# CHARACTERISTICS OF FRICTION STIR WELDS IN AA 5083 AND AA 6082 ALUMINIUM

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**ABSTRACT** The microstructure and hardness of friction stir welded AA 5083 and AA 6082 aluminium have been studied and correlated to weld strength. A typical "annual ring" feature was seen in the central, recrystallized, equiaxed weld nugget zone in both materials. The microstructure and hardness in rings did not differ from that in between rings and the fracture path was not correlated to the ring pattern in transverse tensile testing. Most likely the nugget zone ring pattern is due to periodic variations in crystallographic orientation of grains, or relative orientation of adjacent grains. Hardness varied little across the weld in AA 5083 whereas a marked minimum was seen in the thermomechanically affected zone in AA 6082, which was clearly the weakest region.

**Keywords:** *Friction Stir Welding, Aluminium, Microstructure, Hardness, Strength*

## 1. INTRODUCTION

Friction Stir Welding (FSW) is an exciting, recently introduced method, particularly suited for joining aluminium alloys. The components to be joined are placed on a backing plate and clamped using a powerful fixture. A rotating tool, consisting of a specially profiled pin with a shoulder, is forced down into the material until the shoulder meets the surface of the material. The material is thereby frictionally heated to temperatures where it is easily plasticised. As the tool is moved forward, material is forced to flow from the leading to the trailing face of the pin.

The technique was developed at TWI in the beginning of the 1990's [1] and processing technologies have been further developed by Esab AB [2]. The first installation has been used successfully for more than one year for joining, up to 6m by 16m, long plate and panels, mainly in AA 5083 and AA 6082 aluminium [2]. Although practical application of the FSW technique has been successful, there is still a lack of design data and understanding of failure mechanisms. Furthermore, as pointed out in a recent summary, much of the microstructural knowledge about friction stir welds is in its embryonic state [3].

An earlier paper comparing microstructures and properties of friction stir welds to those of MIG welds in AA 5083 and AA 6082 aluminium described features of FSW joints not found in fusion welds [4]. The most obvious feature in a cross section is the, usually asymmetric, "nugget" at the centre of a friction stir weld. This contains a well defined "annual ring" structure (or "onion ring" structure [3]) typically consisting of concentric ovals. Immediately adjacent to the nugget is the plastically deformed and heat affected so called "thermomechanically affected zone" [3]. Further away from the nugget, there is a "thermally affected zone", which only has been affected by the heat flow [3]. An age-hardened alloy will show a decrease in hardness in the weld zone, while an annealed alloy will be virtually unaffected [5]. However, a detailed knowledge of the metallurgical processes in the various zones is still basically lacking [3, 5].

The present investigation focus on FSW of AA 5083 and AA 6082 aluminium alloys with primary purpose to better understand the formation and influence of features typical of friction stir welds. Results of a detailed metallographic investigation, including hardness measurements, are presented and correlated to macroscopical mechanical properties (see also [5, 6]).

## 2. EXPERIMENTAL

### 2.1 Welding and materials

Friction stir welds were produced in AA 5083 and AA 6082 aluminium using different combinations of plate thicknesses and welding speeds according to Table 1.

Table 1 Plate thickness and welding speed for friction stir welds.

| Alloy | AA 5083 | | | | | AA 6082 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Plate thickness (mm) | 15 | 10 | 10 | 6 | 6 | 10 | 10 | 5 | 5 |
| Welding speed (cm/min) | 4.6 | 6.6 | 9.2 | 9.2 | 13.2 | 26.4 | 37.4 | 53 | 75 |

Alloy AA 5083 is a non heat treatable Al-Mg alloy (4.6%Mg, 0.6%Mn, 0.3%Si) with good corrosion resistance, commonly used in sea water applications. AA 6082 aluminium is alloyed with Mg and Si (0.7%Mg, 0.5%Mn, 0.9%Si) and age hardens by formation of $Mg_2Si$ precipitates.

### 2.2 Microstructural studies

The most thorough microstructural investigation was carried out on the 5 mm AA 6082 welded at 75 cm/min, and on the 6 mm AA 5083, welded at 13.2 cm/min. Overviews of the microstructure were obtained by light optical microscopy (LOM) whereas scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used for the more detailed studies.

### 2.3 Hardness measurements and mechanical testing

A detailed hardness assessment was made on the two welds subjected to an in depth microstructural study. The hardness (HV1) was measured horizontally and vertically through the centre of the nugget, on cross sections. Detailed microhardness measurements (HV25g) were made to clarify whether any hardness differences existed between the ring pattern and locations in between rings. The accuracy was estimated to 2 - 3 units for HV1 and 4 - 6 units for HV25g.

Transverse tensile testing of the welds was also made and the location of the fracture relative to the weld centre was examined.

## 3. RESULTS

### 3.1 Microstructure

Macrographs in Figures 1 and 2 show one weld in AA 5083 and one in AA 6082, respectively, in three perpendicular sections. The cross sections (Figs. 1a and 2a) illustrate that the overall shape of the nugget is very variable, depending on the alloy used and the precise process conditions. However, a common feature is the central "ring structure" and the more well defined nugget boundary on the side (to the right in Figs. 1a and 2a) where the tool travel and rotation direction coincides. Appendages to the nugget, extending to the edge of the tool shoulder on the upper surface, can also be seen on this side of the nugget. The complex shape of the nugget and the "ring structure" is evident also in sections parallel to the top surface (Figs. 1b and 2b) and in longitudinal sections parallel to the original joint face (Figs. 1c and 2c). However, it should be born in mind that the appearance of the "ring structure" in these sections is dependent on the precise location of the section.

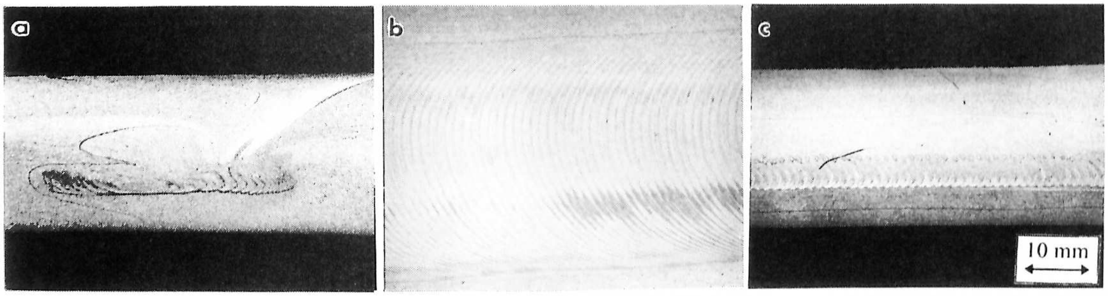



Figure 1 Macrographs showing the appearance of a friction stir weld in 6 mm AA 5083, welded at 13.2 cm/min. The nugget zone ring pattern is clearly seen in all three perpendicular sections.
a) Cross section.
b) Section parallel to the top surface just below the centre of the nugget region.
c) Longitudinal section to the left (in Fig. 1a) of the original joint face.

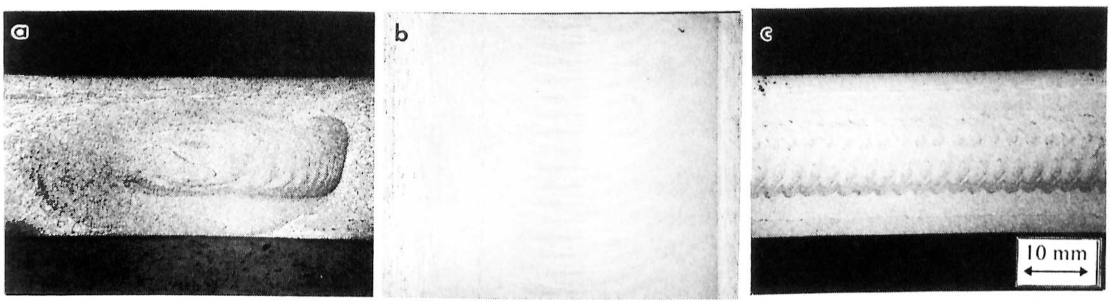



Figure 2 Sections of a friction stir weld in 5 mm AA 6082, welded at 75 cm/min. The macrographs show the nugget zone ring pattern in three perpendicular sections.
a) Cross section.
b) Section parallel to the top surface just below the centre of the nugget region.
c) Longitudinal section to the left (in Fig. 2a) of the original joint face.

The microstructure of the 6 mm AA 5083 material was homogeneous with grains elongated in the rolling direction. Typical grain sizes were 30 μm along the rolling direction and 20 μm across. In AA 6082, the grain size was inhomogeneous (Fig. 3a), due to partial recrystallization. Recrystallized grains were about 10 μm in size whereas non recrystallized grains varied in size typically between 50 μm and 150 μm.

Recrystallization of the nugget zone during friction stir welding effectively wiped out any trace of the previous grain structure. The nugget zone in both materials consisted of fine, equiaxed grains with a grain size of about 10 μm (Fig. 3b). The transition between the nugget and the thermomechanically affected zone was clearly visible in the AA 6082 alloy as seen in Fig. 3c. This figure also illustrates that the "ring contrast" is not due to grain size differences. The contrast instead seem to be related to variations in grain orientation and possibly to the degree of relative misorientation between adjacent grains.

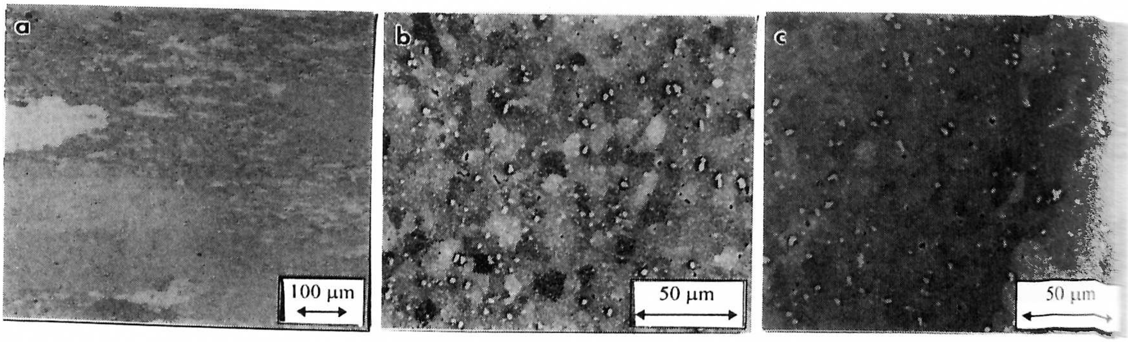



Figure 3 SEM backscattered electron images of weld zone and base material in AA 608
a) Base material. b) Equiaxed grains in the nugget region.
c) Transition between the thermomechanically affected zone (right) and the nugget zone. Note the similar grain size of the "border ring" and the interior of the nugget.

The general observations made by LOM for the AA 6082 alloy were confirmed by TEM. The grain size was larger and the dislocation density was higher in the base material than in the nugget zone (Fig. 4).


Figure 4 TEM micrograph showing the low dislocation density in the nugget zone of friction stir welded AA 6082.

### 3.2 Hardness

The hardness of unaffected base material was approximately 75 HV1 and was practically constant across the weld, both horizontally and vertically, in AA 5083 (Fig. 5).

The horizontal hardness profile across the weld in AA 6082 (Fig. 6) had a significantly different appearance. Unaffected base material is harder (about 110 HV1) and there is a decrease in hardness towards the weld, with a minimum of about 60-65 HV1 in the thermomechanically affected zone. The hardness of the nugget zone itself is typically 70-75 HV1. A slight tendency of decreasing hardness towards the top surface of the weld was noted at the centre of the weld. The location of isohardness curves, corresponding to 85 HV1, approximately corresponds with the width of the tool shoulder at the top side, and becomes more narrow towards the root side.

Microhardness measurements (HV25g) across the nugget zone in AA 6082 did not show any systematic variations that could be correlated to the ring pattern (see also [5]). Neither did measurements in rings and in between rings (Fig. 7) reveal any differences in hardness.

### 3.3 Mechanical properties

There is a considerable difference in transverse strength of friction stir welds in the two alloys (Table 2). The transverse strength was between 303 and 344 MPa for AA 5083 while AA 6082 had a transverse strength in the range 226 to 254 MPa.

An interesting pattern was found when examining the location of the fracture. For welds in AA 5083, fracture in most cases was close to the centre of the weld and the fracture surface in general

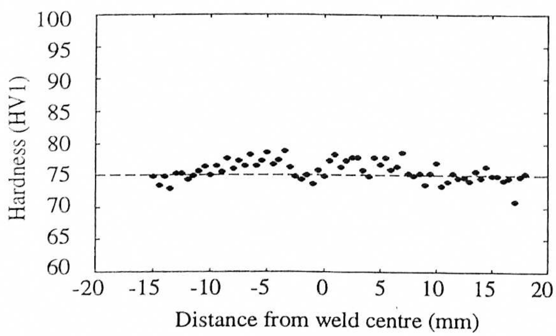



Figure 5 Horizontal hardness profile across friction stir weld in AA 5083 measured 1.7 mm from the root face.

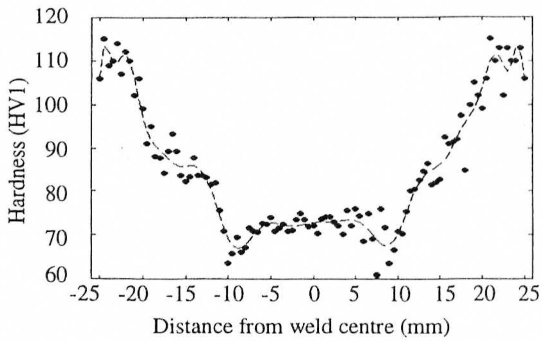



Figure 6 Hardness profile across friction stir weld in AA 6082. The profile was measured 2.5 mm from the root face and shows hardness minima in the thermo-mechanically affected zone.

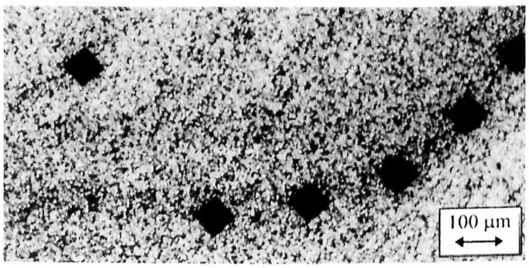
Table 2 Transverse tensile properties of friction stir welds.

| Alloy | AA 5083 | | | | | AA 6082 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Plate thickness (mm) | 15 | 10 | 10 | 6 | 6 | 10 | 10 | 5 | 5 |
| Welding speed (cm/min) | 4.6 | 6.6 | 9.2 | 9.2 | 13.2 | 26.4 | 37.4 | 53 | 75 |
| Tensile strength (MPa) | 318 | 344 | 331 | 312 | 303 | 226 | 236 | 254 | 254 |

was inclined about 45°. The fracture surface was close to the centre of the weld on the root side but the original joint line never appeared to be the initiation point.

In AA 6082, the fracture with few exceptions was close to where the outer edge of the tool shoulder had touched the top side. The fracture surface was inclined with the fracture surface closer to the weld centre at the root side, but still displaced a few mm.

Figure 7 Microhardness indentations illustrating the similar hardness of the microstructure in rings and in between rings in the nugget zone of friction stir welded AA 6082.




## 4. DISCUSSION

### 4.1 Microstructure

Special attention was paid to the annual rings seen in the nugget zone. A similar pattern has previously been observed in pulsed-TIG welded aluminium. This ring pattern is due to varying grain size caused by a periodically changing cooling rate. However, no difference in grain size was noted between rings and areas in between rings in friction stir welds (Fig. 3c). Neither was any difference in particle distribution detected [6]. The absence of hardness differences between rings and areas in between rings also supports the assumption that the ring structure is not connected to precipitation. A likely explanation, therefore, is that the movement of the rotating, profiled pin-tool through the material result in periodic variations in straining. This produce variations in grain orientation, or in the relative orientation of adjacent grains, resulting in differences in etching response. However, further investigations are needed to verify this hypothesis.

### 4.2 Hardness distribution

Hardness of annealed AA 5083 is affected marginally by friction stir welding (Fig. 5 and [3]). However, the marked hardness decrease in the thermomechanically affected zone in AA 6082 (Fig. 6 and [7]) is most likely due to local overaging. A significant effect of variations in dislocation density is not expected, as illustrated by the small hardness variation in AA 5083 welds.

Andersson et al [7] present temperature cycles for 4 mm thick AA 6063 aluminium friction stir welded at 50 cm/min. The temperature cycles experienced by the 5 mm AA 6082, welded at 75 cm/min, will naturally differ somewhat from those presented in reference [7]. However, the central region of the weld will clearly reach temperatures sufficient for dissolution of hardening precipitates. The measurements also show that a region, some 5-10 mm, from the original joint line will be subjected to temperatures where overaging occurs rapidly.

### 4.3 Mechanical properties

Welded AA 5083 had a tensile strength close to that of material in annealed condition whereas the AA 6082 weld strength was between those typical of cold aged and heat treated material. From measured strength levels it would, therefore, be expected that fracture should occur in the "most annealed region" in AA 5083 welds. This is in good agreement with the fracture usually taking place in the fully annealed, equiaxed microstructure in the centre of the nugget zone.

It was difficult to predict where to expect fracture in AA 6082 from strength comparisons. However, there was a clear correlation between fracture path and the measured line of lowest hardness.

## 5. CONCLUSIONS

- The microstructure and hardness in rings, inside the nugget zone of friction stir welds, did not differ from the that in between rings.
- Most likely the nugget zone ring pattern is an effect of periodic differences in crystallographic orientation of grains, or varying relative orientation of adjacent grains.
- The hardness varied little across the weld in AA 5083 whereas a marked minimum was seen in the thermomechanically affected zone in AA 6082.
- Fracture in tensile specimens coincided with the line of lowest hardness for AA 6082 and was located to the nugget zone for AA 5083. The fracture path was not related to the ring pattern.

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