

## **Study of Microstructures and Mechanical Properties of Friction Stir Welded Pure Aluminum**

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### **ABSTRACT**

In this study commercially pure aluminum sheets were welded using friction stir welding (FSW) process. Three rotational speeds of 800, 1100 and 1500 rpm were used. The axial force, passing speed, and tool geometry were constant. Parameters were optimized depending on the results of the macrograph, micrographic, microhardness, and tensile strength. The results showed that the sound joint with the best possible microstructure and mechanical properties was obtained at a rotational speed of 1100 rpm. The microscopic and local mechanical properties proposed that mechanical mixing is the main material flow mechanism in the formation of the nugget zone (NZ).

**Keywords:** Friction stir welding; Microstructure; Heat affected zone ; Weld nugget.

الخلاصة:

في هذه الدراسة تمت عملية اللحام التحريك بين شريحتين من الالمنيوم التجاري النقي وابعاد ( 3 × 100 × 150 ) ملم. في عملية اللحام هذه تم استخدام ثلاث سرع دورانية وهي ( 800 و 1100 و 1500 دورة بالدقيقة). أثناء عملية اللحام تم تثبيت سرعة اللحام والقوة المسلطة وابعاد اداة اللحام. اختيار افضل العوامل المؤثرة على اللحام كانت على اساس فحص التركيب المجهرى وخواص الصلادة وقوة الشد. بينت النتائج ان اللحام بسرعة 1100 دورة بالدقيقة تعطي عينة بدون عيوب وافضل قيم للتركيب الجزئي والخواص الميكانيكية. الفحص الجزئي وتحليل الخواص الميكانيكية اثبتت بان الخلط الميكانيكي هي الميكانيكية الاساية لجريان المادة في تكوين منطقة الكتلة الصلبة.

### **NOMENCLATURE**

AS: Advancing Side

ASTM E3: American Standard Testing of Materials

BM: Base Metal

D: Tool shoulder diameter

d: Pin diameter

FSW: Friction Stir Welding

HAZ: Heat Affected Zones

NZ: Nugget Zone

RS: retreating side

Rt: Rotational speed

SSSW: Solid State Stir Welding

TIG: Tungsten Inert Gas

TMAZ: Thermomechanically Affected Zones

V: Welding traverse speed

## **1. INTRODUCTION**

Friction stir welding (FSW) is a solid state welding process in which the relative motion between the welding tool and the workpieces produces heat. This makes the material soft, and therefore it can be joined by plastic deformation diffusion. FSW has many advantages including low processing temperature, easy workpieces preparation, and it needs less shielding gases in the welds. FSW is a clean, environmental friendly and a non-harmful process as it is not accompanied by an arc formation, radiation and toxic gas emission [7]. This method relies on the direct conversion of mechanical energy to thermal energy forming the weld joint without any external source of heat [9]. This heat causes the latter to “soften” without reaching the melting point and allows traversing of the tool along the weld line [8]. The plasticised material is transferred from the leading edge of the tool to the trailing edge of the tool pin and is “forged” by the intimate contact of the tool shoulder and the pin profile. In FSW process, a non-consumable rotating tool is forced down into the joint line under conditions where the frictional heating is sufficient to raise the temperature of the workpieces where it can plastically deform and locally plasticizes. As the welding tool is moved along the welding direction, severe plastic deformation and flow of this plasticised material occurs. The side where the direction of rotational tool is the same as that of welding is called the advancing side (AS), whereas the other side designated as being the retreating side (RS). This difference in two sides can lead to asymmetry in material flow, heat transfer and the properties of the weld [9]. The schematic geometry of FSW process explained in **Fig. 1**.

There are two tool speeds to be considered in FSW; how fast the tool rotates and how quickly it traverses the interface. These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle. The relationship between the welding speeds and the heat input during welding is complex but, in general, it can be said that increasing the rotation speed or decreasing the traverse speed will result in a hotter weld. In order to produce a successful weld it is necessary that the material surrounding the tool is hot enough to enable the extensive plastic flow required and minimize the forces acting on the tool. If the material is too cold then voids or other flaws may be present in the stir zone and in extreme cases the tool may break. **Jayaraman et al. [4]** studied the effect of process parameters on FSW of cast LM6 aluminum alloy joints. They concluded that the tool rotation speed is the most significant variable since it tends to influence the transitional velocity. For a given welding speed and axial force, Adjusting the rotation speed of the tool leads to a

controlled stirring of the soft metal in the nugget zone and resulted in a smooth, non turbulent material flow. This prevents the formation of tunnel defect on the retreating side. However, the aim of this study is to examine the effect of rotational speeds of welding tool on the microstructures and mechanical properties of the welded joints.

## **2. EXPERIMENTAL WORK**

The material used in this study was commercially available pure aluminum. The plates with a thickness of 3 mm were sliced into the required size (210 × 200 mm) using a cutting band saw machine (MODEL: UE-712A). The chemical compositions of the base metal are presented in **Table 1**. The microstructure of the received base metal is shown in **Fig. 2**. The aluminum base metal has elongated grains in the rolling direction.

Test workpieces rigidly clamped on the backing plate in a butt-joint configuration parallel to the rolling direction of the plates. The surface of the plates was cleaned using acetone to remove dirt and grease. Three pairs of workpieces were friction stir welded by a vertical milling machine, type KAMA (X6325; 3Hp; TRPER R8; 30 KN). A non-consumable tool made of medium carbon steel was used to fabricate the joints which was heat-treated and quenched to 60HRC. The chemical compositions are listed in **Table 2**.

For the welding process, a tool with a smooth shoulder and cylindrical straight pin were used as shown in **Fig. 3**. During the FSW process, 5 KN friction pressure was exerted to ensure that the plates were in good contact. The single pass welding procedure was followed to fabricate the joints. The welding parameters and the tool dimensions are shown in **Table 3**.

The welded samples were prepared for microstructure analysis and mechanical properties evaluation. The specifications of the cutting, grinding and polishing were done according to the American Standard Testing of Materials (ASTM E3). The average Vickers microhardness tester was performed on a (FV-700E), load of 1 kgf and dwelling time of 15 sec. Finally, the FESEM technique was also employed primarily to study the fracture surface of tensile specimens. For the tensile tests, the FSW plates were cut perpendicularly to the tool traverse direction and the test was carried out via 50 KN, INSTRON-5569P7531 (Universal Testing Machine). The specimens were loaded at the rate of 1KN/min.

## **3. RESULTS AND DISCUSSION**

### **3.1 Results of Macrostructure and Microstructure**

The surface appearance of the FSW of similar aluminum using low rotational speed of 800 rpm was shown in **Fig. 4(a)**. The NZ was not well performed and the semicircular metal traces are observed in the stir zone. The opening line between the two welded strips is evident. As the heat generated by the pin and the shoulder is proportional to the rotational speed, however it is clear that the heat input was not sufficient to produce defect free of welded joint [1]. At the root of the aluminum plates it can be seen that the two strips were also not successfully joined as shown in **Fig. 4(b)**. This may be attributed to poor heat generation and to the non firm clamping of the butt jointed aluminum pairs.

At higher rotational speed of 1100 rpm the welded joint as shown in **Fig. 5 (a) and (b)**, explained that the surface morphology became smoother and free of defects, it reveals best possible weld surface as opposed to the welded joint conducted at 800 rpm.

**Fig. 6(a)** shows the surface morphology conducted at the highest utilized rotational speed (i.e. 1500 rpm), the surface shows onion rough rings like striated structure. The back side of the welded joint (**Fig. 6(b)**) showed some cracks. The cracks evolved as a result of the excessive heat generated by **Fig. 6** shows the microstructures of the welded joint taken at magnification 100x using the optical microscope. The microstructure which is characterized by the central welded joints represents the NZ. The material has been plastically deformed in this region which shows a combined action of a high strain rate at elevated temperatures by the FSW pin tool. The NZ is surrounded by a thermomechanically affected zone (TMAZ). It is suggested that this area is below the tool shoulder and the material in this part is plastically deformed without any dynamic recrystallization. The heat affected zone (HAZ) has modified the microstructure and the mechanical properties and fall between TMAZ and unaffected base metal (BM). Thus, there is no plastic deformation associated in this region and it has only a thermal cycle. BM is a remote material from the weld: an experimental perspective; it has a thermal cycle from the weld which is not affected by the heat in terms of microstructure or mechanical properties.

### 3.2 Mechanical Properties

#### 3.2.1 Microhardness Measurements

**Fig. 8** represents the microhardness of the FSW joint at a rotational speed of 1100 rpm. The figure shows that the microhardness of the HAZ and the NZ are lower than that of the BM. The difference in microhardness values between HAZ and NZ is attributed to the grain refinement in NZ due to the interaction of the pin with the material in this region, which leads to increase the microhardness according to **Eq. (1)**. This region experienced large plastic strain and the microstructure is highly refined as opposed to the BM. HAZ adjacent to the TMAZ experiences a thermal cycle and mechanical shearing stress. It is more appropriate to overcome or minimize the HAZ softening to improve the mechanical properties of the welding joints. The microhardness in the stir zone was increased slightly with the decrease in the grain size according to the *Hall-Petch Relationship* [3];

$$H_V = H_0 + K_H \cdot d^{-1/2} \quad (1)$$

Where  $H_V$  is the microhardness,  $H_0$  and  $K_H$  are the appropriate constants associated with the hardness measurements. It was observed that the microhardness of the stir zone increased with the decreased in the friction heat flow because the grain size in the stir zone decreases when the friction heat flow is decreased.

As seen in **Fig. 8**, the traverse Vickers microhardness is not uniform distribution across the stir zone. It can be observed that the microhardness of the BM is higher than HAZ, TMAZ and NZ, while the microhardness at the NZ is a relatively higher than that of the HAZ and TMAZ. This is attributed to the refining of the grain size in this region as mentioned previously in **Eq. (1)**.

#### 3.2.2 Tensile Test

Tensile test was carried out for all specimens. **Fig. 9** shows the tensile stress and strain curves at rotational speed of 1100 rpm. The figure shows that the tensile strength of the welded line was higher than that of 800 and 1500 rpm, due to the best possible parameter of rotational speed. The tensile strength of the specimen welded at rotational speed of 1500 rpm showed lower strength due to excess of frictional heat generation. Similar result was observed when there is insufficient heat generation.

## **CONCLUSION**

In this study, workpieces of pure Aluminum were welded successfully by FSW technique. Microstructure and mechanical properties including tensile strength and microhardness behavior were studied and the following findings were achieved:

1. Four different regions were distinguished in Al-Al FSW process; NZ, TMAZ, HAZ and the BM.
2. Controlling the welding parameters particularly the rotational speeds and the pin shape leads to defect free of the welding joint.
3. It was found that there is an improvement of Vickers microhardness in the NZ due to further grain refinement and optimum amount of heat generation. For the same reasons the tensile strength results showed higher than that of BM when the joint fabricated at 1100 rpm.
4. Rotational speed of 1100 rpm showed no sign of surface defect such as porosities, cracks and inclusions due to effective stirring action of the pin and best possible of heat generated.

## **Acknowledgement**

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**Table 1** Chemical compositions of the commercial pure Al

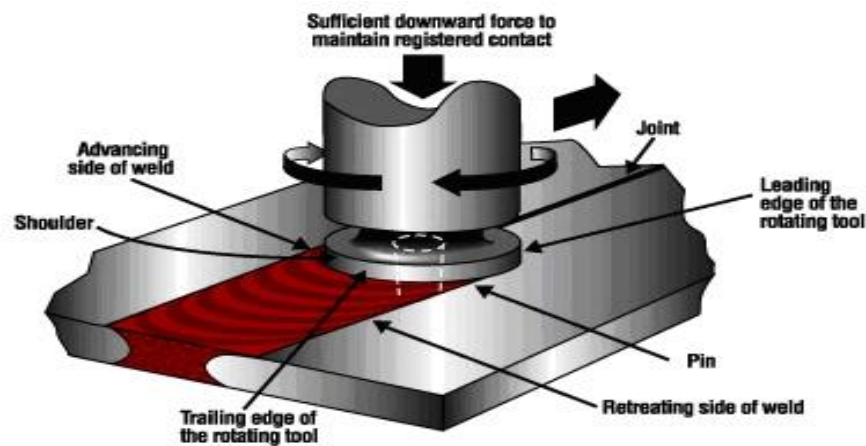
Element	Al	Si	Fe	Mg	Cu	Mn
wt %	Balance	0.114	0.405	0.032	0.08	0.011

**Table 2** Chemical compositions of the welding tool

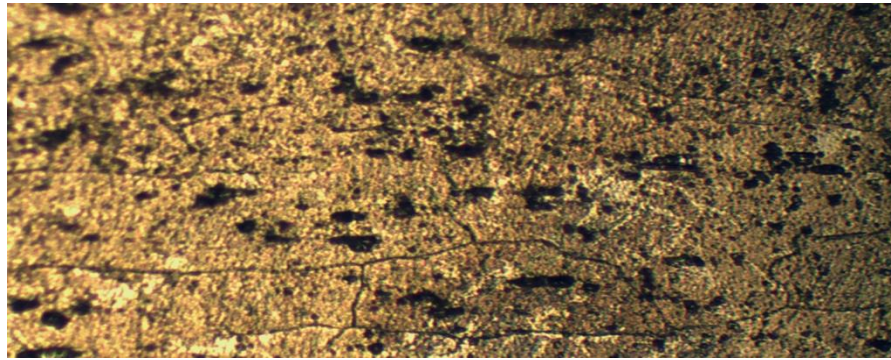
Element	C	Mn	P	Fe
wt %	0.56	0.69	0.02	Balance

**Table 3:** Welding parameters and tool dimensions

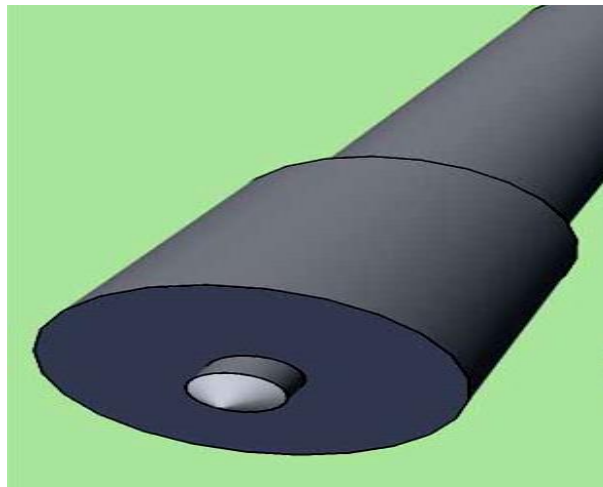
Process parameters	Values
Rotational speed $R_r$ (rpm)	800 , 1100 , 1500
Welding traverse speed $V$ (mm/min)	40
Axial force (KN)	5.0
Pin length (mm)	2.5
Tool shoulder diameter D (mm)	12
Pin diameter, d (mm)	3



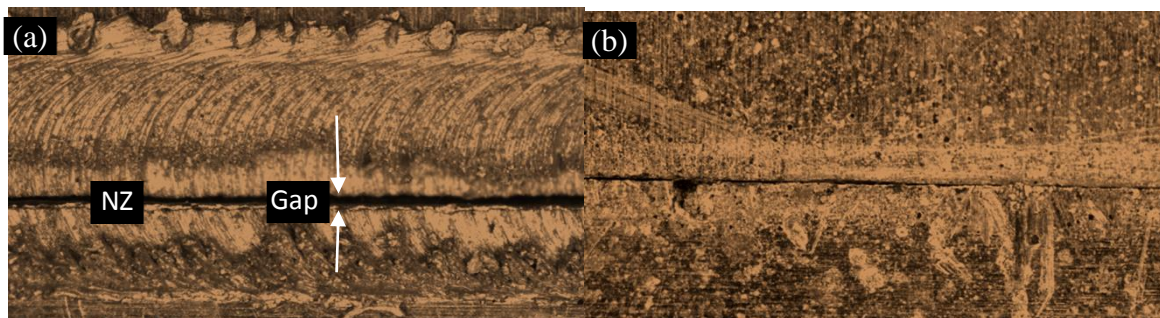
**Figure 1:** Schematic diagram of the FSW process.



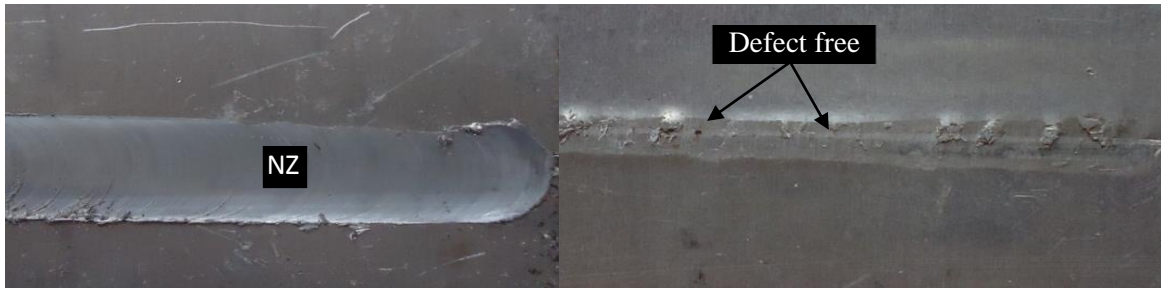
**Figure 2:** Microstructure of the aluminum base metal.



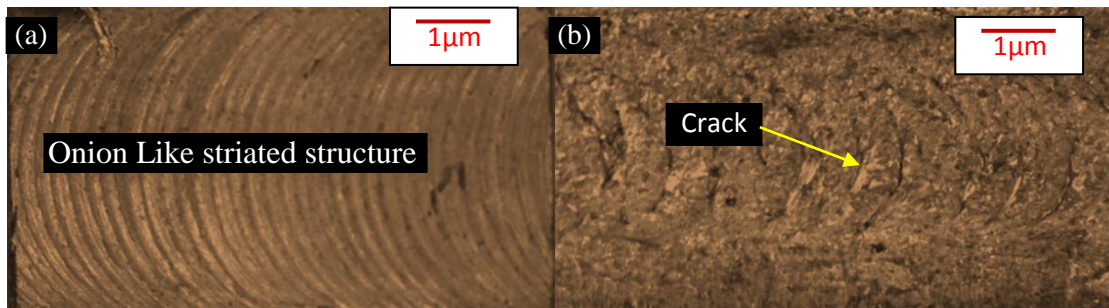
**Figure 3:**The welding tool configuration.



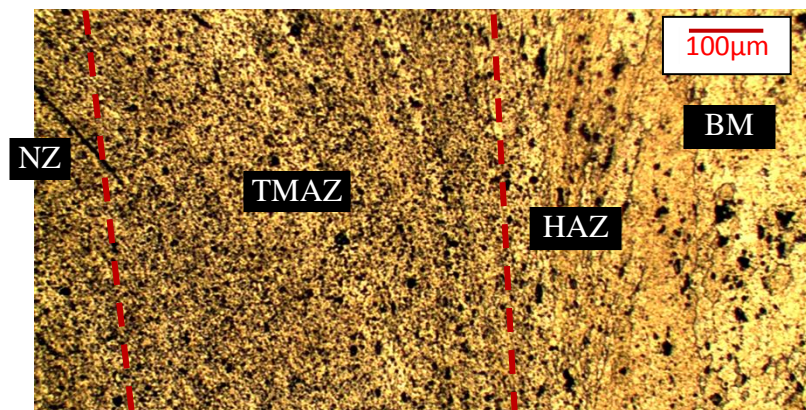
**Figure 4:** (a) Front view and (b) Back view of the AL-AL strips conducted at rotational speed of 800 rpm.



**Figure 5:** (a) Front view and (b) Back view of the AL-AL strips conducted at rotational speed of 1100 rpm.



**Figure 6:** (a) Front view and (b) back view of the AL-AL strips conducted at the highest rotational speed of 1500 rpm.



**Figure 7:** Microstructures regions after FSW process.



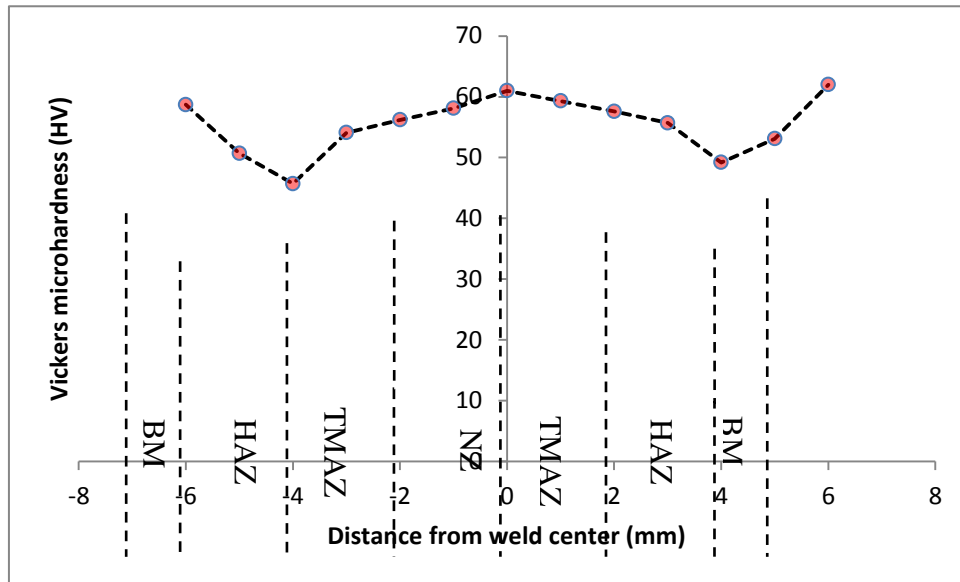


Figure 8: Transverse Vickers microhardness profile for the AL- AL at a rotational speed of 1100 rpm.

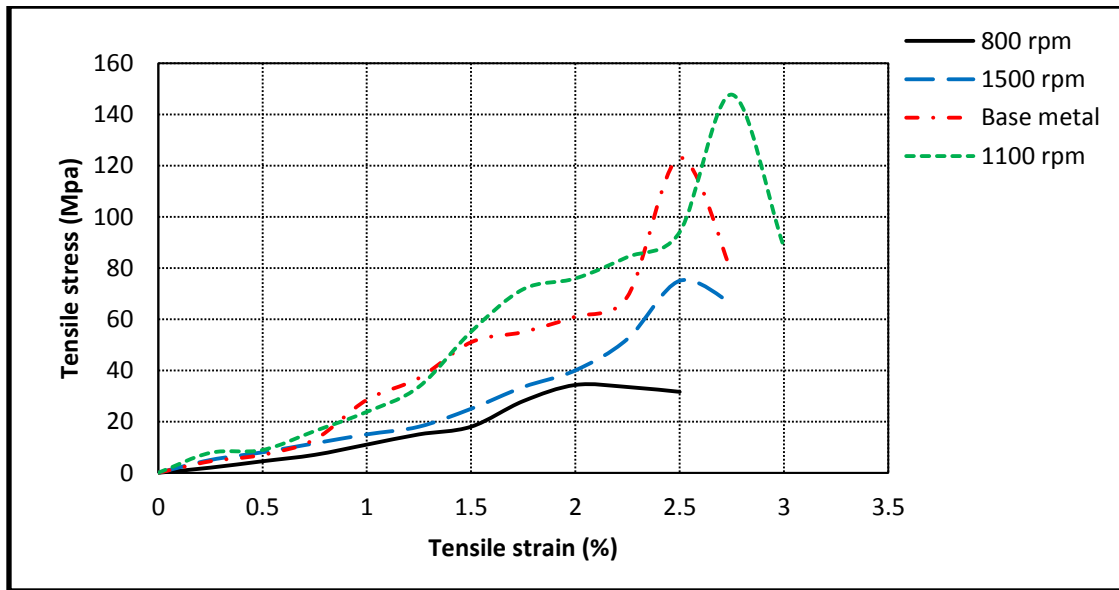


Figure .9: Tensile stress and strain of the welded joints and base metal.