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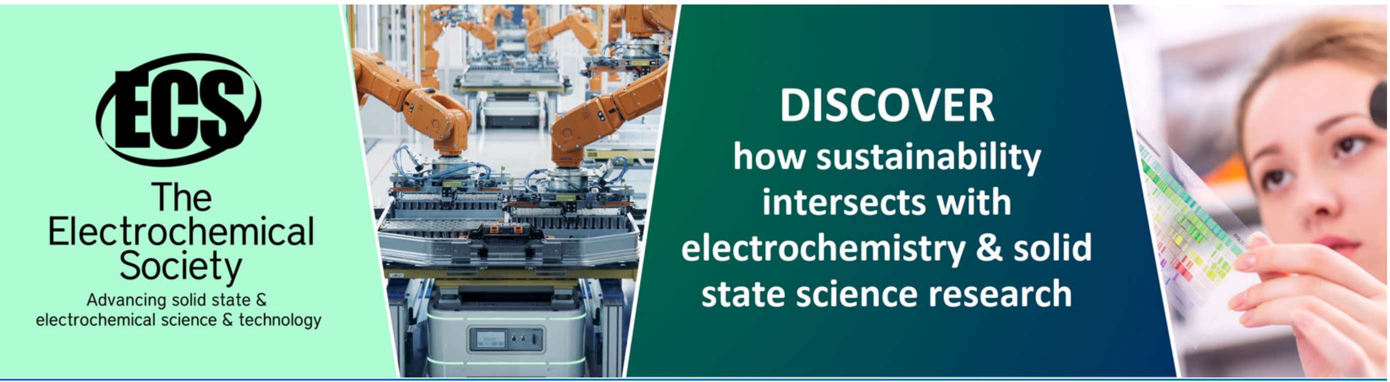

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Analysis of fatigue properties in similar friction stir welding joints of aluminum alloy (AA5086-H32)

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Abstract. Similar aluminum alloys (AA5086-H32 with AA5086-H32) were welded by friction stir welding (FSW) using three different values of linear speeds; namely 50, 75 and 90 mm/min.and different and rotating speed namely 680, 920 and 1500 rpm. Tensile test was used to determine the joint efficiency of welded samples. The microstructure, hardness, tensile tests and fatigue properties were studied for the welded sample which gave the highest tensile strength. The fatigue test was carried out at a constant stress amplitude cantilever fully reversed(R=-1) in the stir zone of weld and nearby zone or region at a distance of 5, 10 and 15 mm from the welding line. The fracture fatigue surface was analyzed using SEM. It was found that the maximum joint efficiency of 80% was obtained at rotating speed of 680 RPM and linear speed of 75 mm/min. The maximum value of hardness was at the stir zone center of the weld and started to decrease away from it. Fatigue strength of the FSW welded samples was less than the parent or base alloy.

Keywords: Frictions stir welding, Microstructure, Fatigue, Aluminum alloy.

1. Introduction

Aluminium alloys have properties such as good strength, lightweight and corrosion resistance that make it used in most parts of structures [1]. The aluminium alloys of series 5xxx are used in the ships, aircrafts and transport vehicle structure fabrications [2]. Welding of these grades of aluminium alloys by gas tungsten arc welding or gas metal arc welding processes result in welding problems due to difference in solidification modes for each type of alloy. Therefore, the FSW process is a solid-state welding technique which was considered as a good method to weld aluminium alloys [3-6]. The fatigue behaviour of friction stir welded of different series aluminium alloys (1050, 5083, 6061 and 7075) was investigated [7]. They concluded that the fatigue behaviour was sensitive to the microstructures of the welding zones. The fatigue strength of the welded samples were equal to or lower than those of the parent materials. The fatigue behaviour of dissimilar FSW joints of different aluminium alloys namely; AA6082 and AA5754 was studied. The fatigue stress ratio was R=0.1. It was observed that the fatigue strength of the welded joints was less than those of the base material. The improvement in strength of dissimilar joints between AA2124 and AA2024 by means of FSW was achieved. The analysis of the fracture surfaces were investigated when located in the thermo-mechanically affected zone (TMAZ) or in the weld centre [8]. Ahmed et al. [9] investigated the fatigue behaviour and fractography of dissimilar friction welded joints of Al-alloys AA7075- T6 to AA5052- H34 . Dissimilar aluminium alloys type 5083-H111 and 6082-T651 plates of 6 mm thickness were welded by FSW and tested by the bending fatigue. Welding parameters were 1250 rpm rotating speed, 64 mm/min travel speed and 2° tool tilt angle. The results showed that the fatigue strength of joints was close to each other with

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small void effect [10]. Fatigue crack propagation for the dissimilar aluminium alloys joints 6061-T6 and 304 stainless steel welded by FSW investigated. The results showed that the rate of fatigue crack propagation of the welded joints were comparable or slightly faster as comparing with the base material of aluminium [11]. The effect of FSW process parameters on the formation of welding defects of dissimilar aluminium alloys: AA5083-H116 and AA6063-T6 were investigated. The tunnel defects were found in the advanced side. The kissing bound were formed towards the retreating side [12]. Dissimilar aluminium alloys AA2024-T3 and AA7075-T6 were welded by FSW. The effect of welding process parameters on the mechanical properties of joints was investigated [13]. The mechanical properties and microstructure of the FSW joints of AA6061 to AA7050 were studied a similar hardness profile distribution was observed about the weld line. This was due to the distinct properties for both alloys. Increasing the rotating speed resulted in increase the joint strength. The first sets of welded specimens were failed in the SZ. The other was failed at the HAZ due to the material softening [14]. In 2016 Muna *et al.* [15] applied the Taguchi method to optimize FSW parameters (rotation speed, welding speed and tool design) for dissimilar AA2024T3 and AA7075T73 aluminium alloys. From ANOVA for the tensile strength result, they concluded that the welding speed was the most significant parameter with a percentage contribution of 66.05 % over the other process parameters.

Muna *et al.* [16] used precipitation hardening and post weld aging to improve the mechanical properties of similar friction stir welded joints for AA2024-T3 and AA7075-T73. The results showed that the best aging conditions for similar welded joints of 2024 and 7075 was in sample at condition (natural aging for two week) and sample at condition (artificial ageing at 120°C for 24 h) respectively.

The aim of this work is to study the fatigue properties of friction stir welded similar aluminium alloys type AA5086-H32 to AA5086-H32, which subjected to cycling loading at different fixing distances from the welding line of joint. The fractography of fracture surface of the welded specimen after fatigue test are analyzing using SEM.

2. Experimental work

2.1. Materials used

The material used in the friction stir welding process was wrought aluminum alloy type AA5086-H32. The measured chemical composition of alloy is shown in table 1.

The standard (ASTM B557M-02a) was adopted for the manufacture of tensile test samples for the purpose of examining the mechanical properties of aluminum alloy. The schematic and photographic shape of a manufactured tensile test sample was shown in Figure 1. Tensile test results are shown in table 2.

Table 1. Chemical composition of Al -alloy AA5086-H32

Element wt%	SI	Fe	Cu	Mn	Mg	Cr	Ni	Ti	Al
AA5086-H3	0.06	0.28	0.07	3.72	0.1	-	0.06	0.01	Rem

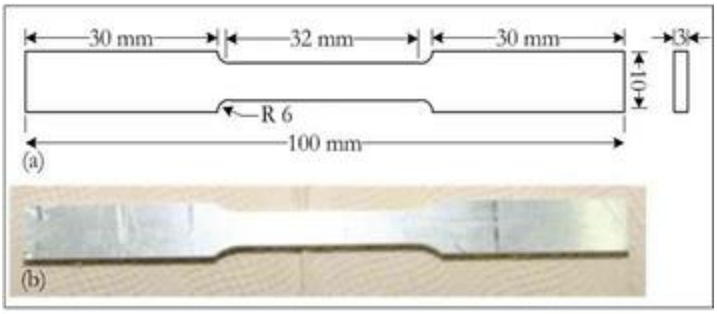

Figure 1. Sample of tensile test (a) schematic (b) photographic

Table 2. Tensile test results of alloy AA5086-H32.

Alloy	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)
AA5086-H32	221	325	8.5

2.2. Preparation of plates for welding process

The samples needed to weld the Al-alloy (AA5086-H32) were cut from a plate with thickness 3mm and dimensions 100 ×200 mm. Oil hardening tool steel (ASTM A681-94 O1 type) is used in friction stir welding. This tool consists of the pin or probe and supported by the shoulder, as shown in Figure 2 b. Before starting the welding process, the samples is fixed using fixture and backing plate tied to the base of the milling machine as shown in Figure 2.

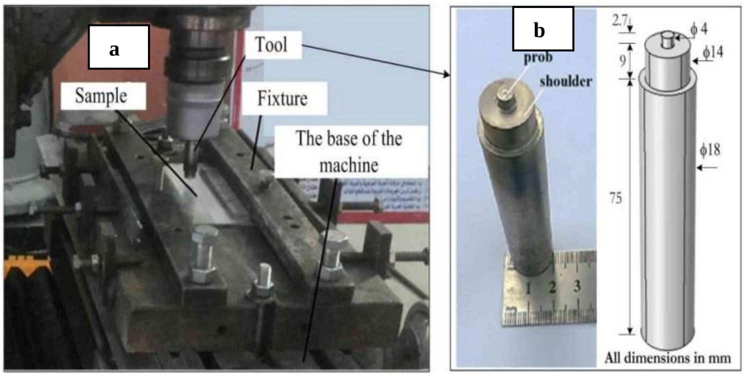

Figure 2. Milling machine parts (a), tool design and dimensions (b)

2.3. Welding Process Parameters

A milling machine was used to accomplish the stir welding (FSW) process. The parameters of the milling machine can be manually controlled the travelling or liner speed, tool rotational speed and the tilt angle of tool. These parameters have a significant effect on the quality of the final product of the welded samples. The mechanical, metallurgical and microstructural properties of the weld, heat affected and thermo-mechanical affected regions affected by the changing the mentioned parameters. The optimum properties of a weld can be obtained by testing a wide range of rotational and linear speed of welding processes.

In this work, three values for both rotational and linear speed are used. The ranges of linear and rotating speeds that used for welding the samples are shown in table 3. The welding process is achieved using butt arrangement of the joint configuration with one side and one pass of welding.

Friction stir welding was performed in four stages: plunging, penetration, stirring and end of welding as shown in Figure 3a. The welding line is divided into two sides. The advancing side where the linear and rotating speed are in the same direction. And retarding side where the aspect in which the linear and rotational speeds are opposite direction [17] as shown in Figure 3a-b.

Table 3. The speeds used in friction stir welding

Sample No.	1	2	3	4	5	6	7	8	9
Linear speed (mm/min)	50	75	90	50	75	90	50	75	90
Rotation sped (RPM)	680	680	680	920	920	920	1500	1500	1500

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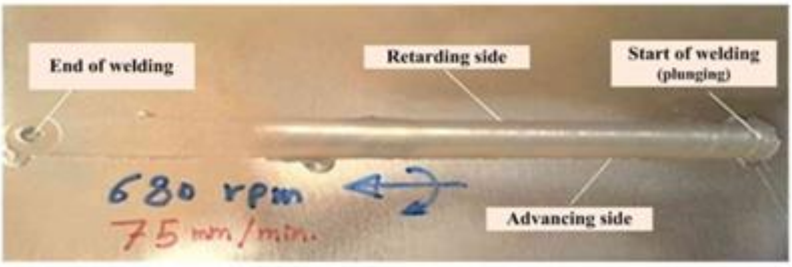
a-



b-

Figure 3. (a) FSW process steps, (b) FSW welded sample

3. Tests and inspections

3.1. X-Ray radiography

The weld internal defects are inspected using x-ray radiography. The optimum macrograph parameters are 130 KV voltage drop, 3 mA at time 2min to determine the sound weldment and source to film distance of 600 mm according to ASTM E747.

3.2.Microstructure and hardness tests

Microstructure and Vickers micro- hardness tests are used to clarify the change in the weld microstructure of the stir zone (SZ), thermo-mechanical affected zone (TMAZ), heat affected zone (HAZ) and base metal(BM). The micro hardness is tested at different points for weld region, HAZ, the TMAZ and BM.

3.3. Tensile test

The tensile test was performed for all welded samples according to the AWS D17.3/D17.3M:2010. The tensile test samples are manufactured such that the welding line is located in the middle of the sample as shown in Figure 4.

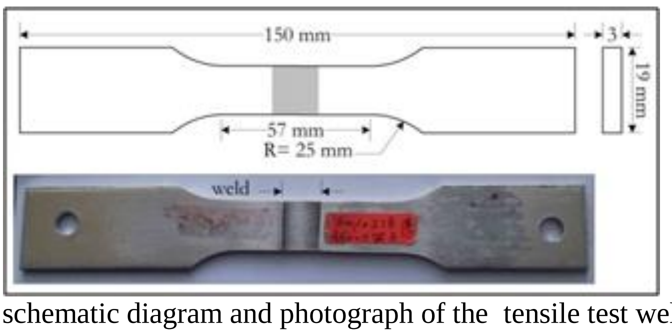


Figure 4. A schematic diagram and photograph of the tensile test welded specimen

3.4. Fatigue test

The best linear speed of 75mm/min and rotating speed of 680 rpm that gave the highest ultimate tensile strength value (260 MPa) in tensile test were approved for the manufacture of fatigue test samples. The fatigue behavior of the welded sample was studied in different regions, such as stir zone or welding line, heat affected zone (HAZ), thermo-mechanical affected zone (TMAZ) and the base metal. The fatigue test used is the type of alternating bending test. Samples of this test were manufactured as shown in Figure 5. The highest fatigue bending stress was studied in four regions (x = 0, 5, 10 and 15 mm). The fractured surface of the fatigue sample was studied using Scanning electron microscope (SEM) device type (VEGA3LM).

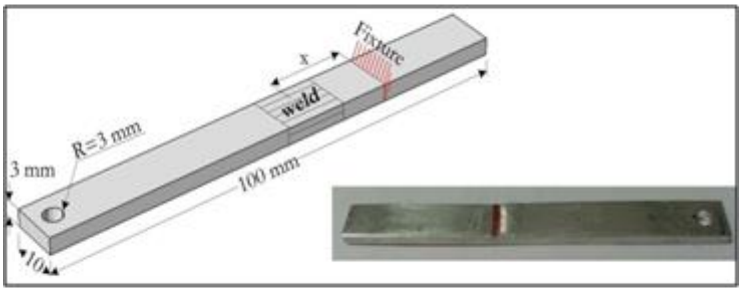


Figure 5. Fatigue test welded used in this study specimen

4. Results and discussion

4.1.Detection of welding defects

Friction stir welding occurs by mixing the solid-state metal that occurs due to the high heat that generated by the friction of the tool with material. This leads to produce internal and external defects during the welding process. The internal defects are produced when the heat generated is not enough to mix the materials

After the welding process is completed, the internal welding defects were detected by using x-ray radiography inspection. Figure 6. shows the results of this examination. It was observed that the welded samples at low speed (N= 680 rpm and V= 50 mm/min.) do not contain internal defects as shown in Figure.6 (a, b & c). On the other hand, because of the high heat generated during welding at high speed, defects such as incomplete coalescence, small crack line in end hole and surface defect are observed as shown in Figure 6 (d, e & f) respectively.

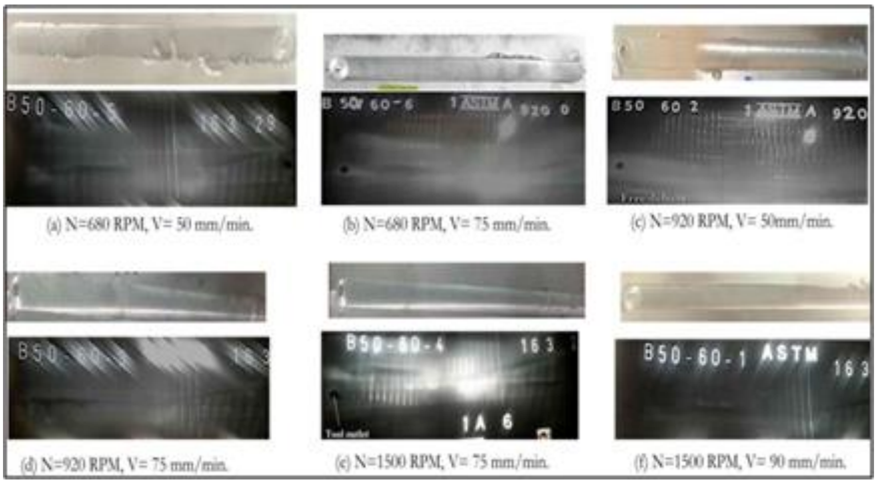


Figure 6. Radiography examination of the welded samples

4.2. Tensile test results

The tensile test results showed that all welded samples had failed in the welding region. This can be attributed to the change in the mechanical and metallurgical properties of metal during the welding process. Figure 7 shows the tensile test results and model of a fractured sample in the welding region. The highest values of tensile strength (260MPa) and joint efficiency (80%)were observed at low speed (N= 680 rpm) and at the intermediate linear speed (V= 75 mm/min). On the other hand minimum joint efficiency (66%) was observed at the same linear speed (V= 75 mm/min.) and at the intermediate rotational speed (N= 920 rpm).

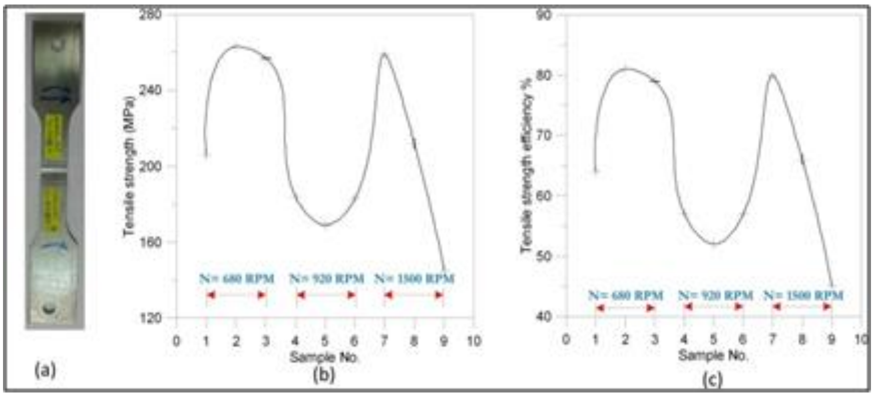


Figure 7. Tensile test results (a) tested specimen (b) tensile strength (c) joint or weld efficiency at speed (N= 680 rpm) and at linear speed (V= 75 mm/min).

4.3. Microstructure results

The microstructure of the welded sample at the best welding conditions (N=680 RPM,V= 75mm/min.) which gave the highest tensile strength were illustrated in Figure 8 . This figure represents the welded joints of two similar Al- alloys; AA5086-H32 with AA5086-H32. In general, the friction stir welded cross section includes four zones as shown in table 4.

The microstructure of the base alloy (AA5086-H32) is shown in Figures .8a and 8e, respectively. Figures 8d and 8h show that the microstructures of heat-affected zone (HAZ) in the advancing and retreating sides are approximately similar to base materials without any significant grain coarsening. The TMAZ for for alloy AA5086-H32 is shown in Figures 8g and 8 c. The microstructure showed that there is a clear and significant bent and elongation in the TMAZ grains at the advanced side compared to the retreating side. This can be attributed to the fact that the plastic flow direction from the advance side to the retreating side produces a fiber-structure pattern during the welding process. In addition to, the direction of the plasticized materials on the advanced side of the weld is in the opposite of the base material, which leads to make the deformation and elongation of the grain is relatively large in that side. While the microstructure of stir zone or nugget zone is shown in Figures 8f and 8b. It contains very fine equiaxed recrystallized grains. This is due to the combined effect of sufficient degree of plastic deformation in the stir zone and friction heat during friction stir welding.

Table 4. Regions or zones of welded cross section

Region	Location	The descriptions	Figure (8)
Nugget zone (NZ)	in the center of weld	fully re-crystallized	b and f
Thermo-mechanically affected zone (TMAZ)	at both sides of NZ	affected by heat and deformation	c and g
Heat affected zone (HAZ)	between TMAZ and BM	affected by heat with no plastic deformation	d and h
Base metal (BM)	Next to the HAZ	-	a and e

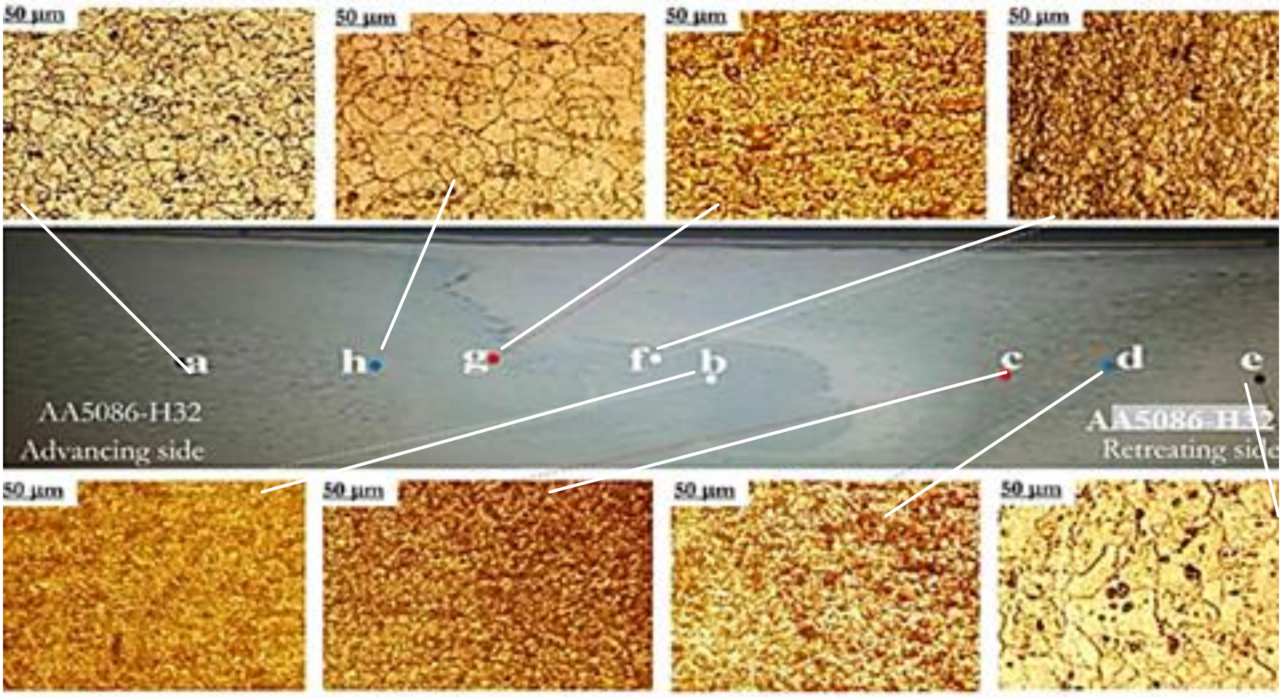


Figure 8. The microstructures of different welding zones for the welded sample at the best welding conditions

4.4. Micro hardness results

The amount of high heat generated during the friction stir welding process leads to refinement grain size and the occurrence of thermal changes in the weld zone [18,19], which in turn lead to a clear variation in the hardness as shown in Figure 9. It was noticed from the Figure that the highest value of the hardness (120HV) was found at the weld region center and decreases in the HAZ through the parent material of AA5086-H32. This can be justified by the refinement and recrystallization of eqaxied grains in SZ and precipitation of second phase of Al_3Mg_2 and Mg_2Si from solid solution of Al-matrix during friction stir welding. These results were confirmed by XRD analysis. It was found that the values of the hardness of AA5086-H32 (85HV) due to the softening process in HAZ region of AA5086-H32 side and coarsening and/or dissolution of strengthening precipitation during FSW. These results are in agreement with results of researchers [20,21,22]. They used FSW process in welding similar and dissimilar aluminum alloys or metals under different conditions.

4.5.Fatigue test results

Fatigue of welded samples was tested at the best welding conditions(N=680rpm ,V= 75mm/min), which gave the highest value for tensile strength. Fatigue test was analyzed in the welding region at distance (x = 0 mm) and away from the welding line (x = 5, 10 and 15 mm) of the alloy AA5086-H32. The stress ratio used was R=-1.

Figure 10 represents the S-N curves resulting from fatigue test of the base alloy AA5086-H32 and welded samples. Results showed that the joint efficiency of welded samples was lower than that of base alloy. This can be attributed to the fact that the heat generated during the friction stir welding process led to a change in the mechanical and metallurgical properties. Also, the developed residual stress and plastic strains resulted in reduce the fatigue strength of weldments. The weakest fatigue properties were observed in the welding region (x=0 mm), which is exposed to the highest temperature during the welding process. Increasing the distance (x) means decreasing the temperature and as a result the residual stress and plastic strain will decrease. Therefore, the mechanical properties of weldment were approached to that of base alloy.

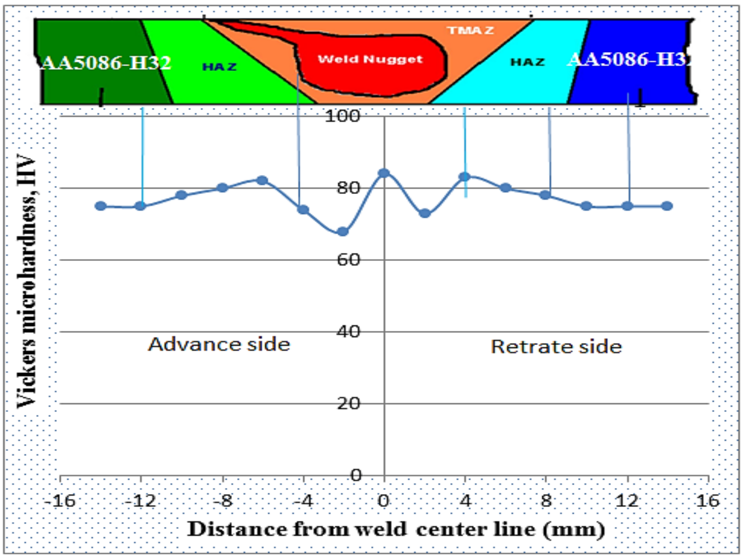


Figure 9. Micro-hardness distribution of welding cross section of AA5086- H32 at the best welding conditions N=680 rpm, V= 75mm/min.

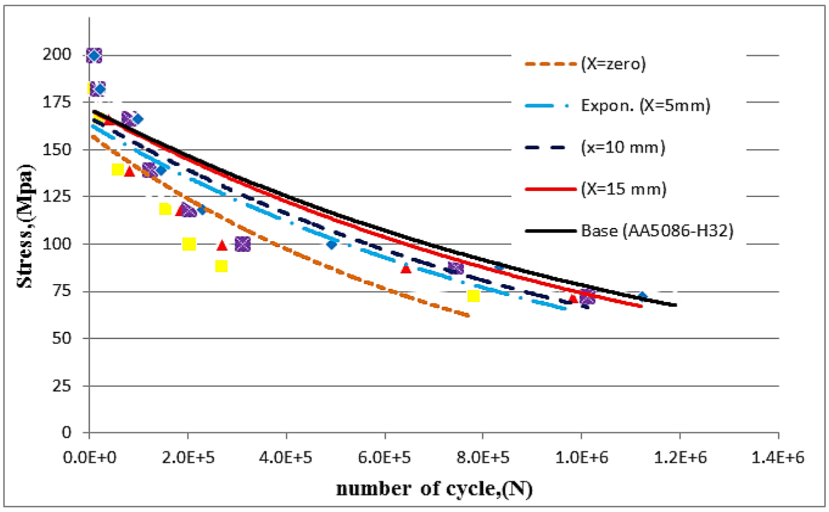


Figure 10. S-N curves of the AA5086-H32 at the best welding conditions N=680 rpm , V= 75mm/min.

4.6. Fractography results

The fracture surface of the welded specimen after fatigue test was studied using scanning electron microscope (SEM). Figure 11 shows the main crack that started from the surface of the fatigue specimen of AA5086-H32. The reason for the imitation of such a crack started at the edge of the sample is the concentration of stress which can be considered as stress raiser [23,24]. On other hand the trans granular fracture was observed in fatigue fracture.

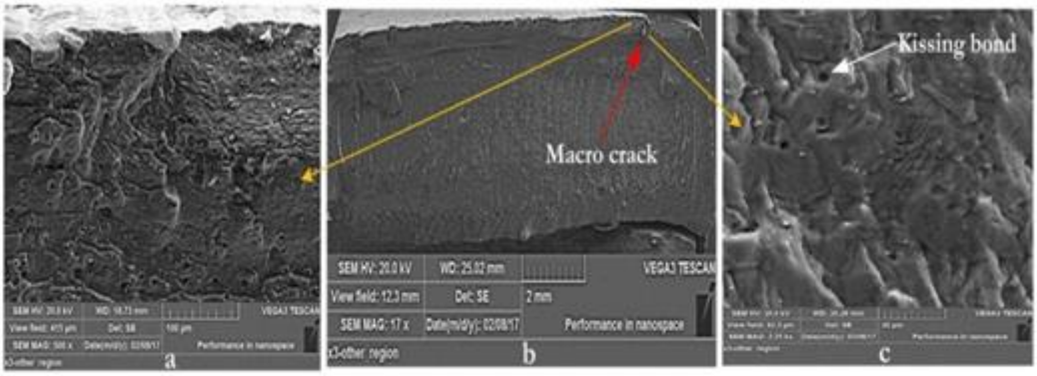


Figure 11 SEM micrographs of fractured sample at 72MPa and 1.1x10^6 cycles for parent alloy AA5086-H32

5. Conclusion

In this study the internal defects such as incomplete coalescence, small crack line in end hole and surface defect are detected in the welding of these alloys due to high temperature produced by the high speed of the tool. It was showed that the maximum joint efficiency (80%) and tensile strength (260Mpa) were found at a lower rotational speed (N= 680 and V= 75 mm/min). The highest hardness value was 85 HV at the stir zone center of weld and then decreases toward the HAZ and the base metal. It was observed that the fatigue properties extracted from S-N curves of the welded samples which were fixed during fatigue test at different fixing distances (x= 5,10 &15mm) from the welding line were approached to that of the base alloy. From SEM images the fractography of fracture surface after fatigue test showed that the main reason for the fatigue failure of the welded sample is the presence of main microcracks, secondary and transverse cracks.

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