# Investigation of Fatigue Behavior and Fractography of Dissimilar Friction Stir Welded Joints of Aluminum Alloys 7075-T6 and 5052-H34

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***Abstract*—The aim of the present work is to investigate the fatigue behavior of friction stir welded joints for dissimilar aluminum alloys 5052-H34 and 7075-T6. Friction stir welding (FSW) has been done on 4.826mm (0.19) in thick plate by using MTS-5 axis friction stir welder. FSW were carried out under optimum welding parameters with travel speed of 187mm/min (7in/min), rotational speed of 400rpm and forge load of 9KN (2000lbf). Mechanical tests and inspection were performed to characterize the welded joints and determine it to be defect-free. Tension–tension fatigue tests have been done at a frequency of 7Hz with stress ratio R=0.1. Also topography analysis was done using scanning electron microscopy combined with energy dispersive spectroscopy. The fatigue failure has been analyzed.**

***Index Terms*—friction stir welding, fatigue behavior, dissimilar joints, aluminum alloys**

## I. INTRODUCTION

Friction stir welding (FSW) is anew solid state welding processes that was invented in 1991 in The Welding Institute (TWI) of Cambridge [1]. This joining technique has been shown to be viable for joining aluminum alloys, since it is essentially a solid- state process, i.e. without melting. High quality welds can generally be fabricated with absence of solidification cracking, porosity, oxidation, and other defects resulting from traditional fusion welding [2].

The application fields of FSW are marine (hulls, superstructures, and storage vessels for the shipbuilding), aerospace (airframes, fuselages, wings, fuel tanks), railway (high speed trains, railway wagon, automotive (chassis, and truck bodies), motorcycle and refrigeration industries [3].

Many studies have been conducted on FSW of heat treatable or non-heat treatable aluminum alloys with respect to microstructural characterization, and the effect of welding parameters on mechanical properties. Emphasis has been given to the effect of welding parameters on hardness, fatigue strength, and microstructure. In order to produce a defect-free weld the optimization of welding parameters is extremely important [4].

The great majority of available data from the fatigue analysis of friction stir welded joints are concerned with uniaxial loading conditions for a simple geometry. In uniaxial loading nominal stress is normally used as reference stress and it is easy to determine. Fatigue failure is a highly localized phenomenon in engineering components [5].

Y. Uematsu *et al.*, [6] investigate the fatigue behavior in friction stir welds of 1050-O, 5083-O, 6061-T6 and 7075-T6 aluminum alloys, under fully reversed axial fatigue loading, and the observed fatigue strengths were discussed based on the microstructure and crack initiation

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behavior. They deduced that fatigue strengths of similar welds of 5083-O and 7075-T6 are nearly the same as those of the parent materials.

M. H. Shojaeefard *et al.*, [7] focused on the microstructural and mechanical properties of the friction stir welding (FSW) of AA7075-O to AA5083-O aluminium alloys. Weld microstructures, hardness and tensile properties were evaluated in as-welded condition. It's found that the joint fabricated, using the FSW parameters of 1400rpm (tool rotational speed) and 20mm/min (traverse speed) showed higher strength properties compared with other joints.

The aim of this research is to investigate the fatigue behavior of friction stir welded joints made from dissimilar Al-alloys (5052-H34 and 7075-T6) that are non-heat treatable and heat treatable and to study the microstructures of FSW zones. An analysis of the fatigue fracture has been conducted based on SEM images.

## II. Experimental Work

### A. The Materials

Aluminum alloys of two type's 5052-H34 (Al-Mg) alloy and 7075-T6 (Al-Zn-Cu-Mg) alloy with 4.826mm (0.19 in) thickness were used in this study, the chemical composition of each is listed in Table I.

TABLE I. The Chemical Composition of Alloys Used in FSW

| | Mg | Cr | Si | Fe | Cu | Mn | Zn | Others | Al |
|---|---|---|---|---|---|---|---|---|---|
| **7075** | 2.5 | 0.25 | 0.4 max | 0.5 max | 1.7 | 0.3 max | 5.5 | 0.15 max | Rem |
| **5052** | 2.5 | 0.25 | 0.25 max | 0.4 max | 0.1 max | 0.1 max | 0.1 max | 0.15 max | Rem |

### B. Specimen Preparation

Tensile and fatigue test specimens were prepared using a milling machine as follow: First, samples were saw cut perpendicular to weld line with 203mm (8") long and 19.8mm (0.78") width, then Machining the samples edges to 19mm (0.75") width. After that, the weldment faces were machined to remove flashes and stress riser .The sample profile was obtained using a milling machine with a special fixture to achieve specimen geometry in accordance with the standard ASTM E8M-04.

### C. Welding Tools

An adjustable pin tool made of H13 tool steel was used for the welding experiments as shown in Fig. 1. The welding was performed at the South Dakota School of Mines & Technology (SDSM&T).

Figure 1. SDSM&T scroll shoulder adjustable pin tool

### D. Process Parameters

In this study, friction stir welding was carried out by using an I-stir 10 Multi Axis friction stir welding system. For all the dissimilar joints produced, 7075 plates were placed on the advancing side and 5052 was on the retreating side of the weld. The weld process parameters (as advised from FS welder) were, Rotational Speed of 400RPM, Travel Speed of 178mm/min (7 IPM), Forge Force of 9KN (2000lbf) (All the welds were made in force control mode) and Tool Tilt of 2˚.

## III. Inspections and Tests

### A. Mechanical Tests

Tensile tests were carried by using Instron universal test system of model 8800R. Tensile and yield strength was obtained from stress-strain curves of the welded joints.

*Microhardness tests* were carried out using a Vickers micro hardness tester, Buehler micromet II. Five lines were taken in the cross section of weld to study the microhardness profiles across mid-thickness of friction stir weldment. The measurements were taken with a spacing of 1mm from point to point with applied load of 1Kg and duration time of 15 second was used.

*Fatigue tests* were done under tension-tension loading, stress ratio R=0.1 and frequency of 7Hz in laboratory air. The fatigue specimens are similar in shapes and dimensions to tensile specimens. Three tests were done at each load condition. Samples were taken from perpendicular section to the weld line of welded plate to perform the test. Fatigue tests were conducted on the same machine that was used for tension tests but with constant amplitude, sinusoidal fatigue loading. A fatigue life of over $2\times10^6$ cycles was considered a run-out test. The relationship between stress amplitude and number of cycles was obtained for the dissimilar FSW aluminum alloys.

### B. Nondestructive Testing

*Ultrasonic testing* is widely used for detection of internal defects in conductive materials. Immersion ultrasonic testing machine type (UNIDEX 11) was used to examine the FSW plate and to check if there is any defect. No significant defect was found. *Surface Roughness test* was done on fatigue sample prior to fatigue testing using optical profilometry, 'Veecowyko NT 9100' to check the average roughness (Ra), which is a very important that can affect fatigue life.

*Scanning electron microscopy* (SEM) is the most widely-used surface topography imaging technique. A highly-focused, primary electron beam with energy of 0.5-30keV is passed over the surface of the specimen that generates many low energy secondary electrons. FEI

Quanta 600 FEG Extended Vacuum Scanning Electron Microscope (ESEM) with energy dispersive spectroscopy (EDS) was used to inspect the fatigue fracture in samples. The procedure begins by selecting the proper voltage which in our case was 10KeV for SEM and 30KeV for EDS. The EDS analysis included spectrum, mapping and line analysis. Samples were cut from vicinity of fatigue fracture surface for this examination. Two fracture samples were investigated, the first fractured at a low load of 70% of breaking load, and second with high load of 90% of breaking load.

*The microstructure examination* of the welded zone was conducted by taking samples from the cross section of FSW weld, and after grinding and polishing; killer etchant was used to develop the microstructure of welded joints and base alloys using optical microscope.

## IV. Results and Discussion

### A. Macro- and Micro-Structure Results

The macro and microstructures of various regions in the cross section of the dissimilar FSW joint are shown in Fig. 2. The macrostructure can be divided into the following zones:

- *The stir zone (SZ)* (also nugget or dynamically recrystallized zone) is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material [8].

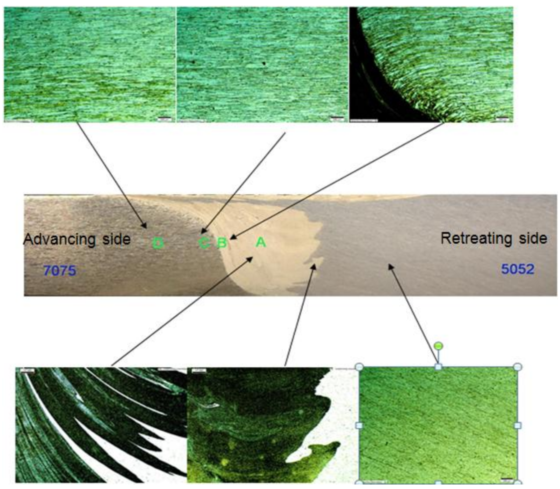


Figure 2. Macro and Micro structure of various regions in te cross section of FSW joint of Al 7075 and 5052.

This zone consists of two aluminum alloys; 5052 (light color) and 7075 alloy (dark color) and is formed due to occurrence of stirring action under the pin and good interference of soft alloy (Al-5052) and harder alloy (Al -7075). It can be seen from Fig. 2 that the nugget or stir zone has a unique feature of the common occurrence of several concentric rings which has been referred to as an "onion-ring" structure which was generated due to material flow during FSW.

- *The thermo-mechanically affected zone* (TMAZ) occurs on either side of the stir zone in the dissimilar joint. In this region the strain and temperature are lower and the effect of welding on the microstructure is correspondingly smaller. The microstructure of this zone is recognizable by its deformed and rotated grains which are different in shape than found in stir zone. The term TMAZ technically refers to the entire deformed region that is not already covered by the terms stir zone and flow arm as in Fig. 2**.**
- *The heat-affected zone (HAZ)* is common to all welding processes. This region is subjected to a thermal cycle but is not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. In fact, in age-hardened aluminum alloys this region commonly exhibits the poorest mechanical properties [9].
- *The base metal zone (BM)* is unaffected material or parent metal which is remote from the weld and which has not been deformed or affected by the heat in terms of microstructure or mechanical properties. This zone appears as longitudinal grain in Al-7075 due to the direction of rolling, while it's appearing as fine equiaxed in Al-5052.

### B. Tensile Test Results

Tensile test was done for dissimilar FSW welded Al-alloys (5052-H34 and 7075-T6) at optimum welding parameters which give maximum joint efficiency of about 87% (comparing to Al-5052-H34)which has the lowest tensile strength, as illustrated in Table II. The average breaking load was 11.1KN (2500lb).

TABLE II. Mechanical Properties of Crrent FSW Joint and Base Metals

| Alloy | Yield stress, MPa | Tensile stress, MPa | % Elongation |
|---|---|---|---|
| Al-5052 H34 | 193 | 228 | 12 |
| Al-7075 T6 | 503 | 572 | 11 |
| 5052-7075 joint | 134 | 198 | 9 |

### C. Microhardness Test Results

Fig. 3 shows the numbered lines along which microhardness distribution through the thickness of dissimilar FSW joint was measured. The interspacing between two lines is 1mm. It was found that the microhardness values are a strong function of the distance from the weld line for the age-hardening alloy (7075-T6) and strain- hardening alloy (5052-H34). This variation is most likely due to the dissolution and reprecipitation of the hardening phases in both alloys. Also this variation is due to the changes in grain size from large longitudinal grains in base alloys and HAZ into fine equiaxed grains in the stir zone.

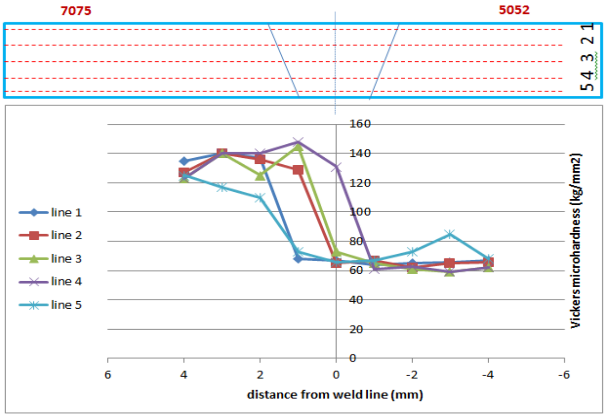


Figure 3. Microhardness distribution a cross FS weld line

It can be seen that the hardness value of friction stir zone is higher than that of base alloy 5052-H34 side. There are two main reasons for the improved hardness of friction stir zone. Firstly, since the grain size of friction stir zone is much finer than that of base metal, grain refinement plays an important role in material strengthening, hardness increases as the grain size decreases. Secondly, the fine particles of intermetallic compounds and precipitation of hardening phases are also a benefit to hardness improvement, according to the hardening mechanism. These results are in agreement with the results of other researchers [10], [11].

*D. Roughness Test Results*

It has been found that the average roughness for the fatigue specimens was Ra=0.22 µm.

*E. Fatigue Test Results*

In this study friction stir weld of dissimilar Al-alloys 7075 and 5052 appear to be of acceptable quality from the point of view of the microstructure and mechanical properties, as shown in Table III. The fatigue limit here is the fatigue strength at $2\times10^6$ cycles and it's lower than that for base materials. The fatigue endurance limit is about 60MPa (8111psi), as shown in Fig. 4. The best fit curve to the finite fatigue life region is represented by the equation below:

$$S = 42254*N - 0.118 \qquad (1)$$

where '*S*' is the stress amplitude in (MPa) and '*N*' is number of cycles to failure.

TABLE III. FATIGUE DATA FOR S-N CURVE OF DISSIMILAR FSW JOINT. BREAKING LOAD 11.1KN (2500LB)

| Sample No. | Maximum Fatigue load as % of Breaking Load | Cycles to failure $N_f$ | Stress Amplitude (MPa) | Fracture Location |
|---|---|---|---|---|
| 1 | 35 | Run out | 30.5 | N/A |
| 2 | 53 | Run out | 45.6 | N/A |
| 3 | 60 | Run out | 51.7 | N/A |
| 4 | 65 | Run out | 56 | N/A |
| 5 | | Run out | | N/A |
| 6 | | Run out | | N/A |
| 7 | 70 | $2*10^5$ | 60.5 | weld |
| 8 | | $4.73*10^5$ | | Base (5052) |
| 9 | | $8.08*10^5$ | | weld |
| 10 | 80 | $2.58*10^5$ | 69 | weld |
| 11 | | $2.74*10^5$ | | Base (5052) |
| 12 | 85 | $1.1*10^5$ | 73.3 | Base (7075) |
| 13 | | $1.98*10^5$ | | weld |
| 14 | 90 | $8*10^4$ | 77.6 | HAZ (5052) |
| 15 | | $1.1*10^5$ | | weld |
| 16 | 95 | $5*10^4$ | 81.9 | weld |

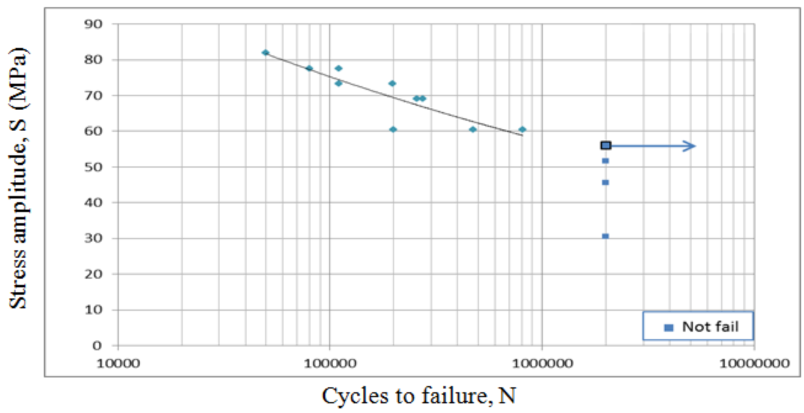


Figure 4. Stress-No. of cycles curve for dissimilar FSW joint

### *F. Fracture Characterization by Scanning Microscopy*

In order to study the fatigue behavior of dissimilar FSW joint, scanning electron microscope images were taken for different regions in the fracture surface. Two specimens had been captured one with low load (high cycle fatigue) and other with high load (low cycle fatigue). In both samples fatigue fracture started from the weld surface and the crack passes through the curved metal flow lines.

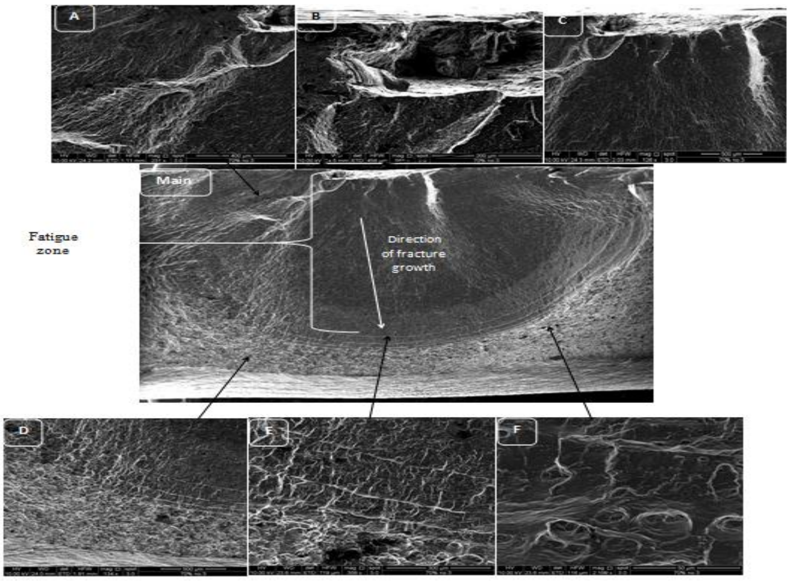


Figure 5. SEM fractographs of the dissimilar FSW (5052-H34 and 7075-T6) specimens for low load (70%) of breaking stress; 60.5MPa), $N_f$: $8.08*10^5$ cycles

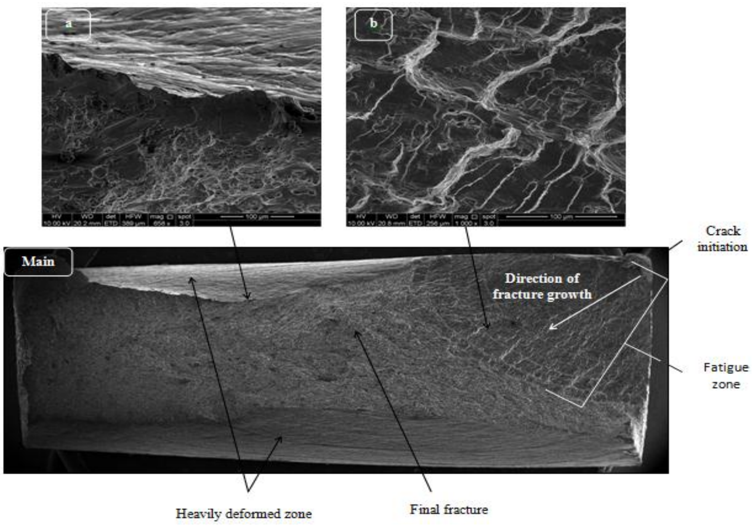


Figure 6. SEM fractographs of the dissimilar FSW (5052-H34 and 7075-T6) specimens for high load (90%; 77.5MPa); $N_f = 1.1 \times 10^5$ cycles.

Fig. 5 shows the topography of fatigue fracture for dissimilar FS joint at low load which is 8777psi, 70% of fracture load for tension, this called High cycle fatigue.

There are a lot of features in main macrograph which includes three zones, namely, crack initiation (white top region), crack propagation (rubbed fatigue zone) which appears like a hemisphere, and final fracture zone.

Micrograph-A- illustrates the main crack (white area) and the secondary (micro) cracks.

Micrograph-B- shows a micro void beneath the weld surface which it is due to excessive feed rate, which became as stress concentration spot to nucleate the main crack.

Micrograph-C- explains the crack nucleation (starting) zone which is the white region in the top.

Micrograph-D- shows the three zones which (from the upper) are crack propagation (part of fatigue zone) then the final fracture which includes the dimples and heavily plastic deformed zone.

Micrograph-E- which is a high magnification of steps which is one of the fatigue features.

Micrograph-F- shows the dimple which is one of characteristics of final sudden brittle fracture.

The fatigue zone in this photo is wide hemisphere shape which mean that the crack take a long time to spread which is correct because of low load with about

70% of fracture load and high cycle which about $8 \times 10^5$ cycles.

Fig. 6 shows the topography of fatigue fracture for dissimilar FSW joint at high load, which is 77.5MPa (11250psi), this called Low cycle fatigue.

The main macrograph shows many zones which are starting with crack initiation then propagation direction which is fatigue zone then the final fracture.

The features her differ a little from the previous one in that the fatigue zone is small and sudden fracture is large due to high load which is 77.6MPa (11250psi ) and low cycle which is about $1.1 \times 10^5$ cycles.

The micrograph-A- shows two zones white which is fibrous heavily deformed fracture, and dark which is the sudden fracture which include dimples, which is the main characteristic of ductile fracture. Micrograph-B- show the fatigue steps with high magnification and this steps represent the final stage in stable propagation after that the crack will propagate suddenly with a high rate till final fracture.

## G. *Analysis of Fracture by Energy Dispersive Spectroscopy (EDS)*

For 70% specimen some lines had been taken (Red lines) as in Fig. (7), which represent the track that had been analysis by EDS. In these data in Fig. 7, Fig. 8 and Fig. 9, Magnesium and smaller amount of zinc had been present in the fracture surface.

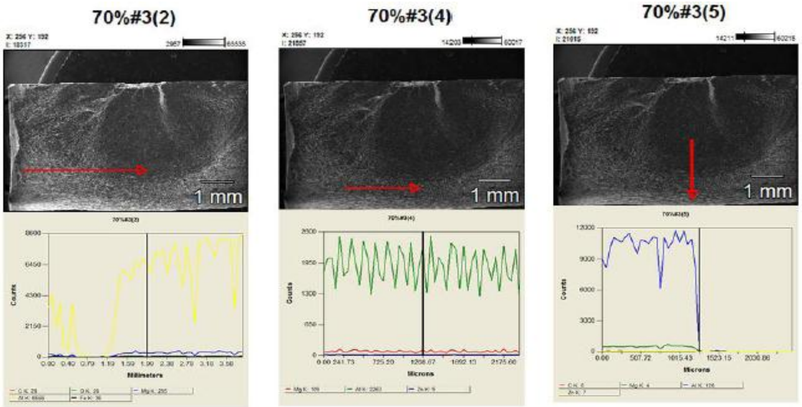


Figure 7. EDS analysis for 70% FSW samples

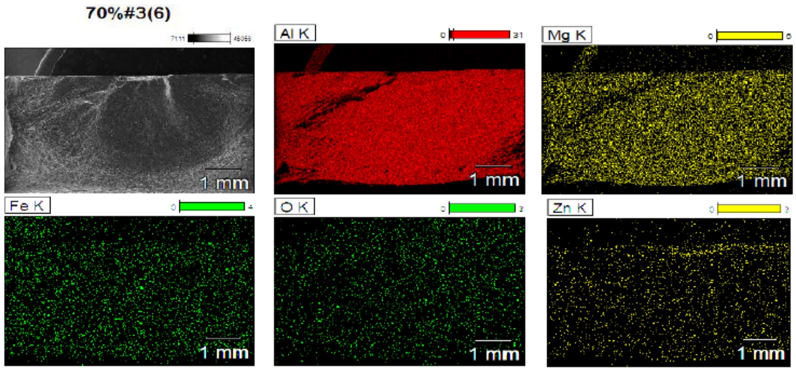


Figure 8. Mapping of elements in 70% FSW joint, Data Type: Counts, Mag: 18, Acc. Voltage: 30.0 kV, Detector: Pioneer

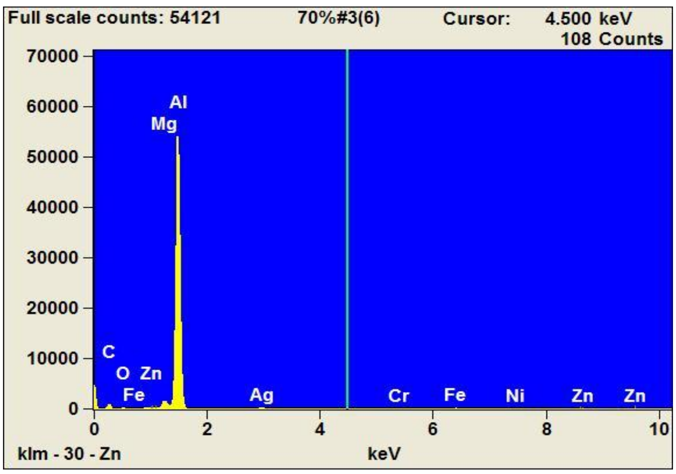


Figure 9. Spectrum of 70% FSW joint fatigue fracture

- The dissimilar 7075-T6 and 75052-H34 aluminum alloys have been successfully joined by friction stir welding with 87% as a high joint efficiency.
- The resulting microstructure has been shown large differences in grain structure, hardening phases and precipitates distribution in friction stir weld of dissimilar AL-Alloys.
- The microstructures of dissimilar Alloys showed the mixture structures of two alloys, this means it exhibits good mixing and observable interference between two aluminum alloys in a stir zone of weld.
- The onion ring pattern, which appeared like lamellar structure, has been observed in the stir zone of weld
- The specimens fracture surfaces after fatigue test have been deeply analyzed by using a SEM microscope, revealing step formation in the end of propagation stage.
- It is safe for the 5052-7075 FSW joint to work with load up to 65% of tension fracture load.

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