

## TENSILE LOAD ANALYSIS DURING FRICTION STIR WELDING OF AL ALLOY AA2219

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### **Abstract**

*FSW is used to weld alloys like aluminum, manganese, copper, and stainless steel that are either difficult or impossible to weld using conventional welding methods. With an emphasis on tensile test analysis, this paper explores FSW characteristics of the age-hardenable Al alloy AA2219 (Al–Cu–Mn). FSW joints were created using 200 RPM rotational rates and a welding speed of 20 mm/min. The joints were found to have lower tensile strength under the T86 condition, which was especially apparent at a thickness of 20 mm, with a recorded value of 281 MPa. On the other hand, among thicknesses of 16 mm, 18 mm, and 20 mm, joints exposed to the T8 condition showed the maximum tensile strength at 258 MPa, underscoring the critical function of the hardening process.*

### **Keywords**

*Fiction Stir Welding (FSW), AA2219, Al Alloy*

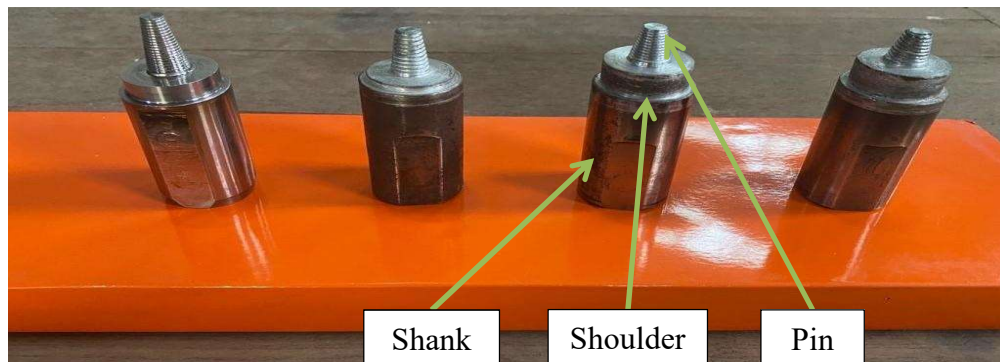
### **1. AA2219**

When developing lightweight structures that require a high strength-to-weight ratio, the use of AA2219 Al alloy has garnered significant attention. Unlike standard fusion welding methods used to combine structural Al alloys, FSW is a revolutionary solid-state joining technology that avoids melting and recasting the material being welded.

## 2. Experimental Work

### 2.1 FSW Tool Selection

The tool's design is important since it affects the weld quality and expedites the procedure. For an FSW to be successful, the material flow and tool form are essential. Using the latest developments, the new FSW tool was developed to reduce axial forces and improve process resilience. Cylindrical Tapered with a threaded pin tool configuration was chosen from a range of tool geometries, and its effect on weld joints was thoroughly investigated.



Tools Used for FSW of 12 mm, 16 mm, 18 mm and 20 mm Thick Plates

| Thickness of Plates to be Welded (mm) | Pin Height (mm) | Shoulder Dia (mm) | Pitch of Thread (mm) |
|---------------------------------------|-----------------|-------------------|----------------------|
| 12                                    | 11.4            | 27                | 1                    |
| 16                                    | 15.4            |                   |                      |
| 18                                    | 17.4            |                   |                      |
| 20                                    | 19.4            |                   |                      |

Tool Geometry for Various Thicknesses of Plates

### 2.2 Al Alloy Plates

The rolled AA2219 T861 and T8 condition Al alloy plates were cut to the required size of 150 mm by 150 mm using a power hacksaw. The thicknesses of the plates were 12, 16, 18, and 20 mm for T86 and 16, 18, and 20 mm for T8.

|       | % Conc.       |              |             |              |               |               |               |
|-------|---------------|--------------|-------------|--------------|---------------|---------------|---------------|
| Meas. | Si            | Fe           | Cu          | Mn           | Mg            | Cr            | Ni            |
| 1     | 0.0581        | 0.128        | 6.33        | 0.317        | 0.0094        | 0.0017        | 0.0078        |
| 2     | 0.0592        | 0.127        | 6.23        | 0.317        | 0.0097        | 0.0017        | 0.0076        |
| <x>   | <b>0.0587</b> | <b>0.127</b> | <b>6.28</b> | <b>0.317</b> | <b>0.0095</b> | <b>0.0017</b> | <b>0.0077</b> |

|       | % Conc.       |               |               |                    |               |               |                   |
|-------|---------------|---------------|---------------|--------------------|---------------|---------------|-------------------|
| Meas. | Zn            | Ti            | Ag            | Be                 | Ca            | Cd            | Hg                |
| 1     | 0.0438        | 0.0461        | 0.0012        | <0.00010           | 0.0017        | 0.0076        | <0.0020           |
| 2     | 0.0425        | 0.0497        | 0.0012        | <0.00010           | 0.0021        | 0.0075        | <0.0020           |
| <x>   | <b>0.0431</b> | <b>0.0479</b> | <b>0.0012</b> | <b>&lt;0.00010</b> | <b>0.0019</b> | <b>0.0075</b> | <b>&lt;0.0020</b> |

|       | % Conc.            |                    |                |                   |               |                |              |
|-------|--------------------|--------------------|----------------|-------------------|---------------|----------------|--------------|
| Meas. | Li                 | Na                 | Pb             | Sb                | Sn            | Sr             | Zr           |
| 1     | <0.00020           | <0.00010           | 0.00074        | <0.0030           | 0.0081        | 0.00026        | 0.143        |
| 2     | <0.00020           | <0.00010           | <0.00050       | <0.0030           | 0.0070        | 0.00027        | 0.146        |
| <x>   | <b>&lt;0.00020</b> | <b>&lt;0.00010</b> | <b>0.00062</b> | <b>&lt;0.0030</b> | <b>0.0075</b> | <b>0.00026</b> | <b>0.144</b> |

|       | % Conc. |        |        |       |  |  |  |
|-------|---------|--------|--------|-------|--|--|--|
| Meas. | Al      | V      | Bi     | SF    |  |  |  |
| 1     | 92.7    | 0.0749 | 0.0017 | 0.767 |  |  |  |
| 2     | 92.8    | 0.0785 | 0.0016 | 0.766 |  |  |  |
| <x>   | 92.8    | 0.0767 | 0.0016 | 0.766 |  |  |  |

### Chemical Composition of Al Alloy AA2219

### 2.3 FSW Machine

With the following technical specifications, an FSW machine manufactured by MTI, Model No. RM 3 of MTI Welding Technologies, was used to produce the joints utilising different combinations of rotation and welding speeds.

|              |                                                                                                                                   |
|--------------|-----------------------------------------------------------------------------------------------------------------------------------|
| Capabilities | Retractable Pin Technology (RPT), Stationary Shoulder Tool Holder System, Mega Stir Tool Holder                                   |
| Materials    | Alloys: Al, Mg, Ti, Steels, Super Alloys, etc.                                                                                    |
| Spindle      | Speed Range: 100-3000 Rpm, Torque: 300 Nm at 50 to 766 Rpm                                                                        |
| X-Axis       | Stroke: 700 mm (27.5 in), Max Velocity: 3000 mm/min (118 ipm), Max Force: 250 kN                                                  |
| Y-Axis       | Stroke: 305 mm (12 in), Max Velocity: 3000 mm/min (118 ipm), Max Force: 250 KN                                                    |
| Z-Axis       | Stroke: 400 mm (16 in), Max Velocity: 1000 mm/min (39 ipm), Max Force: 100kN                                                      |
| A-Axis       | +/- 6 Deg min (hard stop-to-hard stop), +/- 5 Deg min (soft stop-to-soft stop / working range), +/- 5 Deg min (range requirement) |

|                      |                                                                                                                        |
|----------------------|------------------------------------------------------------------------------------------------------------------------|
| Service Requirements | Air: 80 psi (5.5 bar) 3.5 scfm, Argon: 60 ft <sup>3</sup> /hr (28 l/min), Supply Voltage: 480 VAC/60 Hz, 3 Phase, 100A |
| Data Monitoring      | Temperature Telemetry System (MegaStir™)                                                                               |

### Specification of MTI FSW Machine



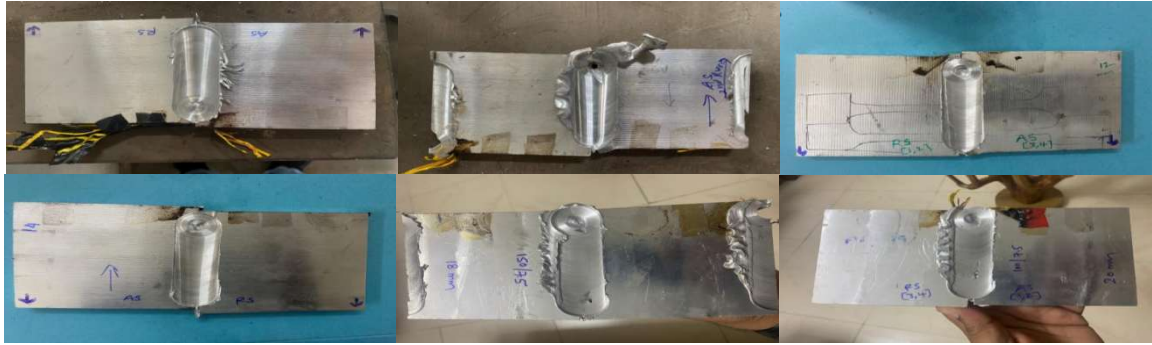
MTI FSW Machine

### 2.4 Tensile Test

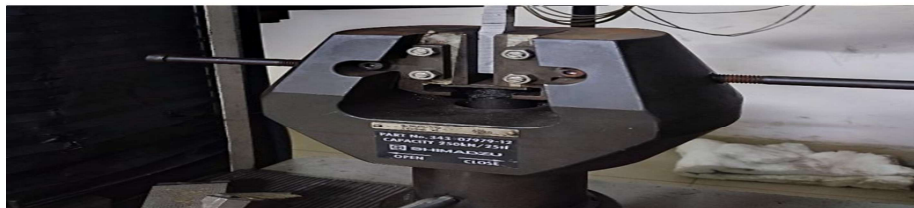
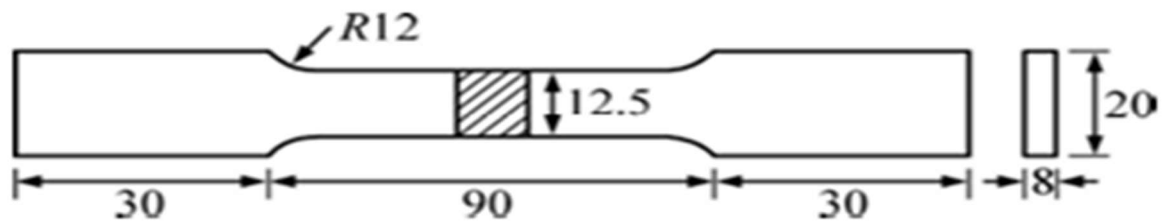
Tensile tests were conducted using a 250 kN hydraulically controlled universal testing equipment (Make: SHIMADZU). The tensile specimen was loaded at a rate of 3 mm per minute in accordance with ASTM recommendations, which resulted in deformation.

| Plate Thickness (mm) | Tool Rotational Speed (Rpm) | Welding Speed (mm/min) | Tool Shoulder Diameter (mm) | Pin Ht (mm) |
|----------------------|-----------------------------|------------------------|-----------------------------|-------------|
| 12 (T86)             | 200                         | 20                     | 30                          | 11.4        |
| 16 (T86)             | 200                         | 20                     | 30                          | 15.4        |
| 18 (T86)             | 200                         | 10                     | 30                          | 17.4        |
| 20 (T86)             | 100                         | 7.5                    | 30                          | 19.4        |
| 16 (T8)              | 200                         | 20                     | 30                          | 15.4        |
| 18 (T8)              | 200                         | 10                     | 30                          | 17.4        |
| 20 (T8)              | 100                         | 7.5                    | 30                          | 19.4        |

Process Parameters of Weld Joints of Various Thickness Plates



Achieved FSW Welds

Standard  
Tensile  
Sample

Dimensions As Per ASTM E 8M

UTM Machine

| Sample Id  | Material Condition | 0.2%PS (MPa) | UTS (MPa) | % El  | Fracture Location |
|------------|--------------------|--------------|-----------|-------|-------------------|
| 12mm Thick | T86                | 195          | 236       | 7.48  | Weld Centre       |
| 16mm Thick | T86                | 227          | 281       | 11.38 | Weld Centre       |
| 18mm Thick | T86                | 190          | 222       | 6.0   | Weld Centre       |

|            |     |     |     |      |             |
|------------|-----|-----|-----|------|-------------|
| 20mm Thick | T86 | 206 | 231 | 5.42 | Weld Centre |
| 16mm Thick | T8  | 193 | 258 | 13.5 | Weld Centre |
| 18mm Thick | T8  | 181 | 209 | 7.5  | Weld Centre |
| 20mm Thick | T8  | 183 | 237 | 10.9 | Weld Centre |

### Mechanical Properties of Various Thickness Plates

#### 3. FSW Process

AA2219–T86 and T8 Al alloy rolled plates with thicknesses of 12 mm, 16 mm, 18 mm, and 20 mm were employed to ascertain the realistic working limits of FSW process parameters. The experimental runs were carried out using a variety of process parameter combinations. Defect-free joints were formed by welding at a speed of 20 mm/min and rotating at 200 rpm, depending on the welding speed. The rotation speed and welding speed were changed within the previously indicated processing range in order to determine which friction stir welded AA2219 joints were defective and which were not.

| <b>Rotational / Welding Speed</b> | <b>Defect</b>               | <b>Probable Cause</b>                          | <b>Thickness/ Condition</b> |
|-----------------------------------|-----------------------------|------------------------------------------------|-----------------------------|
| 200/20                            | No defect                   | Sufficient heat input & adequate flow of metal | 12mm/ T86                   |
| 200/20                            | No defect                   | Sufficient heat input & adequate flow of metal | 16mm/ T86                   |
| 200/10                            | Pin hole under the shoulder | Insufficient stirring of plasticised metal     | 18mm/ T86                   |
| 100/7.5                           | Pin hole under the shoulder | Insufficient stirring of plasticised metal     | 20mm/ T86                   |

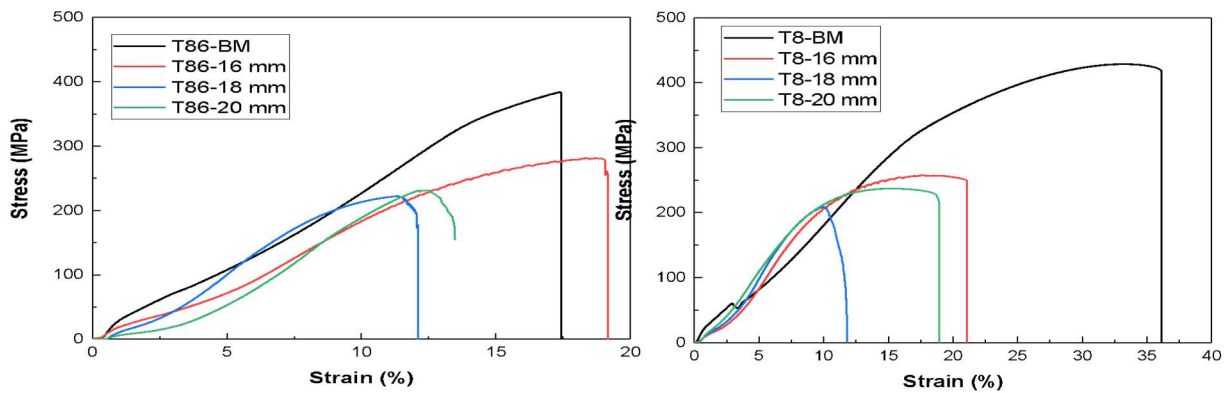
#### FSW of 12mm, 16 mm, 18 mm & 20 mm: T86 Condition

| <b>Rotational /Welding Speed</b> | <b>Defect</b>               | <b>Probable Cause</b>                                           | <b>Thickness/ Condition</b> |
|----------------------------------|-----------------------------|-----------------------------------------------------------------|-----------------------------|
| 200/20                           | No defect                   | Sufficient heat input & adequate flow of metal                  | 16mm/T8                     |
| 200/10                           | Tunnel defect               | Tunnel defect at retreating side due to insufficient heat input | 18mm/T8                     |
| 100/7.5                          | Pin hole under the shoulder | Insufficient stirring of the plasticised metal                  | 20mm/T8                     |

## FSW of 16 mm, 18 mm &amp; 20 mm: T8 Condition

## 4. Tensile Properties

The tensile plot unequivocally demonstrates that material has undergone brittle fracture when contrasted with the basic material (T86 and T8). The T8 and T86 alloys have comparable moduli as plate thickness increases, despite base material having undergone a tensile fracture. The T8 and T86 FSW alloys' modulus increases with thickness (16 mm and 18 mm) in comparison to the base alloy. But when the plate is 20 mm in diameter, the modulus decreases for both T8 and T86 alloy. Regarding the elongation of T86 FSW alloy, there is a slight paradox: for 20 mm plate, the elongation first increases in relation to the base alloy, then decreases, and then increases once again as thickness increases. In contrast, the elongation of T8 alloy plates decreases for 18 mm and then suddenly increases for 20 mm plates. Furthermore, the 20 mm plate's modulus and elongation trend exhibit a unique pattern that distinguishes it from the other samples (BM, 16 mm, and 18 mm plate). When compared to base material, FSW has resulted in a decrease in the UTS



value for both T8 and T86 plates. The influence of plate thickness does not seem to have an effect because there was no appreciable variation in their UTS results.

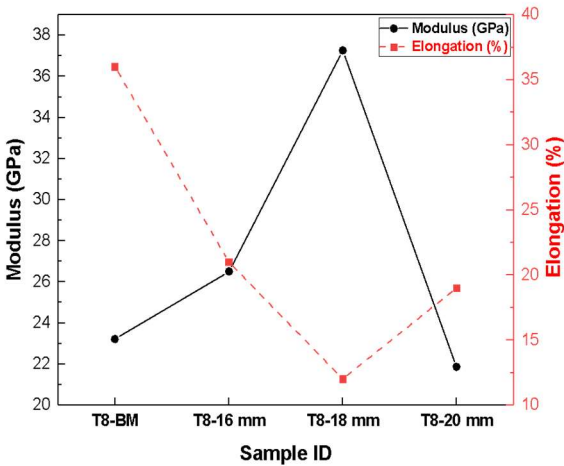
Tensile Plot of T86 FSW Alloy

Tensile Plot of T8 FSW Alloy

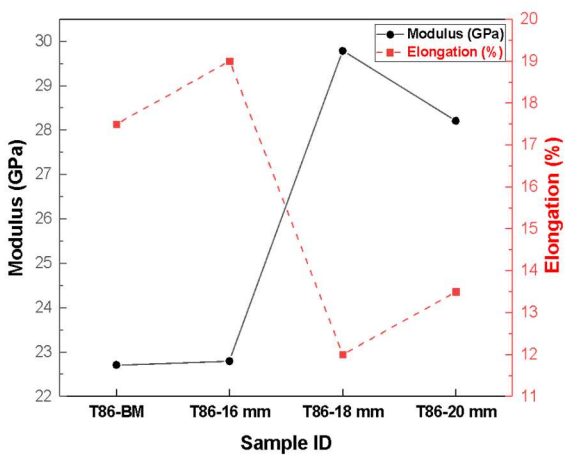
| Thickness (mm) | T86 Modulus (GPa) | T8 Modulus (GPa) | T86 UTS (MPa) | T8 UTS (MPa) | T86 Elongation (%) | T8 Elongation (%) |
|----------------|-------------------|------------------|---------------|--------------|--------------------|-------------------|
| BM             | 22.71             | 23.2             | 383           | 430          | 17.5               | 36                |
| 16             | 22.8              | 26.5             | 281           | 258          | 19                 | 21                |

|    |       |       |     |     |      |    |
|----|-------|-------|-----|-----|------|----|
| 18 | 29.79 | 37.26 | 224 | 208 | 12   | 12 |
| 20 | 28.21 | 21.86 | 232 | 258 | 13.5 | 19 |

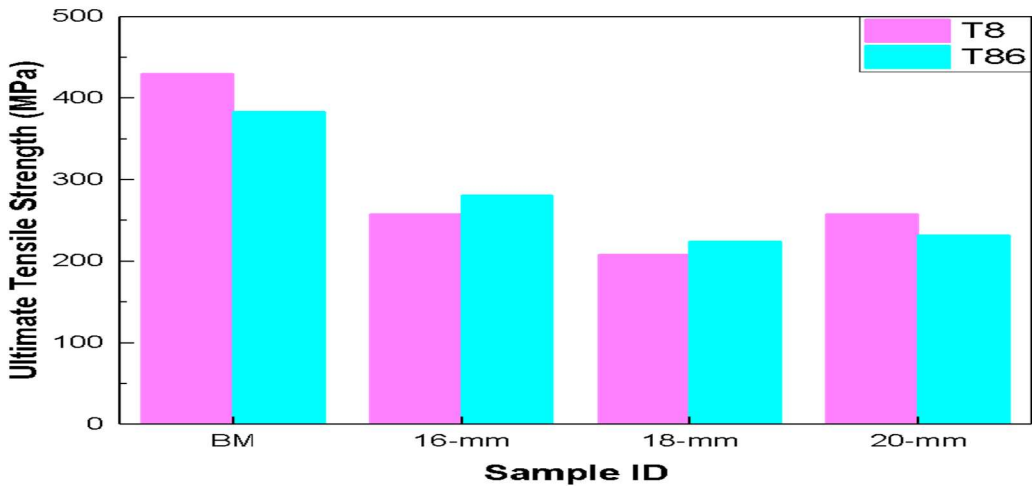
Tensile Properties of Friction Welded T8 and T86 Alloy Plates



Modulus & Elongation Values: T8



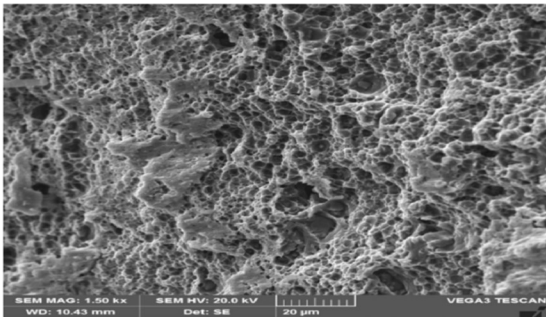
Modulus & Elongation Values: T86



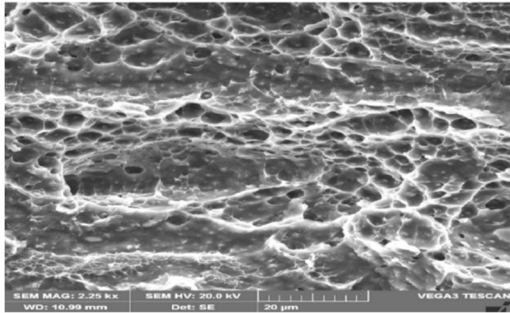
UTS Values of T8 & T-86 FSW Al Alloy AA 2219



T-86 Tensile Specimen Before Failure

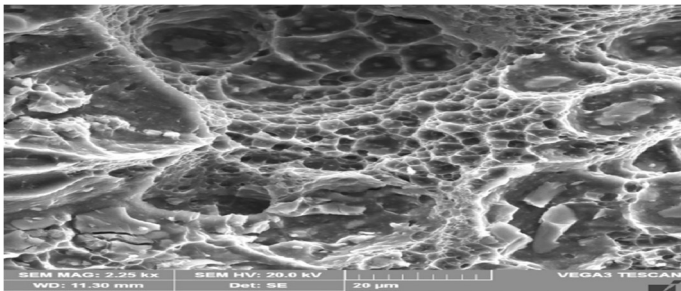


T-86 Tensile Sample After Failure

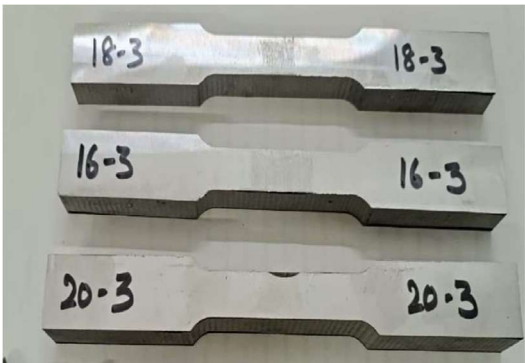


SEM- T 86 FSW AA 2219: 12 mm

SEM- T 86 FSW AA 2219: 18 mm



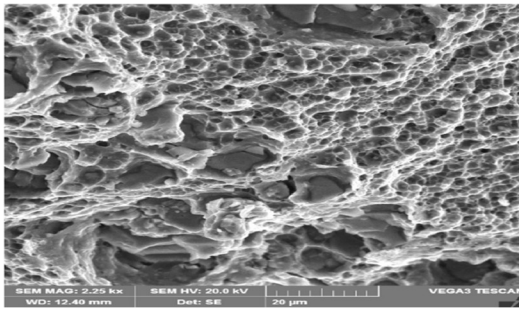
SEM- T 86 FSW AA 2219: 20 mm



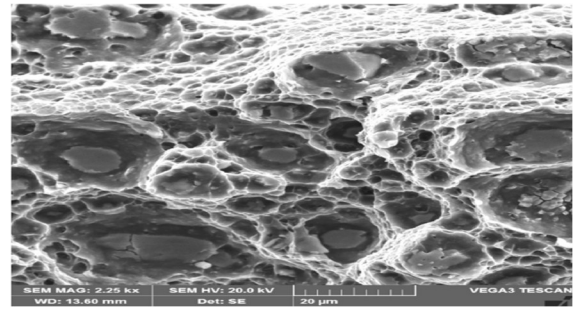
T8 Tensile Specimen Before Failure



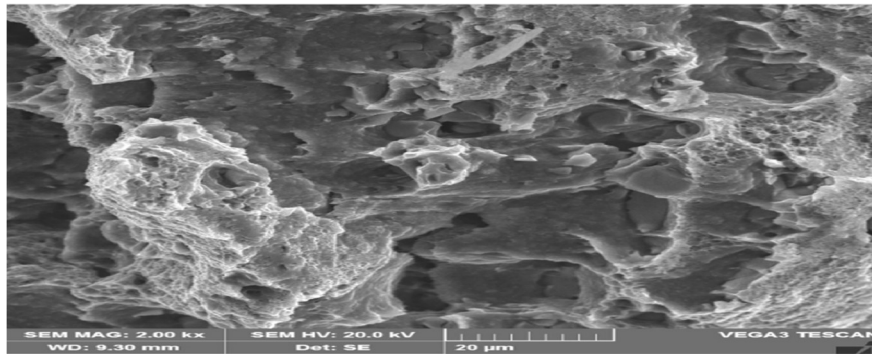
T8 Tensile Specimen After Failure



SEM-T8 FSW AA 2219: 12 mm



SEM-T8 FSW AA 2219: 18 mm



SEM-T8 FSW AA 2219: 20 mm

### 5. Rotational Speed's Impact on Tensile Properties

The tensile properties of six experimental FSW joints with welding rates of 20 mm/min and rotational speeds of 200 RPM were evaluated. A change in tool rotation speed affects the area and temperature distribution of the weld zone. Joint strength was lowered as a result of less churning brought on by the lower heat input. The base metal's microstructure is essentially composed of long grains. The FSW grain size is also influenced by the welding parameters; it was found that the grain size grew as the tool rotation speed increased due to an increase in heat input. The average grain size in the stir zone of the welded joints increases with increasing rotational speed. An increase in average grain size leads to inferior tensile properties and a lower hardness value.

Additionally, at high rotational speeds, particles would fracture more. The microstructural alterations affected the mechanical characteristics. As was the case at 200 RPM, the dynamic recrystallisation process softens the microstructure of the friction stir welded zone, transforming the elongated grains of the base material into equiaxed

fine grain structure. A defect-free FSP zone with smaller grain size and a very fine, uniform particle distribution is what gives the joints described above their higher hardness and superior tensile properties.

## **6. Welding Speed's Impact on Tensile Properties**

The joints created using two different (lower and higher) welding speeds (0.75 mm/min and 20 mm/min) have quite different tensile properties. Compared to other joint parameters, the joints created at a welding speed of 20 mm/min had better tensile qualities. Grain formation and coarsening are observed at lower welding rates (0.75 mm/min) as a result of increasing heat input. The lower welding speed welds showed the existence of several sub-boundaries inside the grains. As the heat input rises during FSW, the subgrain size increases. After the tool has passed, dynamically recrystallized grains statically form as the temperature cycle cools. This suggests that the increased heat input results in larger grains with a lower density of dislocations and sub-boundaries in the stir zone. The grain size of the FSW zone changed suddenly in the joints created with higher welding rates. FSW at higher welding rates usually results in shorter exposure durations at higher temperatures. This is because a welding speed of 20 mm/min resulted in finer grains in the FSW area of the AA2219 alloy than other welding rates, improving the tensile characteristics of the joints.

## **7. Analysis**

- a. Higher rotational speeds and lower welding speeds result in excess flash generation and nugget collapse because the additional heat input during the FSW softens the metal.
- b. Similarly, higher welding speed and lower rotational speed cause wormhole defects that arise from insufficient heat input during the FSW.
- c. Wormhole defects were also seen at higher rotating and welding speeds as a result of anomalous stirring.
- d. The weld quality is determined by the ratio of welding speed to rotational speed, also referred to as the weld pitch or tool advance per revolution. This ratio can be increased by

increasing the welding speed while maintaining a constant rotational speed or decreased by decreasing the rotational speed while maintaining a constant welding speed.

e. Welds that have higher rotational and welding rates will typically be colder than those that have lower speeds.

f. In this study, 16 mm thick weld in T86 condition exhibited maximum tensile strength of 281 MPa, which may be due to the finer microstructure and greater hardness. However, 16 mm thick weld in T8 condition exhibited maximum tensile strength of 258 MPa.

g. The base metal's ultimate tensile strength was found to be 384 MPa in the AA2219 - T86 condition and 429 MPa in the AA2219 - T8 condition.

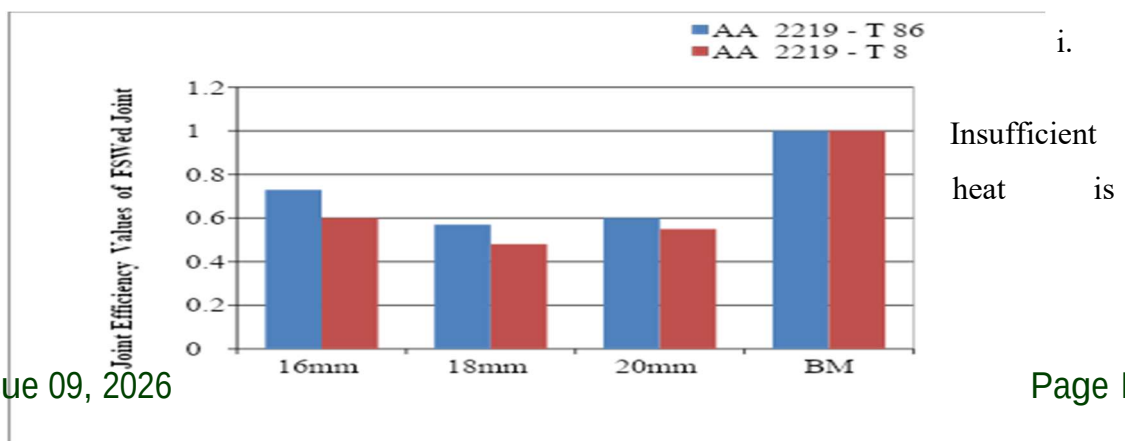
| Sample Id  | UTS of Joint (MPa) | Joint Efficiency Value | Joint Efficiency in Percentage | UTS of BM |
|------------|--------------------|------------------------|--------------------------------|-----------|
| 12mm FSWed | 236                | 0.61                   | 61                             | 384       |
| 16mm FSWed | 281                | 0.73                   | 73                             |           |
| 18mm FSWed | 222                | 0.57                   | 57                             |           |
| 20mm FSWed | 231                | 0.60                   | 60                             |           |

Joint Efficiency Values of all Thickness Welds of AA2219 in T86 Condition

| Sample Id  | UTS of Joint (MPa) | Joint Efficiency Value | Joint Efficiency in Percentage | UTS of BM |
|------------|--------------------|------------------------|--------------------------------|-----------|
| 16mm FSWed | 258                | 0.60                   | 60                             | 429       |
| 18mm FSWed | 209                | 0.48                   | 48                             |           |
| 20mm FSWed | 237                | 0.55                   | 55                             |           |

Joint Efficiency Values of all Thickness Welds of AA2219 in T8 Condition

h. The maximum joint efficiency, 73% for T86 and 60% for T8 welded joints, is found in the 16mm thick FSWed joint of AA2219.



generated at RS in FSW above 16 mm as thickness increases. The impact of transit speed on heat generation at the bottom of the plate diminishes with increasing plate thickness. When the thickness is more than 16 mm, the shoulder dia must be more than 27 mm to avoid defects and enhance material flow. High heat input leads to poor FSW characteristics.

#### Joint Efficiencies of AA2219- T86 & T8 Condition

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