Study Fatigue Behavior of Friction Stir Welded Joints for Dissimilar Aluminum Alloys (2024 -T3 and 7020 -T6)

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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 (2024 -T3 and 7020-T6). Friction stir welding (FSW) had been done for 6.6 mm thick plate by using NC milling machine with R18 tool steel of 18mm with shoulder diameter and 6mm pin diameter with different tool designs; threaded cone with double bevel, threaded cylinder with concave shoulder of 4°, and beveled cone with concave shoulder of 4°. FSW were carried out under various welding parameters, travel speed of 40, 50, 75 mm/min, rotation speed range (275-1250) rpm and tilt angle of (**Ө = 3**°) with counterclockwise revolution.

Many non- destructive inspections and mechanical tests were performed to evaluate welded joints to determine the best welding parameters. Fatigue test has been done at constant stress amplitude cantilever with stress ratio of (R= -1). The results showed that maximum tensile strength and joint efficiency were 360MPa and 86% respectively for dissimilar joints which were welded at 40mm/min travel speed and 550 rpm rotation speed by using threaded cone with double bevels.

Keywords: Friction Stir Welding, Dissimilar Al-Alloys, Mechanical Properties, Fatigue Test .

دراسة سلوك الكلال لوصلات غير متشابهة ملحومة بطريقة الخلط الأحتكاكي من سبائك الألمنيوم *(2024 -T3 and 7020 -T6)*

الخلاصة

يهدف البحث الى دراسة سلوك الكلال لوصلات غير متشابهة ملحومة بطريقة الخلط الأحتكاكي من سبائك الألمنيوم (2024 -T3 and 7020-T6). وأجريت عملية اللحام بالخلط الأحتكاكي لصفائح بسمك 6.6 ملم على ماكنة التفريز المبرمجة باستعمال اداة لحام من فولاذ العدة نوع (R18) وذوكتف قطره 18 ملم ومسمار قطره 6 ملم مع تغيير تصميم الأداة. وقد استعملت ثلاث تصاميم مختلفة للأداة هي مخروط مسنن مشطوف الجانبين, اسطواني مسنن مع

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كتف مقعر للداخل بزاوية 4^0 و مخروط مشطوف مع كتف مقعر للداخل بزاوية $4^{\ 0}$. أجريت عملية اللحام الاحتكاكي عند ظروف لحام مختلفة ، سرع لحام 40 و 50 و75 ملم/دقيقة وسرع دوران (275-1250) دورة/دقيقة .
أجريت عدة فحوصات لا أتلأفية واختبارات ميكانيكية لغرض تقييم وصلات اللحام وتحديد افضل ظروف للحام. أما اختبار الكلال فقد كان من نوع (انحناء دوار) وعند سعة اجهاد ثابت ونسبة اجهاد (R)= -1
اظهرت النتائج ان أعظم مقاومة شد للوصلة الملحومة وأعلى كفاءة للوصلة هي 360 ميكاباسكال و 86 % على التعاقب للوصلات غير المتشابهة الملحومة عند سرعة تغذية 40 ملم/ دقيقة وسرعة دوران 550 دورة/ دقيقة باستعمال عُدة مخروطية مسننة مشطوفة الجانبين.

INTRODUCTION

Friction stir welding (FSW) is a new solid state welding processes was invented in 1991 in The Welding Institute (TWI). The advantages of FSW technique are that it is environment friendly, energy efficient, there is no necessity for gas shielding for welding Al, mechanical properties as proven by fatigue, tensile tests are excellent, there is no fume, no porosity, no spatter and low shrinkage of the metal due to welding in the solid state of the metal and an excellent way of joining dissimilar and previously non weldable metals [1].

Shusheng Di et al. , 2006 [2] made a comparative study on fatigue properties between 4 mm thick plate of Al 2024-T4 friction stir welds and base material, also studied the influence of zigzag-curve defects across weld section on the fatigue properties of FSW joints. The welding parameters used were rotational speed of 800–1000 rpm, travel speed of 150–250 mm/min and the tilt angle of 3◦. The fatigue tests were carried out in a high-frequency fatigue test machine with stress ratio $R = 0.1$. They conclude that the fatigue crack always appeared at the weld root site also root flaws produced by ‘zigzag-line’ defects up to 0.35 mm deep hardly influenced the mechanical properties.

V. Sinka 2010 [3] studied Friction stir lap welding of two high strength heat treatable aluminum alloys (2024 with 7075). EDS microanalyses were carried out in the nugget by means of a scanning electron microscope in order to map the extension of the mixing of the two alloys. The mechanical properties were evaluated by means of microhardness measurements in the mixed region of the FSW joint. Joint microstructure showed a characteristic mixture pattern of the two alloys. It exhibited a regular pattern of elongated stripes on the advancing side and a turbulent pattern on the retreating side of the joint, while maintaining the difference in their hardness values. Also no detectable interdiffusion of the alloying elements was found.

D.Muruganandam et al., 2010 [4] investigated the mechanical and microstructural properties of dissimilar 2024-T3 and 7075-T6 aluminium plates with 5 mm thickness had been joined by friction stir welding (FSW). Optimized welding parameters were set to welding speed of 160 mm/min and clockwise rotating axle with tilt angle of 3^o. High cycle fatigue tests (axial stress amplitude) had been performed using a constant stress ratio of (R=0.1). They concluded that the maximum microhardness value reaches to 150 HV in the weld center and decreases in the HAZ and the welding efficiency reached to about 87% and the fatigue strength was 44 MPa at about $2*10^6$ cycles.

A.A.M. da Silva et al., 2011 [5] investigated mechanical properties and microstructural features as well as material flow characteristics in dissimilar friction stir welded joints of 10 mm thick (2024-T3 and 7075-T6 sheets). Welds have been performed at fixed feed rate (254 mm/min) with varying the rotation speed in three levels (400, 1000 and 2000 rpm). The conclusions can be drawn as follows :(1) The minimum hardness value of naturally aged samples has been found in the HAZ at the retreating side (about 88% of 2024-T3 base material). (2) The weld efficiency in terms of tensile strength for the 1000 rpm FSW condition is approximately 96%. Fracture of the specimens has occurred in the HAZ at the retreating side (2024-T3).

Pouya et al.,[6] investigated the effect of friction stir welding (FSW) parameters on the weldability and the characteristics of dissimilar welds Al-alloys (2024-T3 and 7075-O). A number of FSW experiments are carried out to obtain high-quality welds by adjusting the rotational and welding speeds. The weldability and blending of two materials are evaluated by using the macrostructural analysis; also the mechanical properties of the welds are studied through microhardness distribution and tensile tests. It was clarified that increasing the rotational speed and reducing the welding speed resulted in a decrease in the overall hardness value in the stir zone.

The aims of the present work are; first, is to find the best conditions of friction stir welding parameters to join the dissimilar Al-alloys (2024-T3 and 7020-T6) after welding at different welding speeds, rotation tool speeds and tool designs. Second, investigation of the fatigue behavior of dissimilar welded joints for above mentioned alloys.

EXPERIMENTAL WORK

Materials

Aluminum alloys of two types’ 2024-T3 and 7020-T6 (T3: Solution heat treated and cold worked, T6: Solution heat treated and artificially aged) with 6.6mm thickness were used in this study. Plates were cut into the required size of 150 ×50 mm by punch cutter and then machined to the required size using CNC milling machine. Butt joint configuration was prepared to fabricate friction stir welding (FSW) joints. XRF analysis had been done for those Al- alloys which inspected by spectroscopy Oxford X-Met 3000TX and the results of chemical compositions are represented in the Table (1).

Welding Tools

The welding tool used in this study was made of R18 tool steel (depending on DIN standards) with 18mm shoulder diameter, 6mm pin diameter and 6.3 mm pin length (95% of plate thickness). Figure (1) indicates the tool designs used for FSW process.

Experimental FSW Procedure

NC milling machine had been used to join dissimilar alloys (2024 T3-7020 T6) with 6.6 mm thick plate with reversed revolution (tool rotation: counter clockwise) by placing 7020-T6 alloy (the softer material) on advancing side and 2024-T3(the harder material) on retreating side with tilt angle(ϴ) of 3^o.

Inspections and Tests

Nondestructive Testing

Portable ultrasonic flaw detector has been used for detecting internal defects in the weld using angle probe of 70^o and 2 MHz frequency. Also ERESCO MF4 X-ray radiography technique has been used to examine the internal defects in weldments. The optimum macrograph conditions for this inspection were: Voltage: 60 volt, Amperage: 5.5 mA, exposure time: 200 sec. and (Source to film distance): 600 mm.

X-ray diffraction (XRD) analysis

XRD analysis was carried out on five samples which cut from transverse dissimilar welded joints. The dimensions of samples were (L: 10×W: 10× T: 6) mm which includes four zones; [Stir zone (SZ), Thermo-mechanical (TMAZ), Heat affected zone (HAZ) and base metal (BM)] as shown in Figure (2). XRD instrument type Scintag inc X2 X-ray was used with parameters as follows: Voltage: 42 KV, Current: 37 mA with Cu-radiation as x-ray source.

Microstructure Examination

Samples were taken from the cross section of FSW welds, and then grinding process was carried out using Al_2O_3 emery papers in sequence, 320, 500, 1000 and 1200 with using water for cooling the samples in each step. After that polishing process was carried out with using diamond paste to get polished mirror surfaces. Etching process was done to these samples using Keller's etchant which consists of (95ml H_2O+2.5 ml HNO_3+1.5 ml HCl+ 1 ml HF) to develop the microstructure of welded joints and base alloys. Microstructure examination of these samples had been investigated using MEIJI MT9430 high resolution optical microscope.

Mechanical tests

Tensile Test

Tensile specimens had been cut perpendicular to the weld line of FSW plates using CNC milling machine to the sub-size specimen geometry according to (ASTM E8M-04). Tensile strength had been conducted from stress-strain curves of the base alloys and welded joints.

Microhardness Test

Microhardness test was carried out using Vickers hardness tester type (HVS-1000). The measurements were done on transverse section to weld line for all welds after surface preparation from grinding and polishing processes until reaching to mirror polished surface .This test was done by measuring the microhardness values at spacing 1mm apart from one point to another with applied load of 9.8 N for 15 seconds.

Fatigue Test

Fatigue test was done at constant stress amplitude cantilever with fully reversed (R= -1), and the specimen dimensions according to the apparatus standard was L (length) ×W (width) ×T (thickness) =100×10×6.6 mm respectively. Ten samples were taken from each welded plate to implement the tests.

RESULTS AND DISCUSSION

Radiography Inspection Results

Radiography test inspection has been done as shown in Figure (3) which represents the x-ray photograph for accepted dissimilar FS welds, which mean with small or no defects. It was seen from welded sample (A1) that there is a crack in the end which is not defect but it's due to tool outlet that will cut away with the tool entrance. For welded sample (3A) there is a surface defect due to low or incomplete heat flow. This defect was removed by machining processes. For welded sample (B2) there is a small line defect which called (Joint line remnant) or what called (kissing bond). This is due to inadequate removal of oxide from plate edges also the increase in tool shoulder diameter may lead to this type of defect. This defect is not considerable and has a little effect on the mechanical properties. This defect appears in retreating side near the weld line [7,8] **.**The welded sample (B3) is free from defects when examined by this technique.

Macro and Microstructure Results

Stereoscopy microscope was used to examine the cross section of some FS welding joints. Figure (4) shows the uniform flow in sample (B3) between two alloys [2024-T3 (black region) with 7020-T6 (white region)] at a tool revolution of 920 rpm and feed of 40 mm/min. Also the FSW zones, advancing and retreating sides are clear in this image. Microstructure examination had been done for the three modes as follow:

Mode 1

The used tool was R18 tool steel which includes threaded cone pin with double bevel. FSW process was conducted with rotation speed of 275rpm and travel feed of 40mm/min. The nugget zone in this case contains an ultrafine grain with second phase precipitates as shown in Figure (5a and b). Also the same microstructure has been observed using higher rotation speed of 550 rpm but with better properties. With increasing the feed rate (as in sample A3) a reduction in mechanical properties will happen, also same flow lines has been noticed as in Figure (5c).

Mode 2

The R18 tool steel with threaded cylinder pin and concave shoulder of 4^{o} was used to increase the flow of alloys. Using revolution of 800 rpm and feed of 40 mm/min as in sample (B1) didn’t give good properties in spite of evolution of onion rings and flow lines as in Figure (6a and b) because of inappropriate conditions; also the heat affected zone (HAZ) has similar grain size and distribution to the base metal (alloy) as in Figure (6c). While using a revolution of 920 rpm for this tool as in sample (B2) lead to a defect named “kissing bond” which is an entrance of oxygen to form high density Al_2O_3 with an amorphous structure [9], as shown in Figure (6d).

It was found that increasing of tool revolution to 1100 rpm enhances the mechanical properties as shown in sample (B3) which gives the best properties in this case. While the rotation speed of 1250 rpm reduces the mechanical properties as in sample (B4). The three weld zones were illustrated in the photographs Figure (6e, f and g).

Mode 3

The R18 tool steel with beveled cone and concave shoulder of 4° is used.
A revolution of 1250 rpm and feed of 40 mm/min give the best properties for this case. The microstructure is similar to the previous cases due to convergence of welding conditions.

Tensile Test Results

The tensile strength (σ_t) of two base alloys was 499 MPa and 418 MPa for Al 2024-T3 for Al 7020-T6 respectively.

Table (2) Indicates the FSW welding conditions and tensile test results for dissimilar welded joints. Different feed rate have been used with mode 1 tool design; it has been found that 40 mm/min travel speed gives the best result, so it has been generalize for other tool designs modes.

Microhardness Results

A summary of results for three cases are illustrated in Figure (7). From these results minimum microhardness has been got in nugget zone due to high heat input, while in some cases a little rise or drop in HAZ zone has been got due to different heat flow and distribution of 2^{nd} phase precipitates. This is clear from x-ray diffraction results as in Figure (8) which represents the nugget zone phase analysis. This variation result from different tool designs and welding conditions. Microhardness values were lower in the retreating side than that in the advancing side because the material dragged by the shoulder during the welding from the retreating side of the weld, around the rear of the tool, and deposited on the advancing side. [10]

Fatigue Test Results

Fatigue test results of base alloys 2024-T3 and 7020-T6 were 160MPa and 150 MPa respectively as shown in Figure 9. While Figure (10) shows the S-N curve of dissimilar joints welded at the best welding parameters of travel speed of 40mm/min and rotation speed of 550 rpm with using tool Mode 1, and the fatigue endurance was 130 MPa.

Figure (11) shows S-N curve of dissimilar joints welded at the best welding parameters of travel speed of 40mm/min and rotation speed of 1100 rpm with using tool Mode 2 , and the fatigue endurance was 124 MPa. While Figure (12) shows S-N curve of dissimilar joints welded at travel speed of 40mm/min and rotation speed of 1250 rpm with using tool Mode 3 and the fatigue endurance was 115 MPa.

It has been found that increasing feed and travel speed had a deterioration effect on fatigue properties due to the reduction in required input heat to get sound weld. Also the best fatigue properties has been shown for FS welded specimen (A1) with maximum joint efficiency (86%) which is defined as the ratio (tensile strength of weld / tensile strength of base metal), This result is in agreement with other workers [11].

Analysis Fatigue Images by Scanning Electron Microscope

In order to study the fatigue behavior of dissimilar FSW joint, a scanning electron microscope images were taken for different regions in fracture section surfaces.

Figure (13a) shows the facets that formed in fracture section of FSW joint (sample A1) which is one of the aspects of cleavage fracture; also micrograph Figure (13 b) shows the macro cracks that generated from the surface in the fracture zone. A fatigue zone has been noticed in fracture section of FSW joint (sample B3), which is the upper part in macrograph while the lower part is the final fracture region and some grooves has been noticed as shown in Figure (13c). Different topography and fractography related to the difference in FSW parameters are also investigated.

CONCLUSIONS

1. The tensile test results showed that the fracture was in the weld zone or in the weld / HAZ borderline.
2. Mechanical and fatigue properties of the FS welds are reduced with increasing welding speed for dissimilar Al-alloys (2024-T3 and 7020-T6), and the lower speed gives better mechanical properties.
3. Making flutes in the tool design increases the flow of metals thus increases the mechanical properties, while making concave shoulder has less effect.
4. The best mechanical properties and fatigue endurance have been obtained at FS welding parameters, tool revolution speed of 550 rpm and feed rate of 40 mm/min with using threaded cone with double bevels.

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Table (1) The chemical compositions of Al- alloys.

	Alloy wt%	*Si*	*Fe*	*Cu*	*Mn*	*Mg*	*Zn*	*Ni*	*Ti*	*Pb*	*Sn*	*Others*	*Al*
Measured value	***Al-2024-T3***	**0.57**	**0.37**	**4.9**	**0.7**	**1.01**	**0.18**	**0.13**	**0.17**	**≤0.05**	**0.196**	**≤ 0.05 Cr**	**Rem.**
	Al-7020-T6	**0.67**	**0.15**	**0.55**	**0.08**	**0.60**	**4.8**	**≤0.05**	**0.22**	**≤0.05**	**0.16**	**…….**	**Rem.**
Standard value	***Al-2024-T3***	**≤0.5**	**≤0.5**	**3.8-4.9**	**0.3-0.9**	**-1.2 1.8**	**≤0.25**	**≤0.05**	**≤0.15**	**≤0.05**	**≤0.05**	**≤ 0.05 Cr**	**Rem.**
	Al-7020-T6	**≤0.35**	**≤ 0.4**	**≤ 0.2**	**0.05-0.5**	**1-1.4**	**4.5**	**≤0.05**	**≤0.05**	**……**	**……**	**0.22Cr+ 0.14Zr**	**Rem.**

Table (2) Results of tensile tests for dissimilar welded joints.

Tool Design	No.	Tool Rev (rpm)	Travel Speed (mm/min)	Al- alloys	σ_t ,MPa (weld)	Joint Efficiency %
Mode 1	A1	275	40	2024-7020	360	86.1 %
	A2	550	50	2024-7020	144	34.5 %
	A3	550	75	2024-7020	184	44 %
Mode 2	B1	800	40	2024-7020	160	38.3%
	B2	920	40	2024-7020	260	62.2%
	B3	1100	40	2024-7020	345	82.6%
	B4	1250	40	2024-7020	275	65.8%
Mode 3	C1	630	40	2024-7020	185	44
	C2	920	40	2024-7020	205	49
	C3	1250	40	2024-7020	290	69.4%

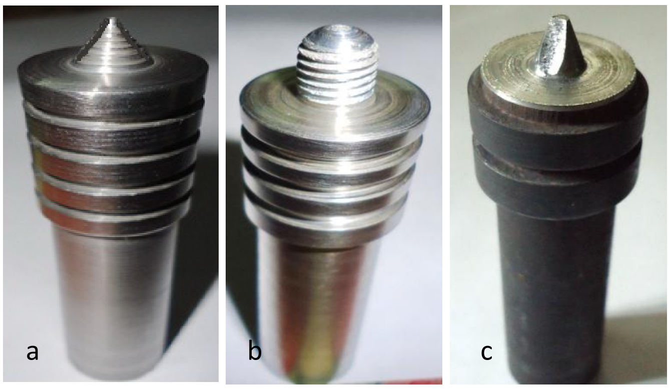

Figure (1) Tool designs used in FSW
a) Mode 1, b) Mode 2, c) Mode 3.

7020 (Advancing side)		*weld center*	*2024 (Retreating side)*	
1(Base Metal)	2(HAZ+TMAZ)	NZ(weld)	3(HAZ+TMAZ)	4 (Base Metal)

Figure (2) XRD specimen parts or divisions for FSW joint of dissimilar Al-alloys.

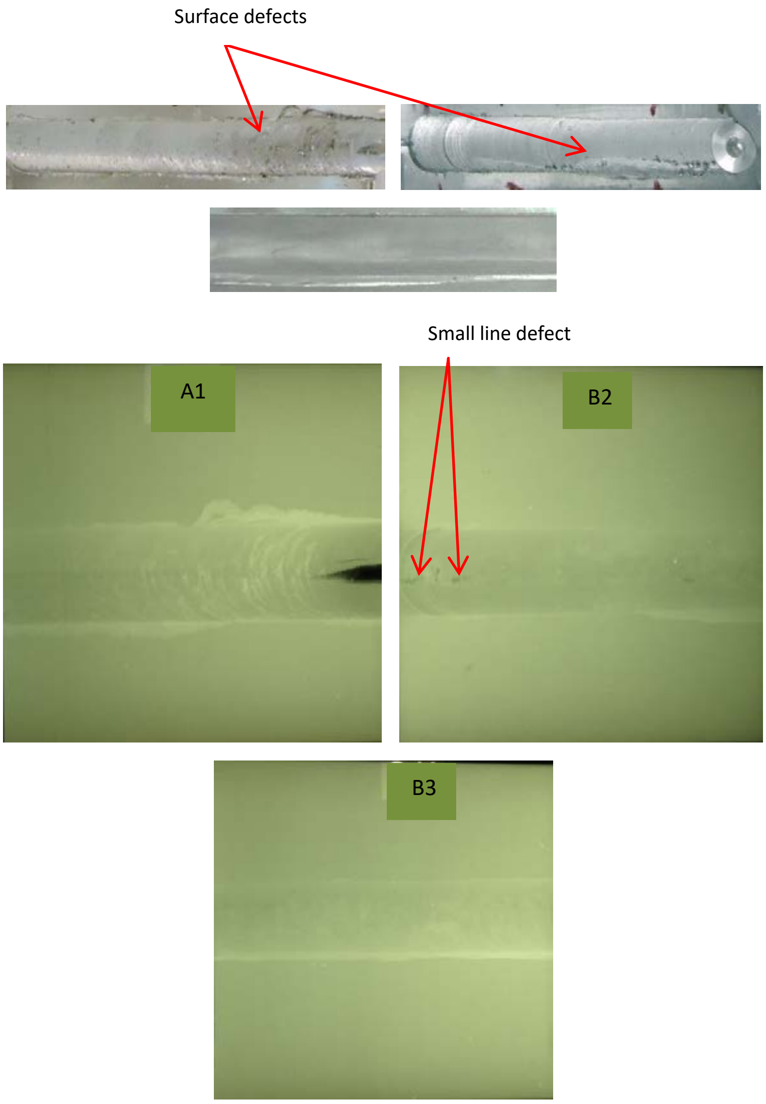

Figure (3) Photographs of X-ray radiography for FSW joints of samples A1, B2, B3

Figure (4) Macrograph of cross section of welded sample (B3).

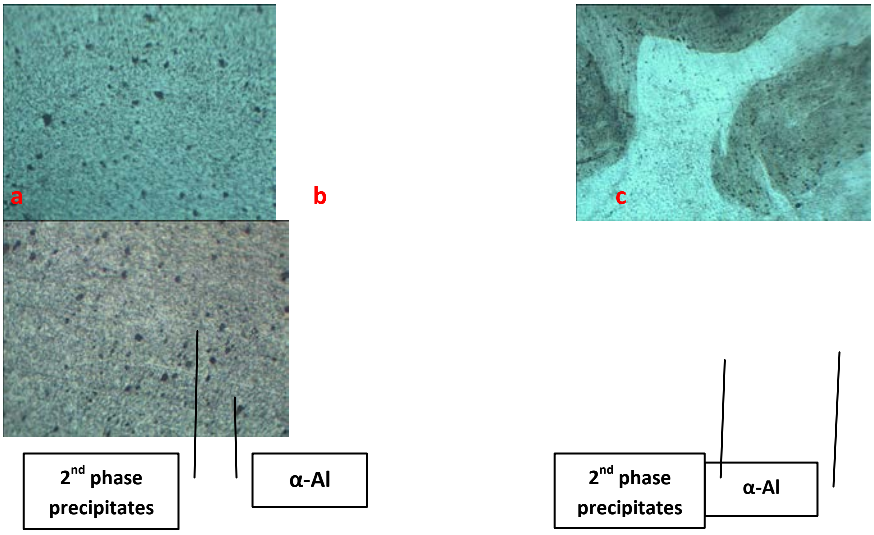

Figure (5) Microstructures of nugget zones in dissimilar welds with double bevels threaded cone tool, 400X.

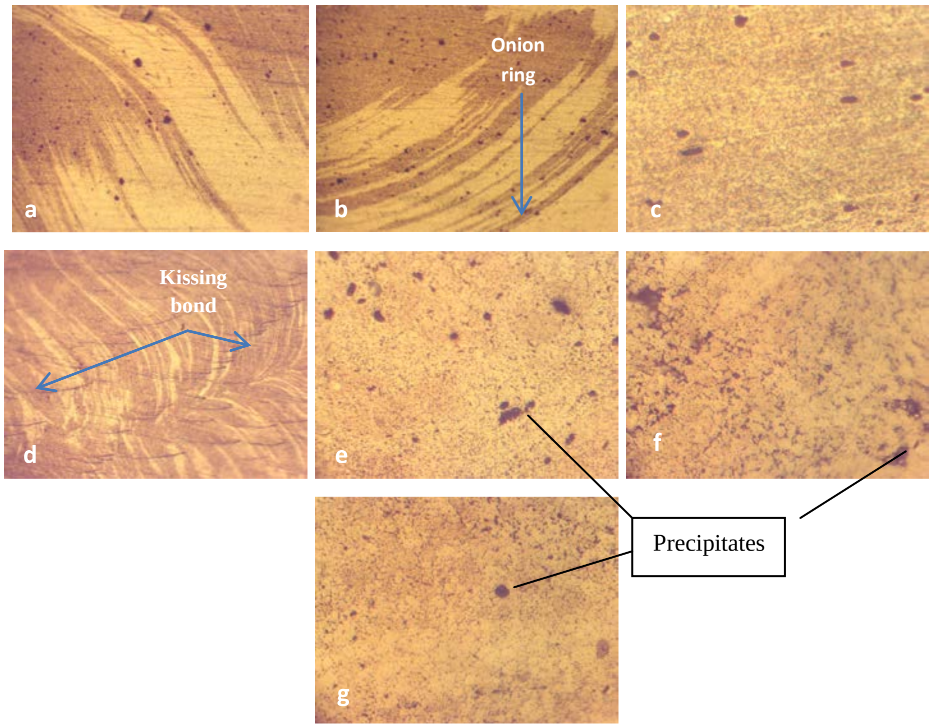

Figure (6) Microstructures of FSW welds for samples B1, B2 and B3.

a) Flow lines of sample B1 400X,b) onion rings,400X ,***c)*** Base metal in sample B1 1400X ***d)*** Kissing bond in sample B2 200X, e***)*** HAZ of sample B3 1400X , ***f)*** TMAZ of sample B3 1400X, ***g)***nugget zone of sample B3

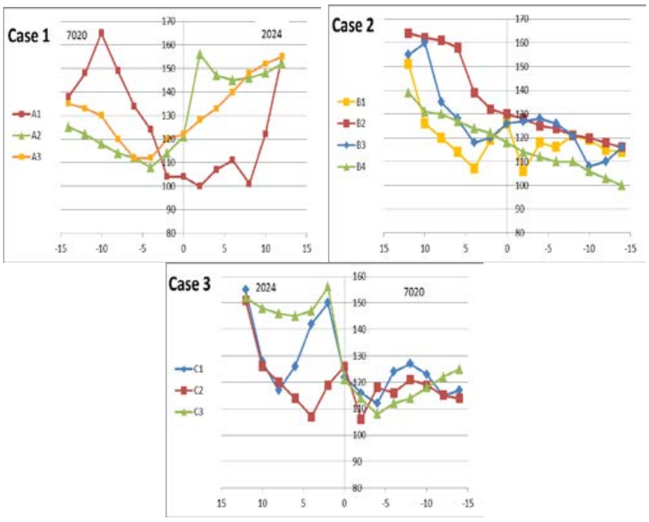

Figure (7) Microhardness distrbutions for three cases of dissimliar welds.

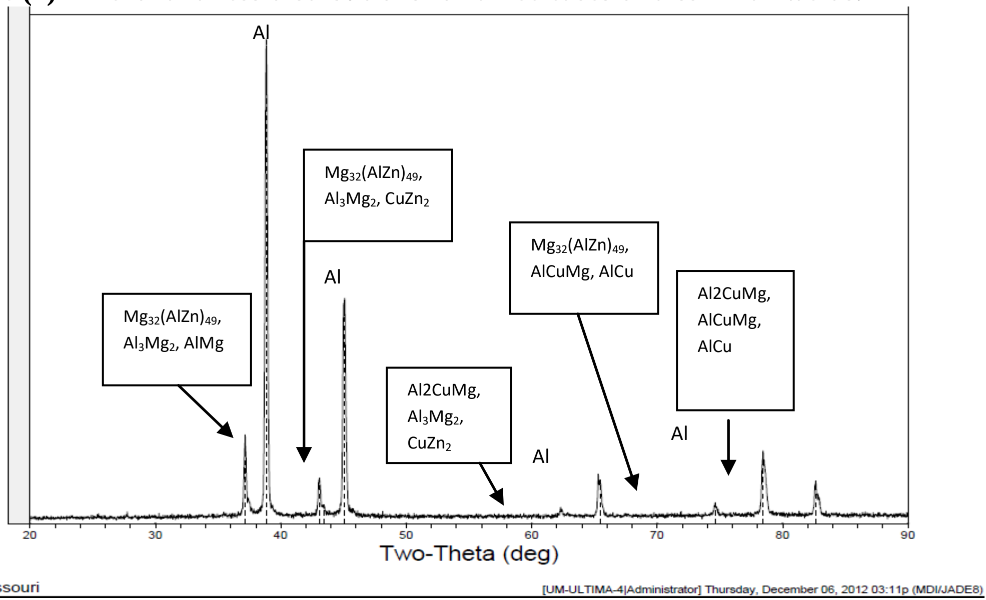

Figure (8) XRD analysi result for nugget zone of dissimilar weld (A1 sample).

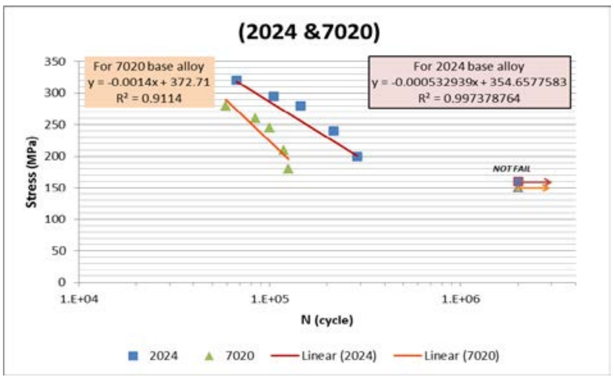

Figure (9) S-N curves of base alloy 2024-T3 and 7020-T6.

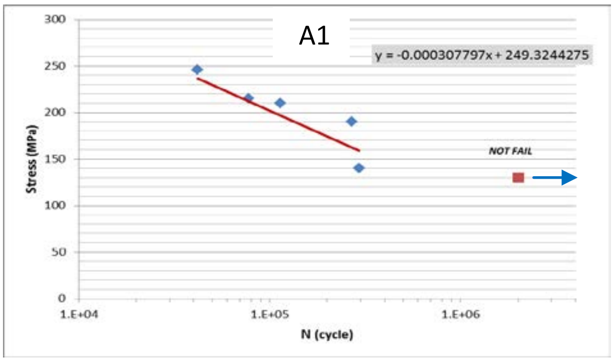

Figure (10) S-N curve of dissimilar joint welded with tool Mode 1.

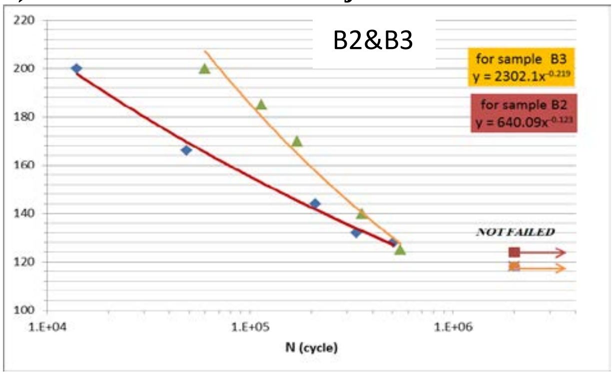

Figure (11) S-N curves of dissimilar joints welded with tool Mode 2.

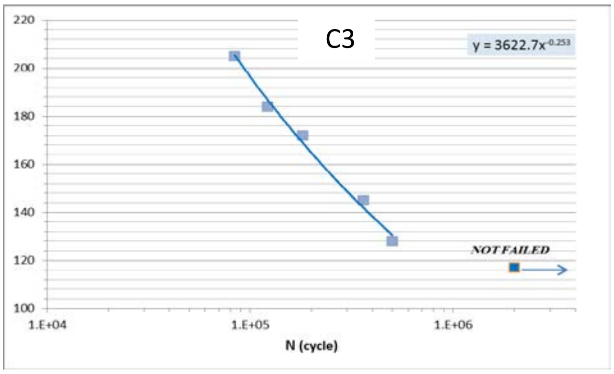

Figure (12) S-N curve of dissimilar joint welded with tool Mode 3.

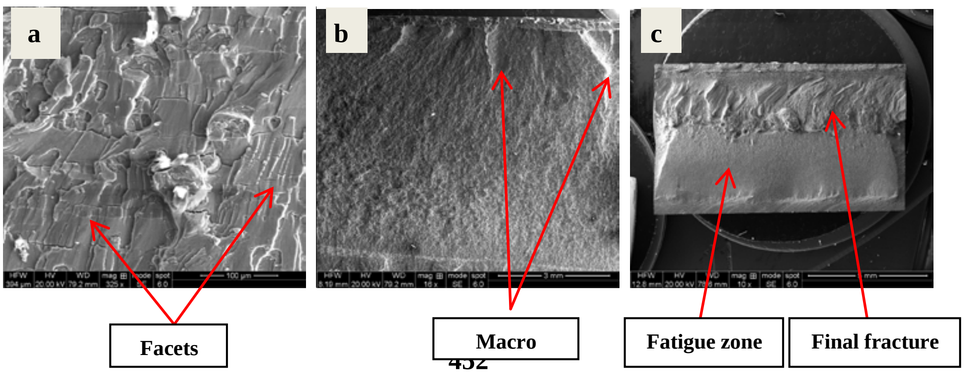

Figure (13 a) Striation in fracture section of dissimilar weld (sample A1),
b) Primary cracks in the same sample (A1)
c) Fatigue zone in fracture section of sample (B3).