EXPERIMENTAL EVALUATION OF BUTT WELDED SPECIMENS OF AA2024-T3 ALLOY WELDED BY FRICTION STIR WELDING WITH TWO CONSEQUENT PASSES +

تقييم تجريبي لوصلات اللحام التناكبي للالومنيوم AA2024-T3 الملحومة بطريقة اللحام الاحتكاكي بالخلط وبتمريرتي لحام متعاقبتين

Hatim Mohammed . Mahmood *

المستخلص:

الهدف من البحث هو تقييم الخواص الميكانيكية والتركيب الماكروي للوصلات التناكبية الملحومة بطريقة اللحام الاحتكاكي بالخلط و بتمريرتي لحام متعاقبتين (واحد من كل جهة).المعدن المستخدم هو صفائح اللحام (AA2024-T3) وبسمك ٥ ملم .سرعة اداة اللحام الدورانية ٩٠٠ دورة بالدقيقة وبتغذية خطية ٢٥ ملم /دقيقة.

في التمريرتين كانت اداة اللحام اما متداخلتين مع بعضهما بمقدار ٠،٥ ملم او بينهما خلوص مقداره ٠،٥ ملم .العينات الملحومة فحصت بجهاز الشد في درجة حرارة الغرفة وذلك لتحليل الخواص الميكانيكية ومقارنتها بالمعدن الاساس. التركيب الماكروي للعينات الملحومة تمت دراسته ايضا.كذلك تم قياس الصلادة المايكروية لمنطقة اللحام في العينات الملحومة.

اضهرت النتائج ان العينات الملحومة بخلوص مقداره ٠,٥ ملم بين اداة اللحام في التمريرتين تمتلك اجهاد خضوع اعلى من العينات الاخرى ولكن نسبة الاستطالة المئوية لهذه العينات اقل من العينات الاخرى ،في حين ان العينات التي تداخلت فيها اداة اللحام اضهرت اجهاد اقصى اعلى ونسبة استطالة مئوية اعلى من العينات الاخرى

Abstract:

The aim of the present work is to investigate the mechanical properties and macrostructure of butt joints friction stir welded (FSW) specimens welded with two subsequent passes (one from each side).The material used is AA2024-T3 aluminum alloy 5 mm thick .Pin rotational speed of 900 rpm and 25 mm/min feed is used in this work .

The two passes either interferes each other by 0.5 mm or a gap of 0.5 mm between them is existed. The welded specimens have been tensile tested at room temperature in order to analyze the mechanical properties with respect to the parent metal. The macrostructure of the welded specimens has been studied by employing optical microscopy. Micro-hardness examination is also performed on the welded specimens.

The two passes FSW specimens with 0.5 mm clearance showed higher yield stress and less percentage elongation than the others ,while specimens with 0.5 mm interference showed higher ultimate tensile stress and higher percentage elongation.

Keywords: AA2024-T3, Friction stir welding, subsequent passes , mechanical properties

+ **Received on 19/12/2010 , Accepted on 18/7/2011 .**

* **Assistant Lecturer /Technical College – Baghdad**

Introduction:

Friction stir welding (FSW) is a solid state welding process invented by the Welding Institute (TWI) in 1991 . It has widely used for welding soft materials such as Al and Mg alloys since then. In FSW the rotating pin is plunged into a rigidly held work piece and traversed along the joint to be welded .Welding is achieved by plastic flow of frictionally heated material from a head of the pin to behind it [1]. Such joining process is demonstrated to avoid severe distortions and the generated residual stresses are proved particularly low, compared to the traditional welding processes [2–3].

The FS Welded material produces three different areas: the weld nugget, the thermo-mechanically affected zone and the external heat affected zone. The micro-structural grain structure in the weld nugget is usually very fine and equi-axed due to the continuous dynamic re-crystallization process which leading to elevated mechanical properties[4-5].

Even that the FS Welded specimens show lower proof stress at 0.2% and limited total elongations with respect to the base metals, the mechanical results are extremely good considering the drastic conditions to which the materials are subjected during the Friction Stirring process[6]. The tensile properties of the welded joints are lower than those of the base materials [7,8,9,10].

This advanced technology is capable to weld aluminum alloys difficult to be welded with traditional fusion techniques such as the 2xxx series alloys which shows limited weldability .Dendrite structure occurs in the fusion zone due to conventional TIG and laser welding ,leading to a drastic decrease of the mechanical behavior [11].The FSW process is a sold- state process, therefore the solidification micro-structure is absent in the welded metal and the presence of brittle inter- dendritic and eutectic phases is avoided [12].

In this study the mechanical properties and microstructure of butt joints friction stir welded (FSW) specimens welded with two subsequent passes are investigated.

2.EXPERIMENTAL WORK

The base metal used in the present work was AA2024 alloy plate (4.2 Cu, 1.3 Mg, 0.7 Mn, 0.5 Si, 0.5 Fe, 0.25 Zn, 0.15 Ti, 0.1 Cr on wt% bases) of 5 mm thick in T3 conditions. The plate was cut and machined into square samples of (100x100) mm and they were butt welded using HMT milling machine. The longitudinal direction of FSW line was perpendicular to the rolling direction of the plate. HSS tool with a pin of 5 mm in diameter and 20 mm shoulder diameter was used to achieve the weldment ,see Fig. 1 , Two tools of different pin lengths are used for the pin length depending on whether the two passes were overlap on each other or a gap is presented between them see Fig. 2 and 3 .The rotational speed of the tool was set to 900 rpm and 25 mm/min travel speed according to optimized welding parameters determined so far.

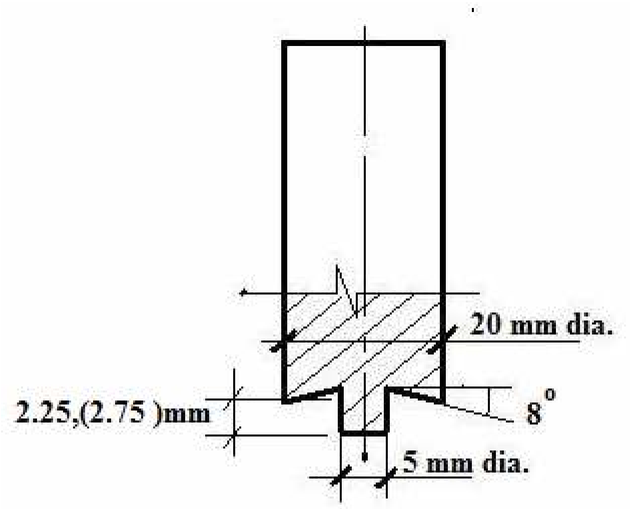


Fig.1. HSS tool

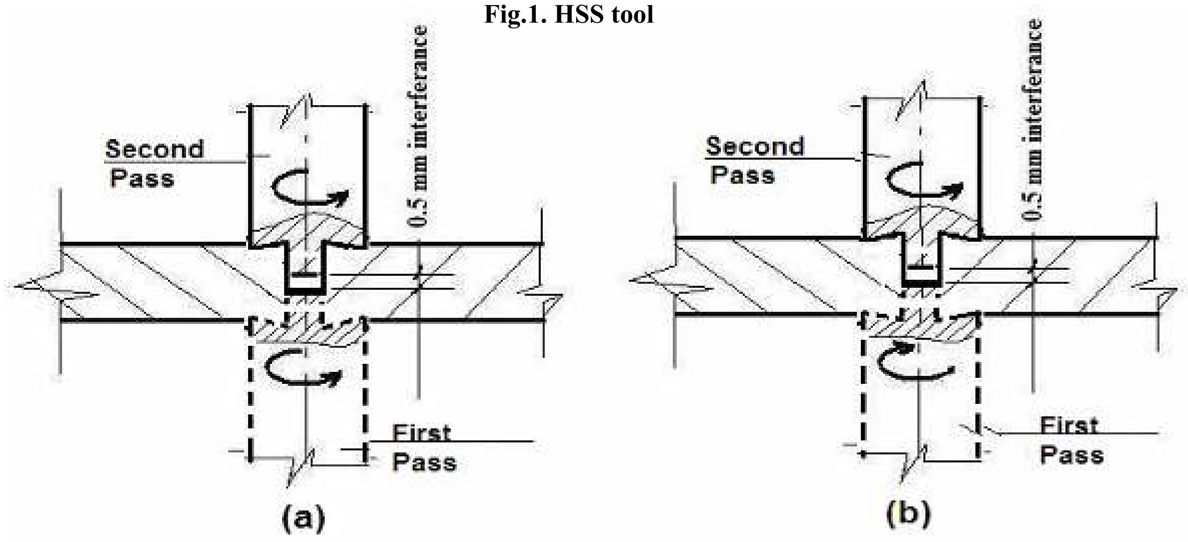


Fig. 2. Schematic of Welded specimen with 0.5 mm pin interference , a-same direction of pin rotation, b- opposite direction of pin rotation .

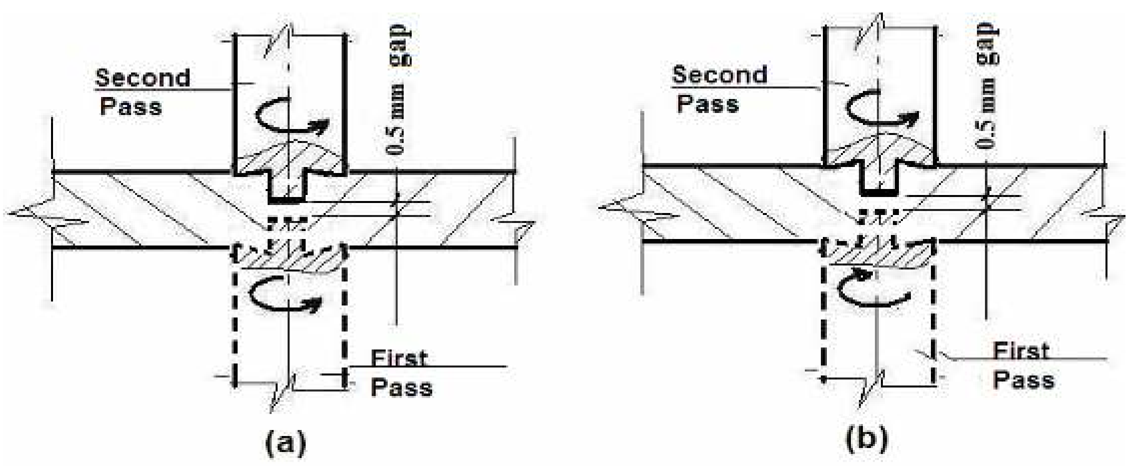


Fig.3. Schematic of Welded specimen with 0.5 mm pin gap , a-same direction of pin rotation, b- opposite direction of pin rotation .

The FSSW fixture and the welded plates during welding process are shown in fig.4. Tensile test have been executed at room temperature, the axial applied load was perpendicular to the weld line, the specimens having standard dimensions, fig.5.

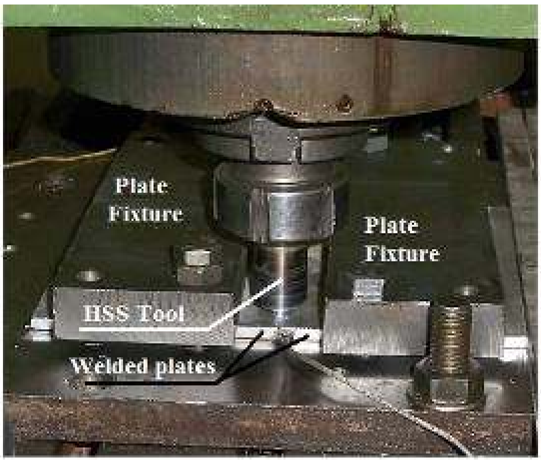


Fig.4. The fixture used to achieve the weld

The Vickers hardness profile of the welded zone have been measured on the weld cross-section using a Vickers indenter with 200gf load for 15 sec.

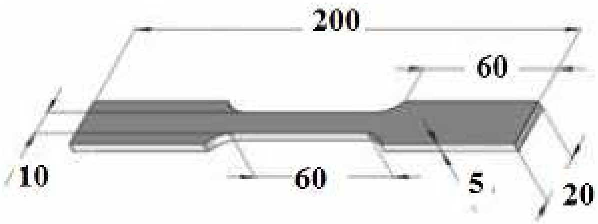


Fig.5 . The tensile test specimen

Results and discussion:

1.Tensile properties

Friction stir welded specimens welded with 900 rpm rotational speed and 25 mm/min traverse speed were tensile tested to evaluate the joint strength. Three specimens were tested for each condition ,the average value for these three tests were recorded. Tensile test results of the welded specimens as well as the base metal value are listed in table 1.

Table 1. Mechanical properties of welded specimens compared with base metal

	Modulus of Elasticity (GPa)	σ_y Yield stress (MPa)	σ_u Ultimate stress (MPa)	$(\sigma_{uw} / \sigma_{ub})^{\$}$ %	(ε%) Elongation %	$(\varepsilon_{w} / \varepsilon_{b})^{\$\$}$ %
Base Metal	77.4	361	482	100	17.2	100
0.5 mm Cl[#]. s. r.s.d.*	73.1	236	299	62.03	5.6	32.55
0.5 mm Cl. o. r.s.d.**	72.3	238	307	63.69	6.8	39.53
0.5 mm In[##]. s.r.s.d.	68.3	222	333	69.08	14.8	86.04
0.5 mm In. o.r.s.d.	72.3	211	333	69.08	14.4	83.72

*** (s.r.s.d.) Same rotational speed direction of the pin. ** (o.r.s.d.) Opposite rotational speed direction of the pin.(#) clearance between two passes, (##) pin interference between two passes, \$(σ_{uw}: ultimate stress of welded specimen, σ_{ub} : ultimate of base metal), \$\$ (ε_w : elongation % of welded specimen, ε_b : elongation % of base metal.**

The stress strain curves of the tested specimens and base material are shown in Fig.6-8 . It is clear from the tensile test results that the yield stress of the welded specimens with 0.5 mm pin gap is about 65.37% of base metal yield stress and it is higher than that of 0.5 mm pin interference welded specimens which represents 58.44% of base metal yield stress, while the ultimate tensile stress of the welded specimens with 0.5 mm pin interference was 69.08% which is higher than those of 0.5 mm pin gap welded specimens with a value of 63.69% .

The ultimate tensile strength of the welded specimens with 0.5 mm gap and opposite pin rotational speed records little bit higher than the ultimate tensile strength of the specimens with 0.5 mm gap and same direction of pin rotation , the reason is, when welding with opposite direction of pin rotation the advance side of the two passes are opposite each other, also the retreated sides were, which results in symmetric cross section during tensile test, while when the pin rotated in the same direction for the two passes the advance sides were in the same side of the pin and the retreated sides in the other side which produce unbalanced section during tensile test.

The FSW specimens with 0.5 mm pin interference record a percentage elongation for the both specimens (of same and opposite pin rotation) of 86.04% and 83.72% of the percentage elongation of the base metal respectively .

Welding with 0.5 mm pin interference leads to defect free weld while welding with 0.5 mm clearance results in un-welded area (the gap) which acts as a crack inside the weld results in lowering the weld strength and percentage elongation.

The percentage elongations of both FS welded specimens (specimens with same and opposite pin rotation) welded with a pin clearance of 0.5 mm were 32.55% and 39.53% of the percentage elongation of the base metal respectively. This low percentage elongation maybe due to the gap between the two passes which acts as a crack inside the weld results in low elongation. When the pin interfere each other in the two passes higher percentage elongation recorded (83.72 %,86.04%), this high elongation is due to defect free weld also to the stirring of the two plates together .

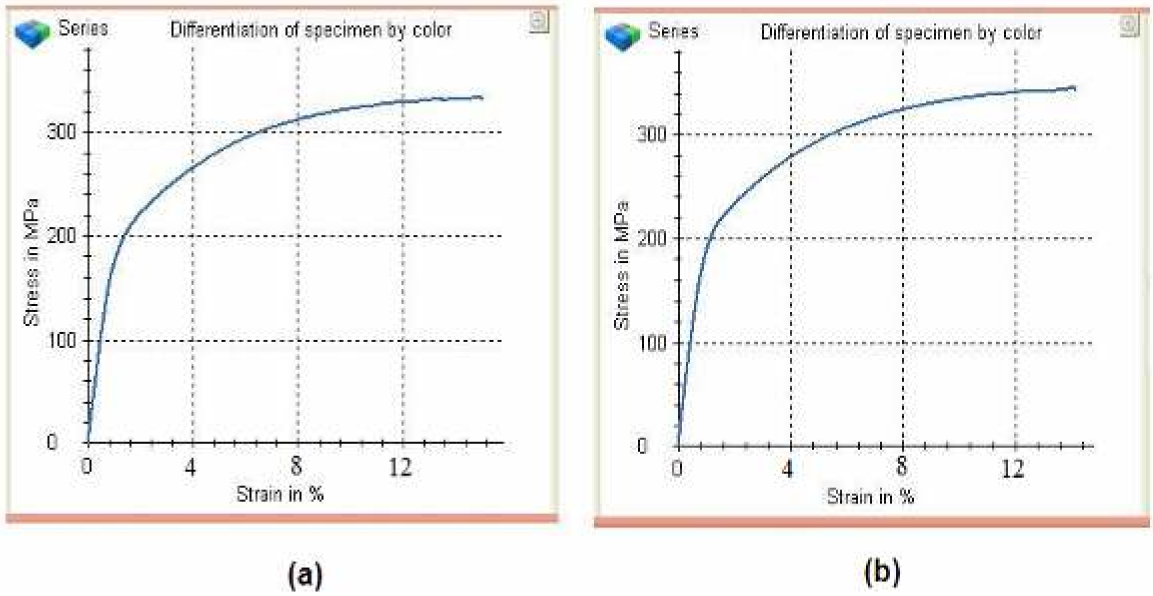


Fig. 6 . (a)Stress strain curve of welded specimens with0.5 mm pin interference and same rotational speed direction.(b) Stress strain curve of welded specimens with 0.5 mm pin interference and opposite rotational speed direction

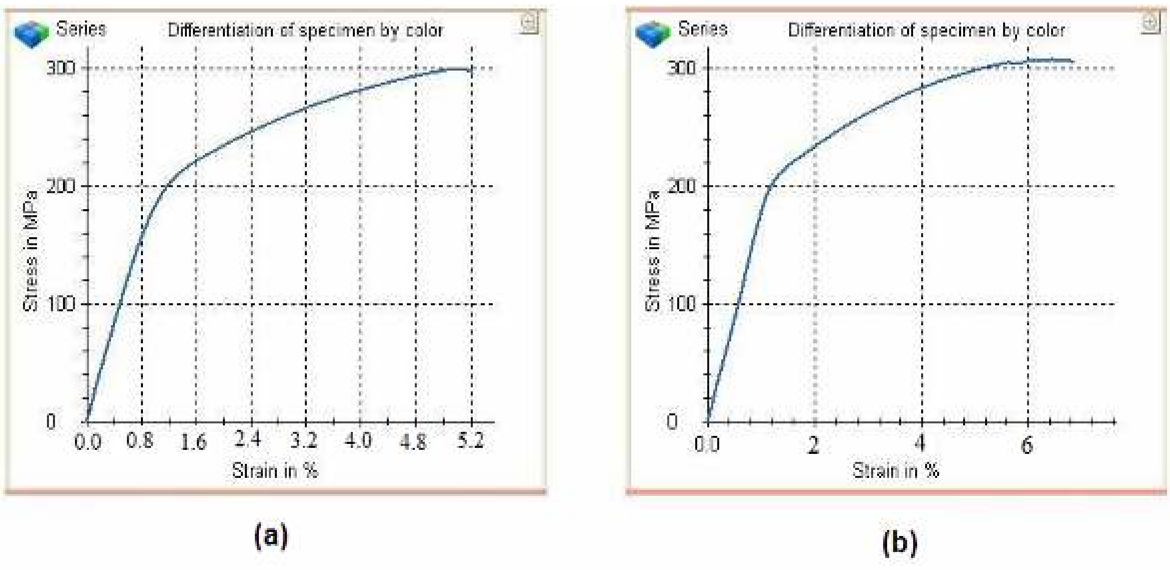


Fig. 7 (a) Stress strain curve of welded specimens with 0.5 mm pin clearance and same rotational speed direction.(b) Stress strain curve of welded specimens with 0.5 mm pin clearance and opposite rotational speed direction.

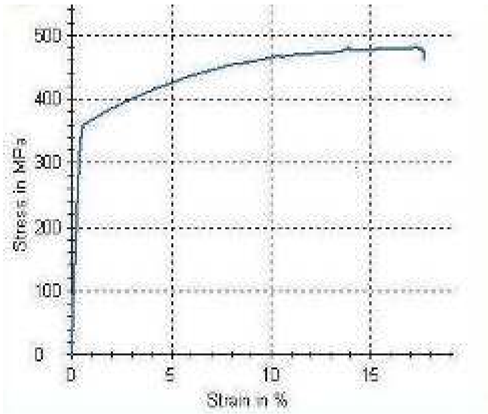
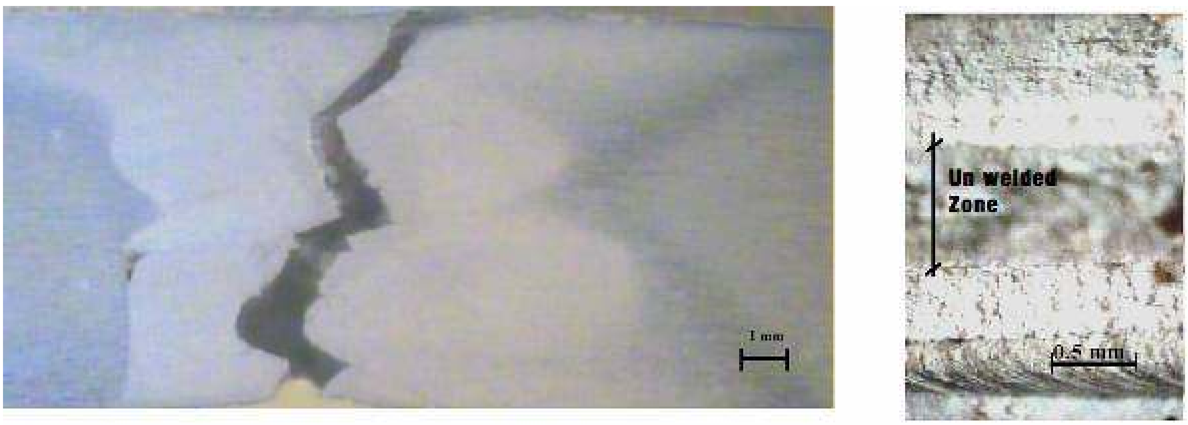


Fig. 8 . Tensile stress strain curve of base metal (tested).

2.Fracture of the joints:

2.1.Specimens with 0.5 mm pin gap

Visual inspection of the fractured specimens shows that the specimens with 0.5 mm pin gap failed in the weld zone with an intermediate un-welded area along the 0.5 mm gap between the two passes ,Fig.9 .
This inspection showed that the gap which was already existed between the two passes was not welded .So that this un-welded gap acts as a crack inside the welded specimens and this is the reason behind the reduction of the ultimate tensile stress and percentage elongation of these specimens ,fig.10.



(a) (b)

Fig. 9 . (a)Failure of 0.5 mm pin gap specimens .(b) Intermediate un-welded zone

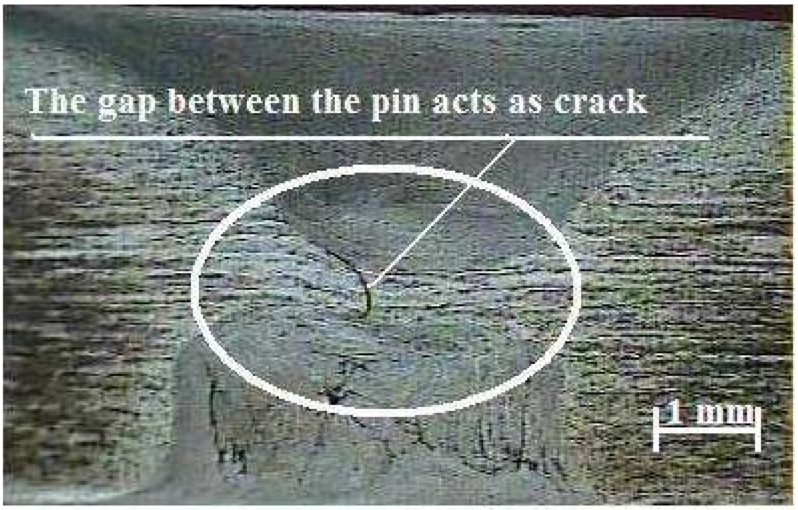


Fig. 10 .0.5 mm gap between the two passes acts as crack to initiate failure

2.2. Specimens with 0.5 mm pin interference

This specimens failed in the heat affected zone (HAZ) in the plane of maximum shear ,Fig. 11 .This is because the heat affected zone contains the region of lowest hardness due to coarse grains of this region compared with the nugget which composed of fine –equiaxed recrystallized grains [8].

Fig. 11 .Failure of 0.5 mm pin interference specimens

3-Macrostructure examination:

The welded specimens were cut vertically through the meridian plane. Cold mounted, polished . Etched with an etching solution of 0.5 vol.% HF in water.
The friction stir welding resulted in a grain refinement within the stir zone in all the joints produced .Nugget in which the dynamic recrystallization occurred consisted of grains which were much smaller and equiaxed when compared to base metal ,Fig.12-13 . This refinement depends on the heat input applied to the plates during friction stir welding.

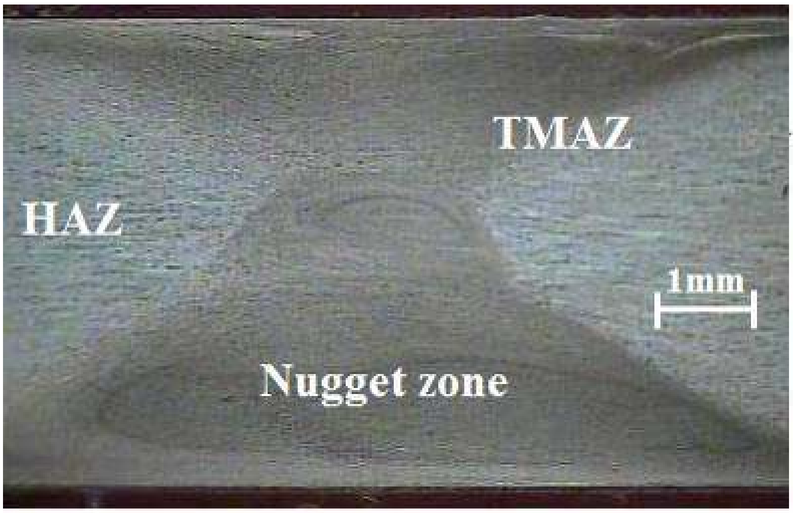


Fig.12 .Macrostructure of specimen welded with 0.5 mm interference and same rotational speed direction

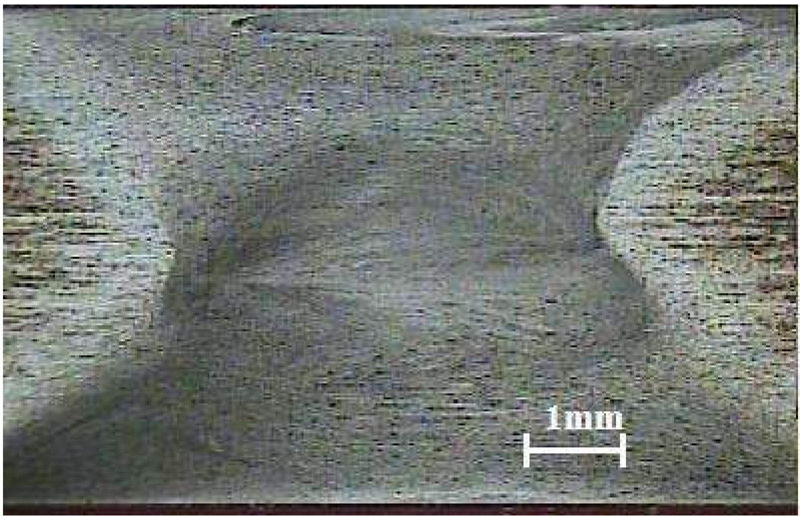


Fig.13 .Macrostructure of welded specimen welded with 0.5 mm pin interference and opposite direction of rotational speed

In specimens of opposite pin rotation the opposite rotation of the pin forces the grains beneath it to change its alignments and rotate with the pin so that an intermediate zone of mixed direction was existed and this is true for both pin clearance and pin interference specimens ,Fig.14. While unidirectional mixed zone is formed in the specimens of same pin rotational speed direction, Fig.12.

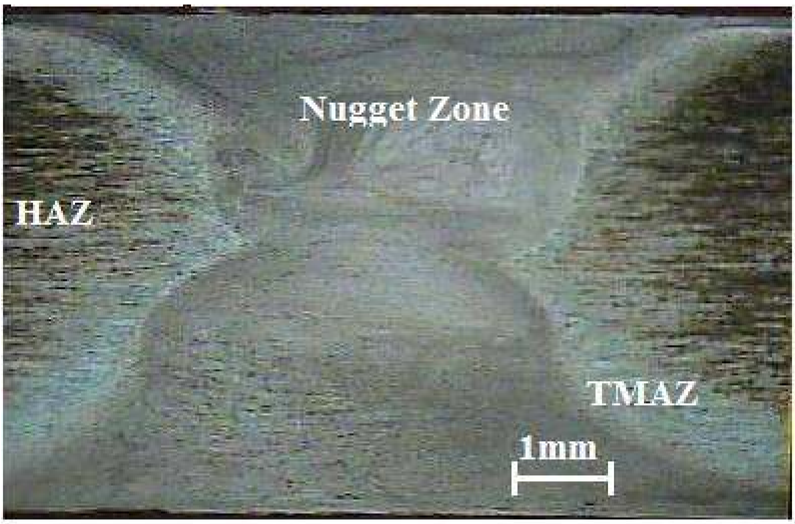


Fig. 14 .Macrostructure of welded specimen welded with 0.5 mm pin clearance and opposite pin rotational speed direction

4-.**Micro-hardness examination:**

The micro-hardness as a function of distance from the centerline of the friction stir weld and the depth of the weld were shown in Figs.15-17.

Fig.15. shows three regions of hardness distribution; (1) the central part of the weld (nugget zone) corresponds to the fully plasticized region of the FSW weld which shows low hardness ; (2) the thermo-mechanically heat-affected zone (TMAZ) has a hardness higher than the central zone(nugget) because this region suffer from high strain rate deformation during welding, the grains at this zone are coarser than these of the nugget zone, and (3) the heat affected zone (HAZ) which has a hardness higher than the preceding zones but lower than the base metal hardness.

The hardness on two sides of the FSW weld show a slight difference in hardness value , possibly due to the asymmetric nature of the process (advance and retreat sides).

The hardness across the thickness of the welded specimens shows that the hardness across the second pass is higher than that across the first pass due to the additional heat results from the second pass which decrease the hardness of the first pass.

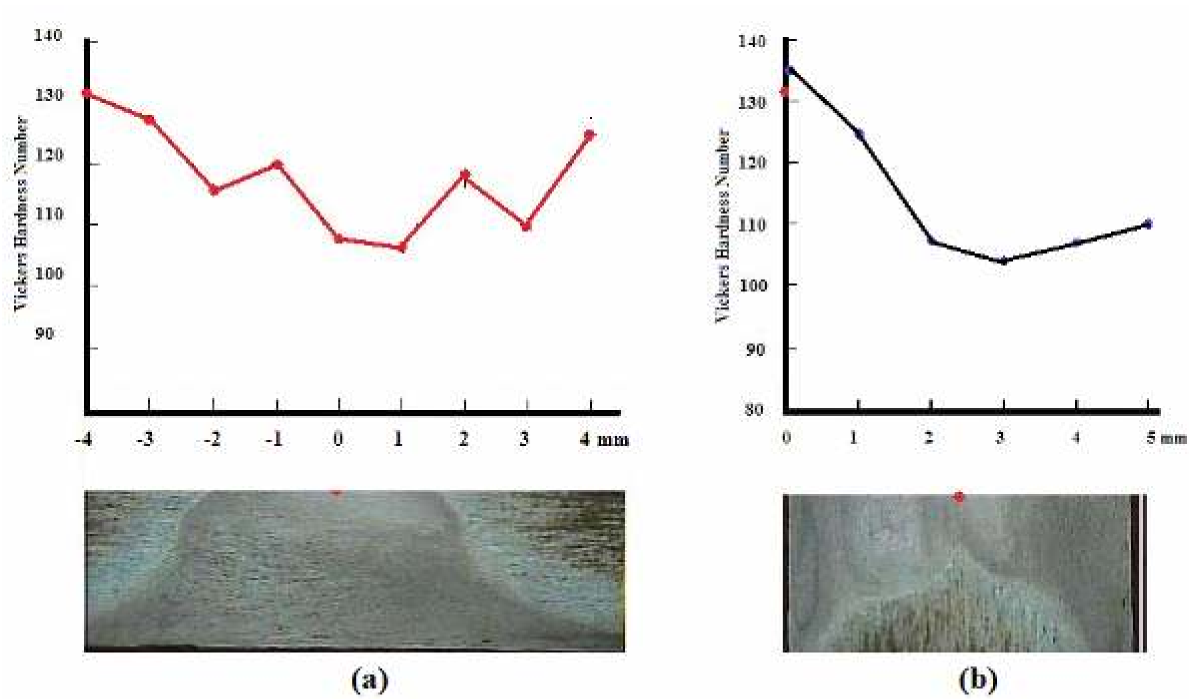
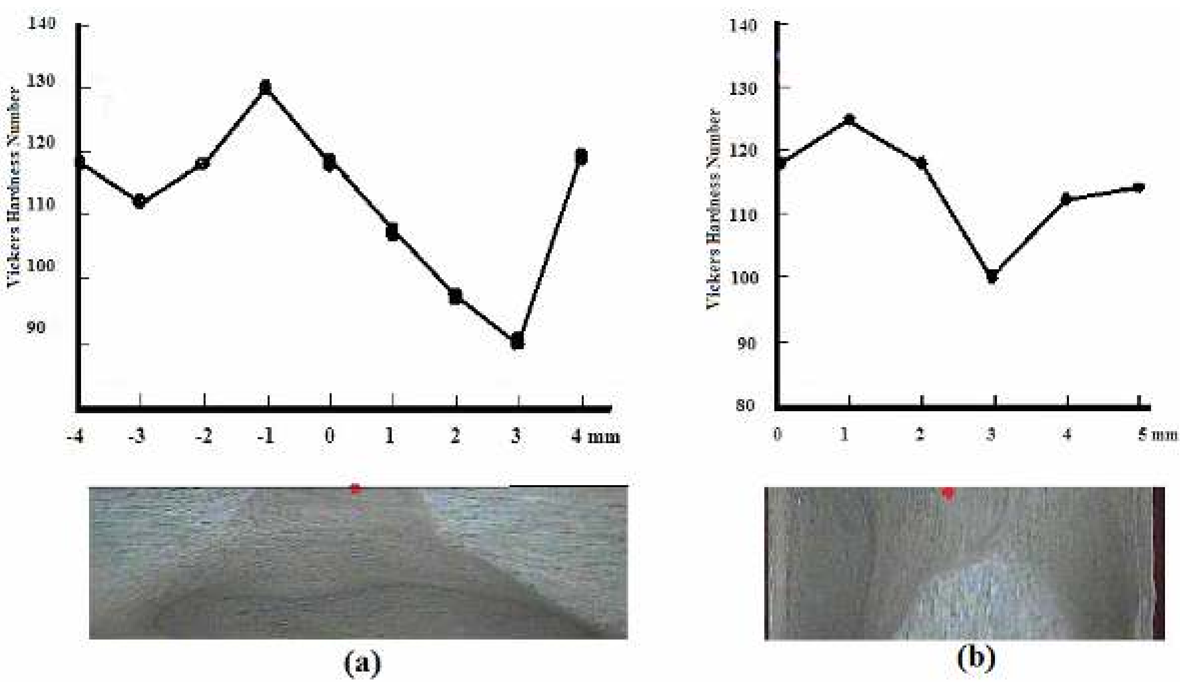


Fig. 15 .Microhardness distribution of specimens welded with 0.5 mm pin gap and opposite rotational speed direction,(a) along the weld, (b) across the thickness of the plate.



Fig,16 .Microhardness distribution of specimens welded with 0,5 mm interference and same direction of pin rotation, (a) along the weld, (b) across the thickness of the plate.

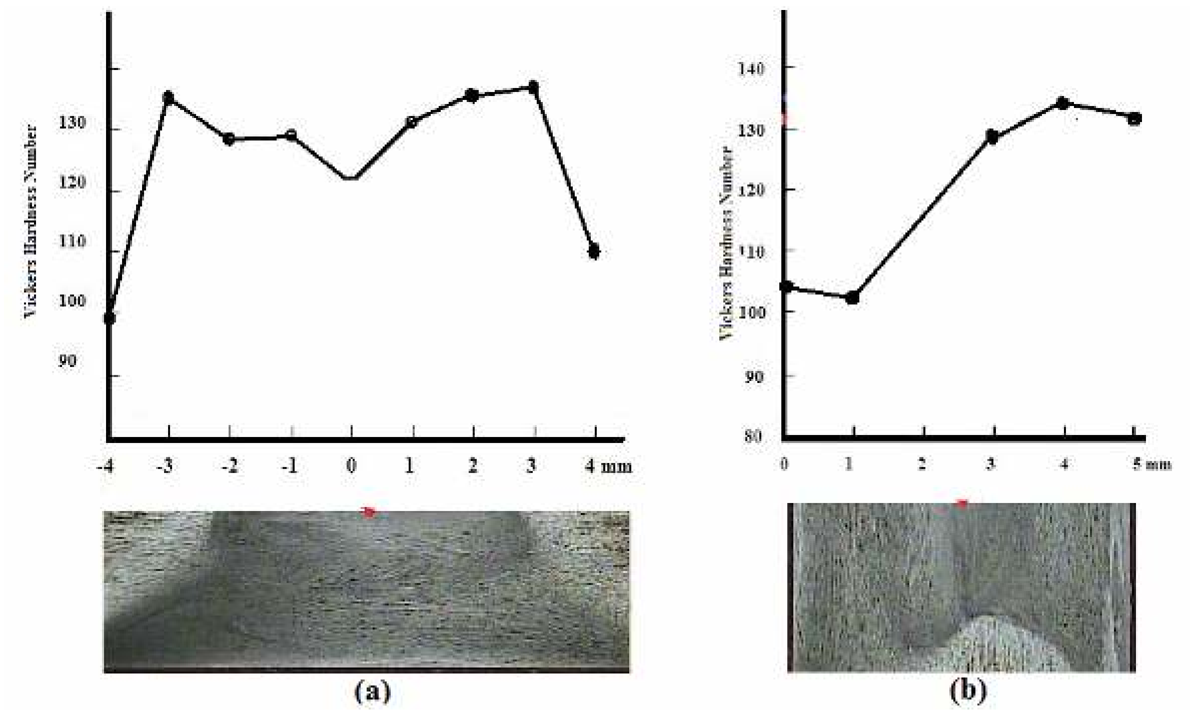


Fig.17. Microhardness distribution of specimens welded with .0.5 mm interference and opposite pin rotational speed, (a) along the weld, (b) across the thickness of the plate

Fig.16-17. Shows that the central part of the weld recorded higher hardness than the HAZ and this is may because the pin interference resulted in strain hardening of the central part which resulted in high hardness at this part of the weld, while the heat generated from stirring resulted in a coarse grains at the HAZ this coarse grains leads to low hardness of this region.

Conclusions:

From the results of two consequent passes of friction stir welded specimens discussed previously following we can conclude the following;

1. The gap between the passes acts as a crack inside the weld which causes lower strength and elongation of the welded specimens.
2. According to the above conclusion and in order to get weld without crack in single pass butt FSW, the pin must have a length longer than the thickness of the plate to be welded (packing plate of material similar to that of welded plates must be used) or the un-welded part of the plates beneath the pin must be removed.
3. If welding with two consequent passes is essential , the welding must be achieved with pin interference and same direction of pin rotation.
4. The direction of pin rotation was slightly affecting the strength and elongation of the fractured specimens.

References:

1. Y. K. Yang, H. Dong, Y. A. Chang, and S. Kou, Liquation of Mg alloys in Friction Stir Spot Welding, *Welding Journal*, Vol.87(July 2008) 167-177.
2. G. Bussu, P.E. Irving, The role of residual stress and heat affected zone properties on fatigue crack propagation in friction stir welded 2024-T351 aluminium joints, *International Journal of Fatigue* 25 (2003) 77–88.
3. K.V. Jata, K.K. Sankaran, J. Ruschau, Friction stir welding effects on microstructure and fatigue of aluminium alloy 7050-T7451, *Metallurgical and Materials Transactions* 31A (2000) 2181– 2192.
4. I. Charit, R.S. Mishra, M.W. Mahoney, Multi-sheet structures in 7475 aluminum by friction stir welding in concert with post-weld superplastic forming, *Scripta Materialia* 47 (2002) 631–636.
5. K.V.Jata, S.L. Semiatin, Continuous dynamic recrystallization during friction stir welding of high strength aluminum alloys ,*Scripta Materialia* 43(8)(2000)743-749.
6. P. Cavaliere ,R. Nobile, F.W. Panella, A. Squillace,Mechanical and microstructural behavior of 2024-7075 aluminum alloy sheets joined by friction stir welding,*Int. j. of machine tool manufacture* 46(2006) 588- 594.
7. A.Parcellona, G. Buffa, L. Fratini, D. Palmeri, On micro structural phinomena accurring in friction stir welding of aluminum alloys*, Journal of material processing technology* 177(2006) 340-343.
8. H.J.Liu,H.Fujii,M.Maeda,K.Nogi,Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy, *Journal of Material Processing Technology* 142 (2003) 692-696.
9. H.J.Liu, M.Maeda, H.Fujii, K.Nogi,Tensile properties and fracture locations of friction-stir-welded joints of 1050-H24 aluminum alloy,*Journal of material science letters* 22, 2003, 41-43.
10. H.J.Liu,H.Fujii,M.Maeda,K.Nogi, Mechanical properties of friction stir welded joints of 1050-H24 aluminum alloys, *science and technology of welding and joining* 2003, vol.8 , No6, 450-454.
11. J.Q. Su, T.W. Nelson, R. Mishra, M. Mahoney, Microstructural investigation of friction stir welded 7050-T615 aluminum *, Acta Materialia* 51 (2003) 713-729.
12. C.G. Rhodes, M.W. Mahoney, W.H. Bingel, Effect of friction stir welding on microstructure of 7075 aluminum*, Scripta Materialia* 36(1997)69-75.