Fatigue and Fracture Behaviours of FSW and FSP Joints of AA5083-H111 Aluminium Alloy

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Abstract. This research study's the fatigue behaviour of friction stir welded (FSW) and friction stir processed (FSP) joints for joining AA5083-H111 aluminium alloy. The Joining has been implemented on 3mm thickness. Fatigue properties of the welded joints were evaluated based on the superior tensile properties for FSW at 1500 rpm and a feeding speed of 20 mm/min. the FSP was at 1500 rpm and a feeding speed of 40 mm/min. Fatigue alternating bending test was performed at a constant stress amplitude cantilever with fully reversed (R~1). The fracture surface topography was also analyzed by the aid of an electron microscope. The experimental fatigue properties for base, FSW & FSP welds of AA 5083-H111 aluminium alloy that were obtained from the experimental work showed that all the tested samples of FSP displayed good fatigue behaviour and better fatigue properties near to base material than what the FSW were. The endurance limits were 81 MPa and 71 MPa for FSP and FSW joints respectively and 87 MPa for base metal.

1. Introduction
AA5083 Aluminium alloy were used in the shipbuilding manufacture for more than fifty years [1]. Due to its high corrosion resistivity and strength at sea water, and its high fracture toughness at very low temperatures, they are easily welded by a different of welding techniques [2]. 5083 alloy application not limited ship building but also find wide variety of application such a Superstructure, construction pressure vessels, Tank cars, Structural beams, Hull material, Off-shore stations, tanks, Coal cars, Cryogenic tankage, where most of this application is considered static load [3]. Also, 5083 alloy is used with ferries which designed for high speed where its consideration dynamic load [4].

Fatigue life of friction stir welded 5083 aluminium alloy has been investigated in many of previous researches [5], and the influence of a friction stir processed (re weld) on the fatigue properties of the welded condition is very important issue to be study. The aim of this work is to understand the mechanisms involved in fatigue and crack initiation of welded AA 5083 joined by friction stir welding and friction stir processing. For this purpose, base material of AA5083-H111 was tested as a reference condition. After this the separate influence of friction stir welding and friction stir processing on the material was investigated. Then, the welded plates were tested using fatigue test device and the different fracture initiation mechanisms were compared.

Friction stir welding FSW and Friction stir processing FSP are joining of metals without fusion or filler materials by using rotating tool (non-consumable) which plunges into a strongly clamped workpiece and travel in linear motion along the joint line to be welded [6] as illustrated in Figure 1.
L. Svensson et al [9] found in most FSW 5083 specimens the initiation of the fatigue fracture was in the base metal, or in the welding zone. While a few specimens, and most specimens showed good fatigue behaviour. C. Zhou et al (2005) [10] FSW and double sided MIG -plus welds of 10 mm thickness of AA5083 aluminium alloy where found that the fatigue life of FS welded AA5083 is longer than MIG approximately by 9–12 times and the evaluated fatigue properties values of FS welds were 67.3 MPa while 39.8 MPa MIG pulse welds was 39.8 MPa. Failed samples, there cracks initiated at the root surface of the weldments, due to imperfection in the weld. K. Sangshik et al (2008) [11] studied the fatigue crack propagation (FCP) behaviour of FSW AA5083-H32 and AA6061-T651 and it was concluded that fatigue crack propagation of FSW samples at the WZ was lower the crack propagation in the base metal due to the action of residual stress on the FSW zone when the later presence in front of fatigue crack propagation that lead to retards the propagation that is occurring when ΔK fatigue tests either perpendicular or 45° and when the R ratio of 0.1

This study included study the effect of friction stir welding and friction stir processing on the fatigue properties and fracture behaviour of AA5083 aluminium alloy.

2. Experimental work

2.1 The Materials

Aluminium alloy of type’s 5083-H111 (Al-Mg) alloy with 3mm (0.118 in) thick was used in this work, the mechanical properties compared with standard is listed in Table 1 and the chemical composition analysis compared with standard composition is listed in Table 2.

| Table 1.Mechanical properties of AA5083-H111 aluminium alloy |
|-------------------------------------------------------------|
| YIELD STRESS (MPa) | Ultimate Tensile Stress (MPa) | Modulus of Elasticity (GPa) | Elongation (%) |
| Data Sheet Value [12] | 145 | 300 | 72 | 23 |
| Actual Value | 143 | 300 | 72.9 | 27 |
Table 2. Chemical Composition of AA-5083 H111 aluminium alloy

|       | Si   | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Al  |
|-------|------|-----|-----|-----|-----|-----|-----|-----|-----|
|       | 0.4-0.7 | 0.4 | 0.1 | 4-4.1 | 0.05-0.25 | 0.25 | 0.15 | BAL. |     |
| Actual value | 0.12 | 0.33 | 0.05 | 0.48 | 4.14 | 0.06 | 0.1 | 0.02 | BAL. |

2.2 Welding Tools

The pin of the tool was taper cylindrical and made of x38 tool steel was as shown in Figure 2. The welding tool was accomplished at MITSUBISHI CNC M70V milling machine.

![Figure 2. Tool shape and dimension](image)

2.3 Process Parameters

The friction stir welding was performed by using MITSUBISHI CNC M70V milling machine. The weld process parameters were, Rotation Speed of 1500 RPM, Welding Speed of 20 mm/min for FSW, while for FSP rotational speed 1500 RPM, travel speed of 40 mm/min.

2.4 Specimen test Preparation

The preparation of fatigue and tensile test specimens were carried out by using a CNC milling machine as follow: First, tensile test specimen geometry prepared according to the standard ASTM E8M-04, while fatigue specimen dimensions according to the machine standard were L (length) × W (width) × T (thickness) = 90×10×3 mm respectively as showing in Figure 3.

2.5 Inspections and Tests

2.5.1 Mechanical Tests. Tensile test was carried out on samples taken in a perpendicular direction to the welding line to determine the tensile properties of the welding joints for both welding processes. All tensile tests were performed at 25° C by TESTOMETRIC instruments, which has a maximum capacity of (25kN). Then the average of three samples (Start, middle and end welding line) was transferred to evaluate the tensile properties of each welded joint.

Microhardness testing of the welded joints was done by Vickers hardness device. Microhardness measurements were taken along the centreline of the surface and cross section of the welded line using diamond pyramid indenter with a load of 200 g within 15 sec according to ASTM-E384. The sample was grinded and polished before the test (according to ASTM-E3 explained in last section) to provide a suitable flat surface. Microhardness profile is taken on the surface with two axes at intervals of 2 mm between the neighbouring measurements to evaluate the microstructural changes taken in both welding processes.

Fatigue tests were done under alternating bending loading by using HI-TECH alternating bending instrument with constant amplitude with constant amplitude, stress ratio R = -1 in laboratory air. Two tested samples were done at each load condition. Specimens were cut at direction perpendicular to the weld line of friction stir welded and processed plate to perform the test. A fatigue limit of over 2×10⁶ for FSW and 3×10⁶ cycles for FSP and base metal was considered a run-out test.
The relationship between stress amplitude and number of cycles was acquired for the FSW and FSP aluminium alloys and compared with base metal. After fracture, the initiation sites were analysed by means of Scanning Electron Microscopy SEM.

![Figure 3](image)

**Figure 3.** a) Tensile test specimen dimension geometry according to ASTM E8M-04  b) fatigue test specimen all dimensions in mm

### 3. Result and Discussion

#### 3.1 Tensile Test Results

Tensile test was done for friction stir welded and friction stir processed 5083-H111 Al-alloys at the best welding parameters that give maximum welding efficiency of about 92% for FSW and 94% for FSP (comparing with base metal), as illustrated in Table 3.

| Material   | Yield stress MPa | Ultimate stress MPa | Elongation % |
|------------|------------------|----------------------|--------------|
| AA5083-H111| 143              | 300                  | 27           |
| FSW        | 143              | 276                  | 12           |
| FSP        | 144              | 284                  | 22           |

#### 3.2 Microhardness Test Results

Figure 4, the result illustrating an essentially fluctuation line with variation in hardness across the nugget into the HAZ following FSW and FSP. The hardness profile show a slight increase in hardness compared to base metal (base metal hardness = 75.7HV). This hardness increase due to the very fine grain size created by FSW and FSP. This is evidence that AA5083-H111 is not affected by the heat treatment; the increase in its hardness value is due to the work hardened effect.
Figure 4. Microhardness distribution across FS weld and processed line

The value of hardness at FS welded zone was higher than that of the base metal alloy. Due to the grain size at the stir zone is finer than the base metal, where grain refinement was an important point in material strengthening, so that when the grain size decreases the hardness increases. And, the hardness improvement also effect by fine particles of intermetallic compounds and precipitation of hardening phases according to the hardening mechanism. These results are confirmed by other researchers [14], [15].

3.3 Fatigue Test Results

The constant amplitude fatigue results of AA 5083-H111 aluminium alloy were shown as S-N curves of the best results of friction stir welding and processing and were compared with the fatigue behaviour of the base metal.

The fatigue specimens were either tested to failure at or near to 3x10^6 cycles. Fatigue results were done and the following results gained are given in Table 4 also Life equation and endurance limit of AA 5083-H111 Aluminium alloy are shown in Table 5.

Typical S–N curves (high fatigue cycle) for base metal, FSP weld, and FSW welding of Al 5083-H111 are shown in Figure 5. The fatigue properties of FSP weldments are presented and compared with those of FSW welding, and base metal. All the tested samples of FSP showed good fatigue behaviour and better fatigue properties near to base material AA 5083 than FSW fatigue behaviour.

Table 4. S-N data results for base metal and friction stir processing and welding process

| Stress (MPa) | AA 5083-H111 base | AA 5083-H111 as welded by FSP | AA 5083-H111 as welded by FSW |
|--------------|--------------------|--------------------------------|--------------------------------|
|              | No. of cycles (cycle) | Stress (MPa) | No. of cycles (cycle) | Stress (MPa) | No. of cycles (cycle) |
| 60           | 3620500 *           | 60             | 3000000 *           | 60             | 2567543 *             |
| 82           | 2430155 *           | 82             | 2250000 *           | 77             | 1753144               |
| 100          | 1805189             | 110            | 1104560             | 99             | 1062115               |
| 121          | 774079              | 121            | 476523              | 110            | 326866                |
| 140          | 477079              | 140            | 346630              | 121            | 154529                |
| 151          | 234739              | 150            | 139332              | 140            | 100182                |

*Not failure
The endurance limit of FSP weld at $2 \times 10^6$ cycles was lower than that of the base metal but upper then FSW. FSW/P process will inherently produce a weld with relatively few residual stresses and distortions and finer and uniform microstructure leads to good fatigue behaviour as compared to base metal.

From measured strength levels it would therefore be expected that fracture would occur in the weld region. This is in good agreement with the metal, equiaxed microstructure in the centre of the nugget zone where the fracture initiation because the stress concentration and residual stress bigger at this region where specimens fixed, crack either propagate in same region (direction) or the crack may impact with plastic region therefore which lead to change the direction to the weaker region.

### 3.4 Fracture Characterization by Scanning Microscopy

Figure 6. shows the flat fatigue fracture surface for base alloy 5083-H111 from fatigue cracks growing orthogonal to the stress concentration area (at fixing area of the cantilever) at stress 100 MPa and number of cycle to fail $1.8 \times 10^6$ cycles. It can be seen from the photograph pictures b and c a main crack that starts from the corner or edge of specimen surface that due to stress concentration is considered as stress raiser on the defects on the sample corners/edges which are less smooth compared with the machined side surfaces of the sample. These stress concentrations are resulted in the cracks initiated either from the matrix or from the debonding of the coarse second phase particles that are not uniformly distributed in the matrix. Also, there are pockets of striation like features that indicate to micro plastic deformation. Photograph pictures (d) show some striation and dimples had been noticed where fracture in this sample look like ductile fracture, while photograph pictures (e and f) appears the final fracture area but in photograph (f) a white zone which is inclined zone.
Figure 6. SEM fractographs of AA5083-H111 specimens for medium load 100 MPa), Nf: 1.8×10⁶ cycles

Figure 7. shows the fractography of FSW joint AA5083-H111 which is fractured at high fatigue loading 140 MPa, and number of cycle to fail (Nf) of 1×10⁵ cycles. This figure shows three zones; lower (narrow zone of plastically deformed zone) due to the FSW tool shoulder pressure, then (fatigue) zone which appears flat and an upper (final) fast fracture, in the middle of specimens appears the curved Trans granular fracture. It can be seen from the photograph picture (b) two zones; fatigue and final fracture zones, while photograph (c) shows the presence of some grooves in final fracture. The lower zone represents crack initiation zone as seen in photography d, while photography e and f shows the same zone but with higher magnification which shows a crack that may resulted from void coalitions due to shoulder load.

Figure 8. a show the fatigue fractography of sample has FSP weld under medium stress of 110 MPa with number of cycles to fail of 1.1×10⁶ cycles, the topography of fracture surface which looks like a combination of two fatigue zone of fracture; upper and lower crack initiation. Photograph b shows the lower crack initiation and fatigue area as shown in photography c with higher magnification while d represents upper crack initiation area and these two cracks growth and joint in meddle of specimens as shown photograph e, while photograph f shows the same zone but with higher magnification which appears a micro cracks and striations as mentioned in Ref. [17].
Figure 7. SEM fractographs of FSW AA5083-H111 specimens for high load 140 MPa, Nf: $1 \times 10^5$ cycles.

Figure 8. SEM fractographs of FSP AA5083-H111 specimens for high load 110 MPa, Nf: $1.1 \times 10^6$ cycles.
4. Conclusion
The joining of AA5083-H111 aluminum alloys by friction stir welding and friction stir processing were successful and the joint efficiency reached 92% and 94% for FSW and FSP respectively. Deep analysis of the specimens' fractured surface showed a step formation at the end of the propagation stage. Fatigue properties in FSP were better than FSW where it is near to the base metal more than FSW. From S-N curve the fatigue limit of baseis 87 while in FSP and FSW are 81 and 71 respectively. Fractography analysis of fatigue fracture surface shows that some welds failed with cleavage fracture type while in most cases especially for high joint efficiency the fracture was of ductile type and micro void coalescence was the dominant mechanism in FS welds. The value of the FS welded zone hardness is higher than that of the base metal 5083-H111.

5. References
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