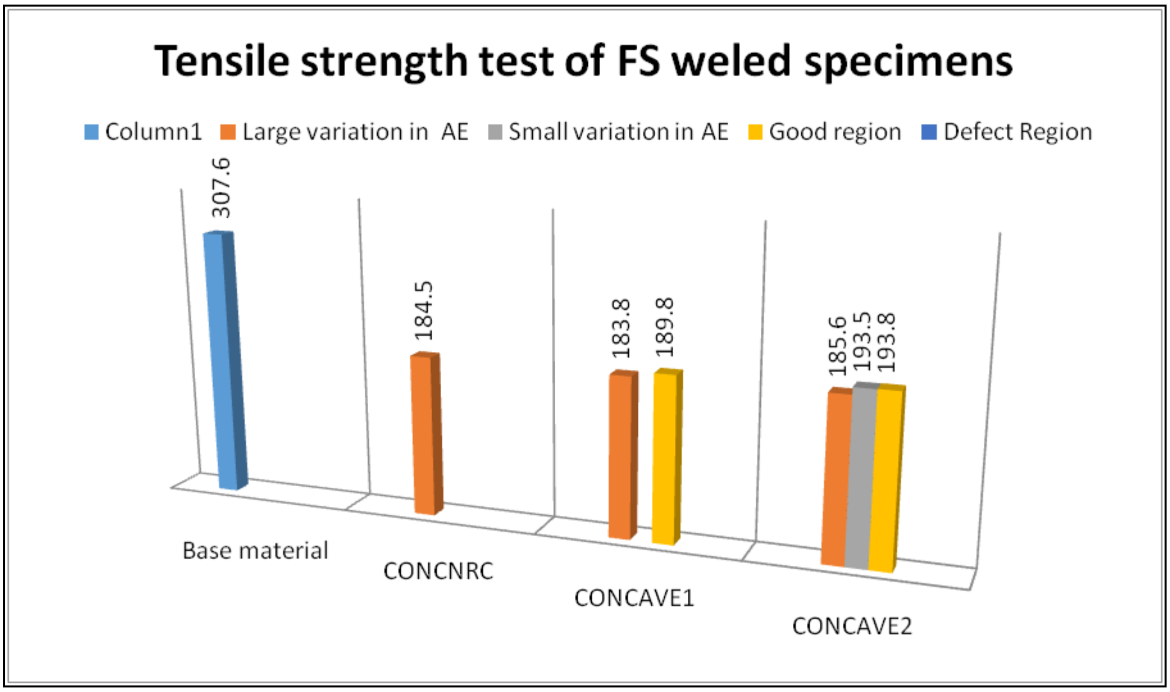

Figure 10: Results of tensile test of friction stir weld specimens

3. Conclusions

Based on the results obtained from the experiments, the following conclusions are drawn:

1. Joining of AA6082-T6 alloy plates with thicknesses of 5 mm and 5.5 mm was successfully achieved using the friction stir welding (FSW) technique.
2. Friction stir welding was performed with tools having different shoulder geometries, including flat, concave, concentric, and scroll shoulders, all equipped with a common conical threaded pin.
3. The Acoustic Emission (AE) technique proved effective for online monitoring of FSW by conducting repeatability studies and determining threshold values.
4. AE data acquisition successfully identified defected and non-defected areas in the welds.
5. The feasibility of the AE technique for defect detection was validated by comparing its results with those from X-ray radiography.
6. Tensile test samples were extracted from weld specimens produced using all tools, selected based on variations in AE signals.
7. Tensile tests on these samples showed variations in joint efficiency corresponding to changes in AE data.
8. Defect regions were characterized by measuring defects and correlating them with AE data.
9. RMS and amplitude values of AE signals varied slightly with changes in the measured defect areas.
10. Tools without threading on their pin length were observed to produce suboptimal weld results.
11. It was concluded from the study that the AE technique can be effectively used to assess the dimensions of tunnel defects in FSW.

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