Comparative Study of Influence Post weld Aging on the Mechanical Properties of Similar Friction Stir Welded Joints for Al 2024-T3 and Al 7075-T73

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ABSTRACT:
The aim of present study is to investigate the effect of precipitation hardening heat treatment at different aging conditions on the mechanical properties and microstructure of similar friction stir welding (FSW) joints of AA 2024-T3 and AA 7075-T73 aluminum alloys. Friction stir welding was carried out using milling machine with best welding parameters (tool rotation speed 898 rpm, welding speed 45 mm/min and threaded cylindrical pin geometry). Tensile test, microhardness test, microstructure examination, and X-ray radiographic inspection of FSW joints were made. The results indicated that the best aging conditions for similar welded joints of Al 2024 and Al 7075 were in sample (natural aging for two week) and sample (artificial ageing at 120°C for 24 h) respectively. Microhardness in the as-welded samples showed fluctuations across the weld zone and minimum hardness occurs in the heat affected zone(HAZ) in both alloys while the hardness after heat treatment at best aging conditions was improved across the whole weldment and increased in stir zone,
Keywords: friction stir welding, aluminum alloys, mechanical properties, post weld aging.

دراسة مقارنة لتاثير التعتيق اللاحق على الخواص الميكانيكية لوصلات اللحام المتشابهة بالخلط الاحتكاكي من سبائك الالمنيوم T3-2024 و T73- 7075

الخلاصة
يهدف هذا البحث الى التحقق من تاثير المعاملة الحرارية التصليد بالترسيب عند ظروف تعتيق مختلفة على الخواص الميكانيكية والبنية المجهرية لوصلات اللحام المتشابهة بالخلط الاحتكاكي من سبائك المنيوم 2024 و 7075. تم اجراء اللحام عند افضل ظروف لحام من سرعة دوران 898 دورة \دقيقة , وسرعة لحام 45 ملم \ دقيقه مع تصميم الاداه اسطواني مسنن. تم اجراء اختبار الشد والصلادة وفحص البنية المجهرية والفحص بحيود الاشعة السينية على الملحومات. وبينت النتائج على ان افضل ظروف تعتيق للملحومات المتشابهة لسبائك الالمنيوم 2024 و 7075 كانت عند النموذج بعد(التعتيق الطبيعي لمدة اسبوعين) والنموذج بعد (التعتيق الاصطناعي عند 120 لمدة 24 ساعة) على التعاقب . واظهر اختبار الصلادة للملحومات تقلب في قيم الصلادة عبر منطقة اللحام وكانت اقل صلادة عند المنطقة المتاثرة بالحرارة لكلا السبيكتين بينما اظهرت الصلادة بعد المعاملة الحرارية عند افضل ظروف تعتيق تحسين عبر الملحومة وازدادت عند منطقة اللحام.

INTRODUCTION:

Friction stir welding (FSW) is a relatively modern and an environment friendly solid-state welding process suited for welding of similar and dissimilar aluminum alloys especially the 2xxx and 7xxx series, which have many difficulties and problems in fusion welding processes [1].

The process of friction stir welding has been widely used in the aerospace, shipbuilding, automobile industries and in many applications of commercial importance .This is because of many of its advantages over the conventional welding techniques some of which include very low distortion, no fumes, porosity or spatter, no consumables (no filler wire), no special surface treatment and no shielding gas requirements [2]. Heat-treatment is commonly applied to change and improve the mechanical properties of aluminum alloys. This treatment is known precipitation hardening which includes the solution treating of the alloy above solvus temperature to allow solutionizing of the second phase followed by quenching in water to room temperature and finally it could be heated to a temperature above room temperature to allow precipitation [3].

Haşim Kafali and Nuran AY. (2009)[4] studied the mechanical properties of friction stir welded joints of AA6013-T6 sheet of 3.6 mm thick. Welding was carried out at welding speed of 1000 mm/min and rotation speed of 1200 rpm. The result shows that both the parent material and the weld region consist of relatively homogenous distributions of the fine and coarse Mg_2Si particles. Uniformly distributed, finer strengthening Mg_2Si precipitates, smaller grain size, and higher dislocation density are the reasons for the superior tensile properties of the FSW joints. Friction stir welding results in a dynamically recrystallized grain structure in the weld nugget with smaller grain size than that in the base alloy.

Q. M. Doos and S. J. Mohmood(2011) [5] studied the effect of tool pin profile and diameter on microstructure and mechanical properties of friction stir welded joints of 3.8 mm thickness of (AA2218-T72) aluminum alloy using different mechanical tests including (tensile, bending and microhardness tests). Rotation speed of (900rpm), welding speed of (30mm/min) and five different tool pin profiles (straight cylindrical, threaded cylindrical, triangular, square, and threaded cylindrical with flat) with three different pin diameter of (3,4 & 5) mm have been used to fabricate the joint. The results show that above aluminum alloy can be welded using FSW process with maximum welding efficiency of (86.95%) and (83.21%) in terms of tensile strength and bending force respectively with using tool pin profile (threaded cylindrical with flat) with pin diameter of (5) mm, rotation speed of 900 rpm and welding speed of 30 mm/min.

Muna K. Abbass and Hassan H. Abd (2013)[6] examined a comparison between the mechanical properties and the microstructure of welded joints of aluminum alloy AA6061-T6 plate of 4mm thick obtained with friction stir welding (FSW) and conventional tungsten inert gas welding (TIG).

The results indicate that the best welding parameters in FSW joints are (1250 rpm-50 mm/min) and (800 rpm-125 mm/min) which give maximum tensile strength and joint efficiency of (79%) of base alloy compared to that of TIG joint of (57%).It was found that the microhardness values in the TIG welded joints are lower than that of the FSW joints. The formation of fine equiaxed grains and very fine strengthening precipitates (Mg_2Si) in the stir or weld region are the reasons for higher tensile strength and hardness of FSW joints compared to TIG joints.

R.K.R. Singh et al.(2011)[7] studied the effect of post weld heat treatment on the microstructure and mechanical properties of friction stir welded plates of 6mm thick 7039 aluminum alloy. FSW was carried out at two welding speeds of (8 and 12 mm/min) and one rotation speed of (635) rpm. PWHT involved solution treated at 550°C for 4 h, followed by water quenching at room temperature and artificial aging at 190°C for 6 h. The maximum joint efficiency was obtained for joint produced at higher welding speed in as welded (92.1%) and heat treated (60.8%) condition .Post weld heat treatment decreases yield strength, ultimate tensile strength but improves percentage elongation.

P. Murali Krishna et al.(2011)[8] focused on the effect of post weld heat treatment (PWHT) on microstructure and mechanical properties of dissimilar friction stir welding of(AA2024-T6 and AA6351-T6) plate of 5mm in thick. Friction stir welding was carried out at rotation speed (800) rpm and welding speed (0.35, 0.7 &1, 2) mm/sec. A post weld solution treatment at 490°C for 2h and subsequent ageing at 180°C for 12h resulted in improvement in mechanical properties (hardness and tensile strength). It was found that the maximum strength in the weld was achieved by post weld solution treatment and ageing which resulted in uniform precipitation throughout the weld zone, HAZ and base metal.

Gu¨ven Ipekog˘ Lu et al.(2014)[9] investigated the effects of initial temper condition and postweld heat treatment(PWHT) on the microstructure and mechanical properties of the friction stir welded of dissimilar aluminum alloys(AA7075-O/6061-O and AA7075-T6/6061 T6) of 3.17 mm thick. Friction stir welds were produced using two different sets of weld parameters for both dissimilar combinations, namely, 1000 rpm and 150 mm\ min (1000 /150) and 1500 rpm and 400 mm \min (1500 /400). Postweld heat treatment (PWHT) consisting of solutionizing at (530°C) for 4 hours followed by quenching and artificial aging at (140°C) for 6 hours, was applied to the dissimilar joints obtained . It was found that sound dissimilar joints can be produced for both temper conditions. A hardness increase was obtained in the joint area produced in the O-temper condition, whereas a hardness loss was observed in the joint area in the T6 temper condition. PWHT generally resulted in an increase in the strength values of both O and T6 joints, very high joint performance values in terms of tensile strength were obtained.

The present work aims to make a comparative study of influence post weld aging on the mechanical properties of similar friction stir welded joints for aluminum alloys Al2024-T3 and Al 7075-T73.

Experiment Work

Material selection

Aluminum alloy plates of AA2024-T3 and AA7075-T73 have been selected to be joined by friction stir welding process due to their wide applications such as aerospace industry, automotive, building and architecture, etc [10]. These plates were cut by punch cutter to the dimensions of (150×70×3) mm. The chemical composition of these alloys was carried out by using spectrometer analysis instrument in the General Company for Examination and Rehabilitation Engineering, as shown in **Table1**. Mechanical properties of these alloys were summarized in **Table 2**.

Welding process

Friction stir welding process was carried out to fabricate butt welded joints for similar aluminum alloys of AA2024-T3 and AA7075-T73 by using milling machine.
The milling machine which was used in this study is (type: Knuth Werkzeugmaschinen GmbH, Germany). Fixture system should be added as shown in **Figure (1).**

The friction stir welding experiment has been carried out using tool made from tool steel type X12M, manufactured in (General Foundation for Mechanical Industry/Al- Eskandria). Welding tool is designed and machined as shown in **Figure (1)**. The tool was subjected to heat treatment (hardening and tempering) and the tool has average hardness value of 53-55HRC. The used tool was threaded cylindrical tool. The shoulder diameter: 18 mm whereas the pin diameter was: 6 mm and its height: 2.8 mm which is slightly less than that of plate thickness (3 mm). As shown in **Figure (2).**

Welding Parameters

Friction stir welding processes were carried out at different welding parameters. Such as rotational speed of (898, 1200 and 1710) rpm and welding speed of (20, 45 and 69) mm/ min. The tilt angle (2◦), plunging depth (0.1) mm and dwelling time (30sec) remain constant.

Tests and Inspections

Tensile Test

Transverse tensile test was performed in order to estimate the tensile properties of FSW joints at all welding parameters. Tensile specimens were cut and machined using CNC milling machine type (C-TEK) from the welds in direction perpendicular to the welding direction, with geometry in accordance with the specifications given in the ASTM standard E8M-09 for sub-size specimens as shown in **Figure (3)** [11].

Precipitation Hardening Heat Treatment

Precipitation hardening heat treatment was performed on friction stir welded specimens at the best welding parameters at rotation speed and welding speed (898 rpm and 45 mm/ min) respectively which gave free defects welded joints and higher tensile strength than other parameters. Precipitation hardening Heat treatment was carried out at different aging conditions for both similar welded joints of aluminum alloys AA2024-T3 and AA7075-T73 as shown in **Table 3.**

Microstructure Inspection and Hardness Test

Optical microscope was used to examine the microstructures of samples which were made from a cross section of the FSW joints and base alloy in sequences steps. The operation of wet grinding was made using water and emery paper of SiC in various grits of 320, 500, 600, 800, 1000 and 1200. The process of polishing was made on the samples using 0.5µm diamond paste and special cloth for polishing and lubricant. The process of etching was carried out on the samples by using etching solution Killer's reagent (composition: 95ml H_2O , 2.5ml HNO_3, 1.5ml HCl, 1.0ml HF) [12]. They were washed and dried. Optical microscope is used to provide information about the microstructure of welded samples.

Digital microhardness tester type (Laryee, Mode HVS-1000) was used to conduct the Vickers hardness test. A 500g load was applied to the welded joint cross section for 15 sec.

Results and Discussion

Tensile strength results

The results of tensile tests of similar welded joints of aluminum alloys (2024-T3) and (7075-T73) at the best welding parameters (rotation speed 898rpm, welding speed 45mm\min and threaded cylindrical pin geometry) are summarized in Table 4.

From Table 4, the tensile strengths of similar FSW joints of 2024-T3/2024-T3and 7075-T73/ 7075-T73 aluminum alloys are lower than those of the base alloys. This is due to inhomogeneity in chemical composition and microstructure in different welding zones of friction stir welded joint and may be presence of some welding defects.

R.K.R. Singh et al. [7] reported similar trend for tensile properties of as welded FSW joints which are lower than those of the base alloys. This is may be due to difference in microstructure between various welding zones and this is also return to the natural of the welded joints and its regions and drawbacks of the joints and heterogeneous microstructures, and dissolution and/or coarsening of second phase particles.

Precipitation hardening heat treatment was conducted to similar FSW joints at the best welding parameters as shown in Table 5 and Figures (4 and 5).

From Table 5, it is seen that AA2024 welded joints for samples H6 is more suitable for aging condition (natural aging for one week) than for AA7075 welded joints. This is due to the natural aging for one week are not enough time to get a stability in mechanical properties and the precipitates needed longer time to appear and re-precipitate than other phases, so that the tensile strength decreases for AA7075-T73 similar welded joints. While for sample H7 (natural aging for two weeks) in AA2024 welded joints give the highest tensile strength compared to 7075 welded joints. A sample H8 is suitable for aging condition (artificial aging at 190°C for 4hr) for AA2024-T3 welded joint but less suitable for AA7075 welded joint. This is attributed to precipitate of 2^{nd} phase particles such as Al_2Cu, and AlCu in alloy matrix as indicated in

XRD analysis results. These results are in agreement with the results of researcher [13] who studied effect of different aging times at 190°C for similar FS welded joints of 2024 aluminum alloy.

Finally sample H9 is more suitable for aging condition (artificial aging at 120°C for 24hr) for AA7075 welded joint. It was seen that the tensile strength increases to the value of 370 MPa, this is due to the formation of coherent precipitates within the lattice of the parent solid solution and to the precipitate of hardening particles ($MgZn_2$) in alloy 7075 T73, and in this form distortion within the a lattice is caused. This effectively hinders the movement of dislocations and so the yield strength and tensile strength are increased.

Microhardenss results

The microhardness profiles of the similar welded joints of aluminum alloys (Al 2024 and Al 7075) can be seen in **Figure (6).** It is noticed that the microhardness increases in stir zone (SZ) in both similar welded joint of (Al2024 and Al7075) compared with that of the thermo mechanical affected zone (TMAZ) and HAZ, which reach to maximum values of (152 HV and 156 HV) respectively. While the hardness values of base alloys are 137HV and 155 HV for Al 2024 and on the Al 7075 respectively. This is because frictional heat and plastic flow during FSW create fine and equiaxed dynamic-recrystallized grains in the stir zone (SZ) and elongated and recovered grains in the (TMAZ). The (HAZ) is often specified by means of only material hardness changes but there is no difference in grain structure compared to the base alloy. This softened HAZ region can be characterized by the dissolution and coarsening of the strengthening precipitates or 2nd phase particles during friction stir welding. These results are confirmed by many researchers [14].XRD result of both alloys can be seen in Figures (8and 9).

Figure (7) indicates the microhardness results of the similar welded joints after precipitation hardening heat treatment at best aging conditions. Best aging conditions for Al 2024 welded joint was sample H7 (natural aging for 2weeks) whereas for Al 7075 welded joints was sample H9 (artificial Aging 120°Cfor 24hr). It was noticed that the hardness values become higher for all zones of weld after solution and age treatments. This is due to the re-precipitation of the precipitates during age treatment.

Microstructure results:

The microstructural observations of cross section of similar FSW joints of 2024-T3 / 2024-T3 and 7075-T73 / 7075-T73 welded at best welding parameters are presented in Figures (10 and 11) respectively. These figures indicate the distinct microstructural regions such the stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ).

Figures (10a and 11a) show the microstructure of base alloys of Al 2024 and Al 7075 respectively. It is observed that the elongated grains with some precipitates are distributed in Al alloy matrix. Figure (10b and 11b) show the microstructure of HAZ which is similar to that of base alloys, and there is no obvious change in the grain structure and there is no plastic deformation in this zone. Figure (10c and 11c) show the distinct grain boundary between the recrystallized zone (stir zone) and deformed zones of the TMAZ. Figures (10d and 11d) represent the thermo-mechanically affected zone (TMAZ), in which grains are deformed, non-recrystallized, elongated and rotated due to plastic deformation caused by stirring process.

Figures (10e and 11e) refer to the stir zone ,this zone is dynamically recrystallized because of this zone undergoes to the largest heat and deformation which lead to very fine grains within an onion rings patterns which were seen in both similar welds Al 2024 and Al 7075 welded joints.

K. Kumar et al [15] reported that the onion ring formation in the friction stir welds are due to the combined effect of geometric nature of pin-driven material flow, and vertical movement of the material due to shoulder interaction.

Figure (12) show micrographs of cross-section FSW joints after precipitation hardening heat treatment and different aging conditions.

CONCLUSIONS

1- Friction stir welding (FSW) of similar welded joints for aluminum alloys Al 2024-T3 and Al 7075-T73 was successfully performed.

2- It was found that the microhardness in SZ is higher than TMAZ and HAZ due to grain refinement and presence of precipitates.

3- The solution heat treatment followed by artificial ageing at (120°C for 24 h) is more effective and beneficial to increase the tensile properties of similar welded joints of Al 7075 alloy.

4- Natural aging for two weeks is more effective and beneficial to increase the tensile properties of similar welded joints of Al 2024 alloy.

Table (1): Chemical composition for AA2024-T3 and AA7075-T73.

Element wt%	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	V	Al
2024	0.126	0.280	4.37	0.593	1.27	0.0133	0.0099	0.166	0.0167	0.008	0.0105	Bal
7075	0.0539	0.296	1.64	0.0105	2.12	0.183	0.0022	5.56	0.020	0.008	0.008	Bal

Table (2): Mechanical properties of 2024-T3 &7075-T73

Alloy	Yield strength YS(Mpa)	Tensile strength TS(Mpa)	Elongation%	Hardness HV Kg/mm^2	Temper
2024-T3	345	450	22	137	T3:solution heat treatment followed by cold work
7075-T73	380	455	16	155	T73: Solution heat treatment and then overaged\stabilized

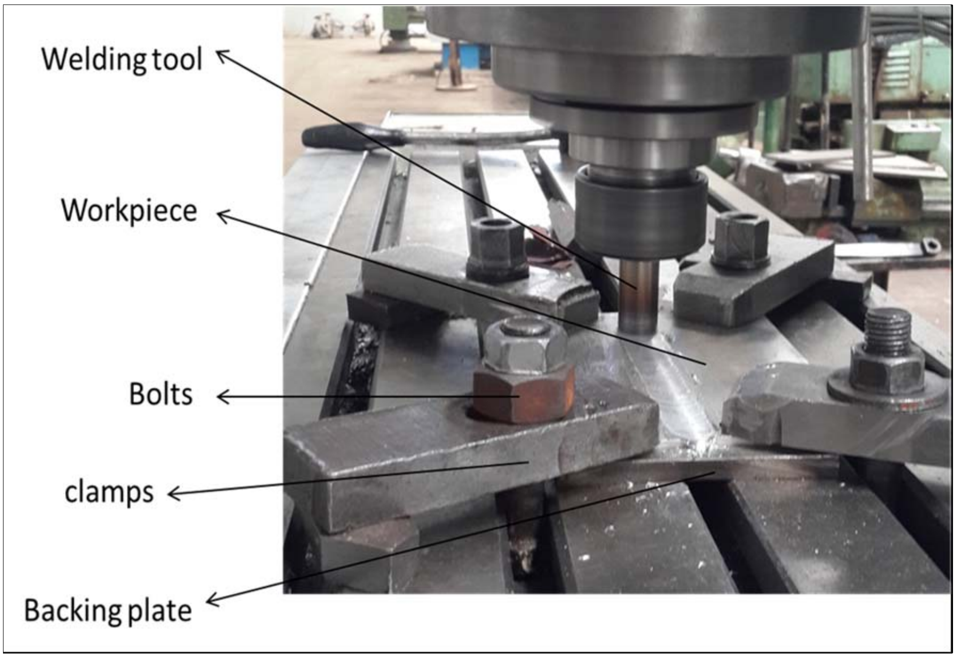
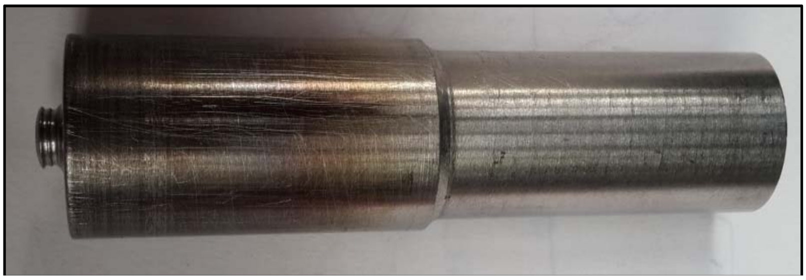


Figure (1) Fixture system, welding tool and work pieces.



Figure(2): Threaded cylindrical pin tool used in this study.

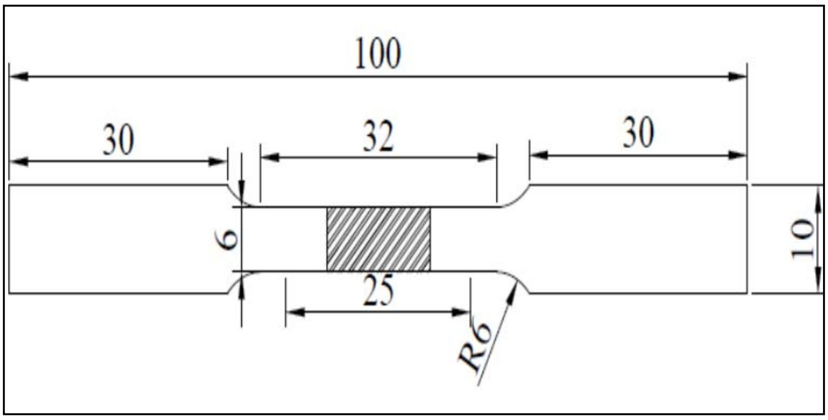


Figure (3) ASTM- E8M Sub-Size Sample for Tensile Test, all dimensions are mm [11].

Table (3): Different aging conditions of similar welded joints for AA2024-T3 and AA7075-T73.

Symbol	Heat treatment at aging conditions
H6	Solution heat treatment (495°C for 30 min) + quenching + natural aging for 1week.
H7	Solution heat treatment (495°C for 30 min) + quenching + natural aging for 2weeks
H8	Solution heat treatment (495°C for 30 min) +quenching + artificial Aging (190°C for 4hr)
H9	Solution heat treatment (495°C for 30 min) +quenching + artificial Aging (120°Cfor 24hr)

Table (4): Tensile test results of similar welded joints for (Al 2024-T3 and Al 7075-T73)

specimen	Tensile strength (Mpa)	Elongation %	joint efficiency %
2024-T3 Base alloy	450	22	-
7075-T73 Base alloy	455	16	-
Weld (2024+ 2024)	330	11.5	73
Weld(7075 + 7075)	320	7	70

Table (5): Tensile test results after different aging conditions of similar welded joints for (Al 2024-T3 and Al 7075-T73).

Sample symbol	Al- alloy	Tensile strength (Mpa)	Elongation %	joint efficiency%
H6	2024+2024	335	14	74
	7075+7075	285	3.5	63
H7	2024+2024	345	16.5	77
	7075+7075	178	2.5	39
H8	2024+2024	310	14	69
	7075+7075	300	3.5	66
H9	2024+2024	285	10	63
	7075+7075	370	4.5	81

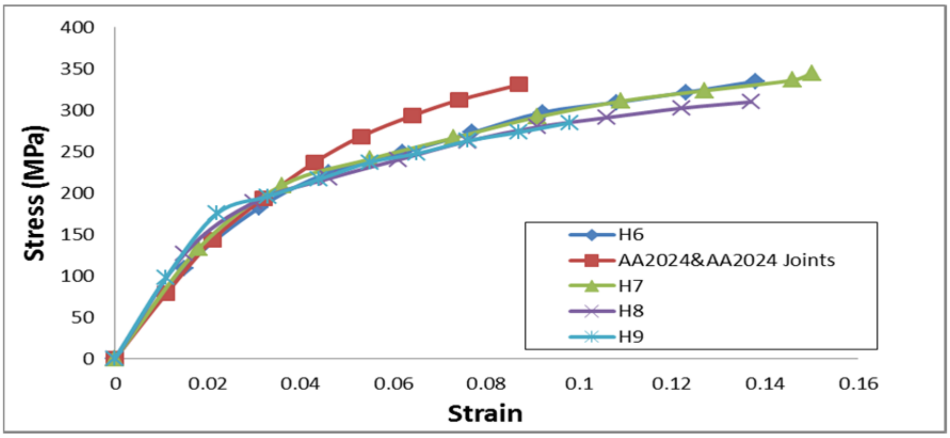


Figure (4) stress-strain curves of similar Al 2024 welded joints after different aging conditions

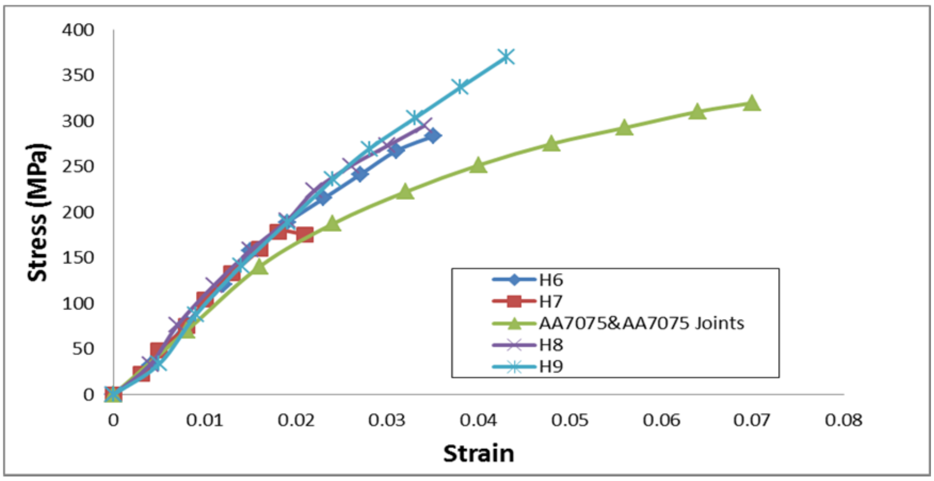


Figure (5) Stress-strain curves of similar Al7075 welded joints after different aging conditions

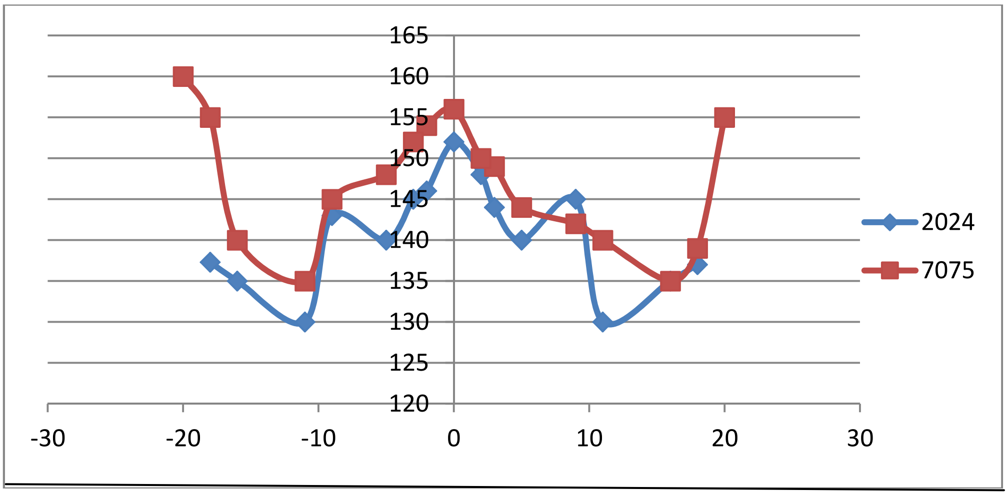


Figure (6) Microhardenss distribution(as welded condition) before heat treatment

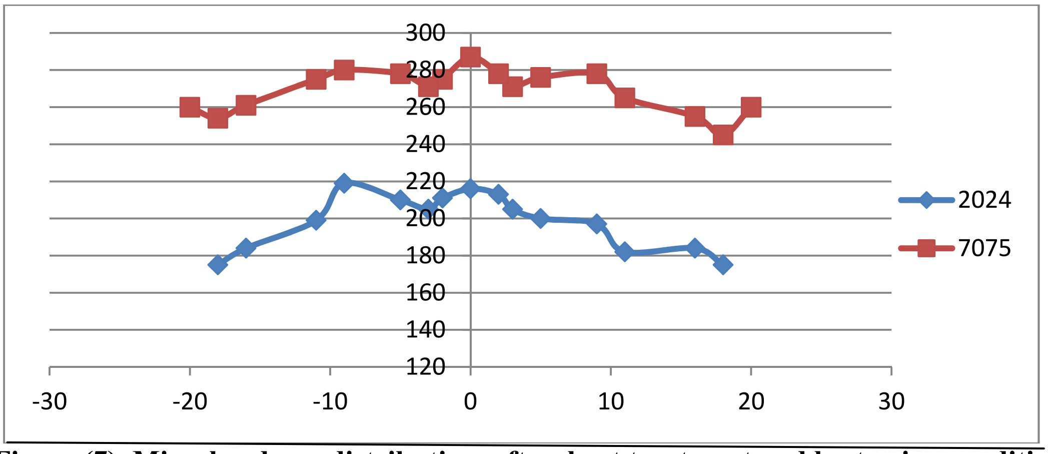
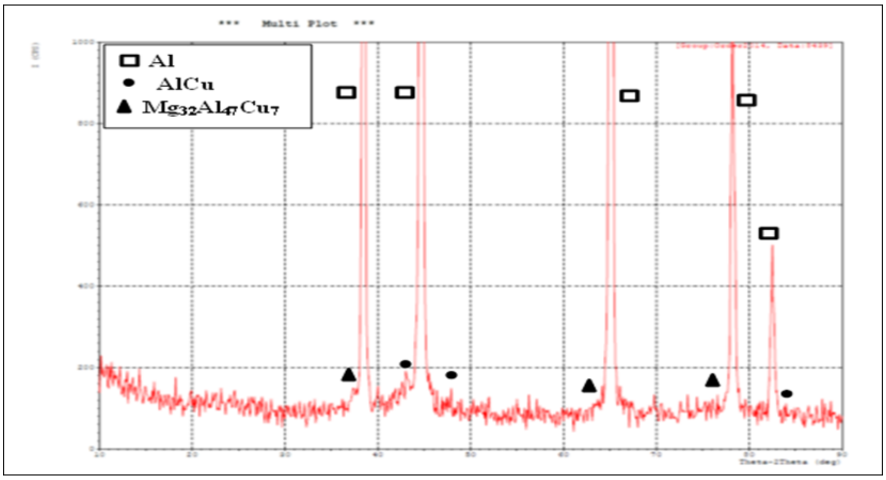


Figure (7) Microhardenss distribution after heat treatment and best aging conditions



Figure(8) XRD results for Al 2024 base alloy

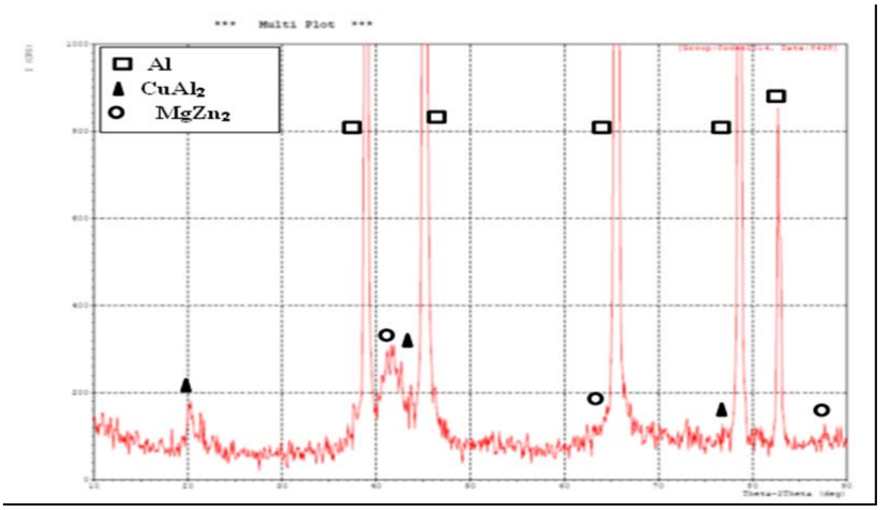


Figure (9) XRD results for Al 7075 base alloy

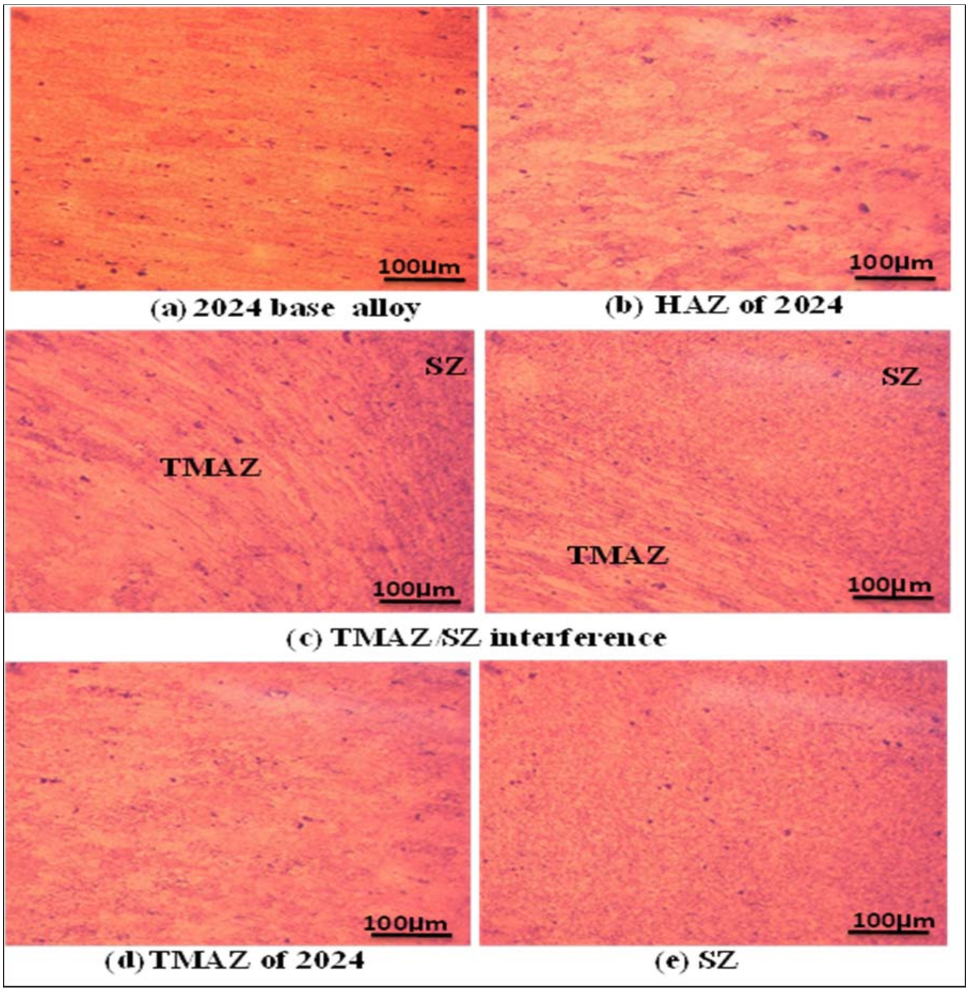


Figure (10) Microstructures of similar welded joints of Al 2024-T3 alloy.

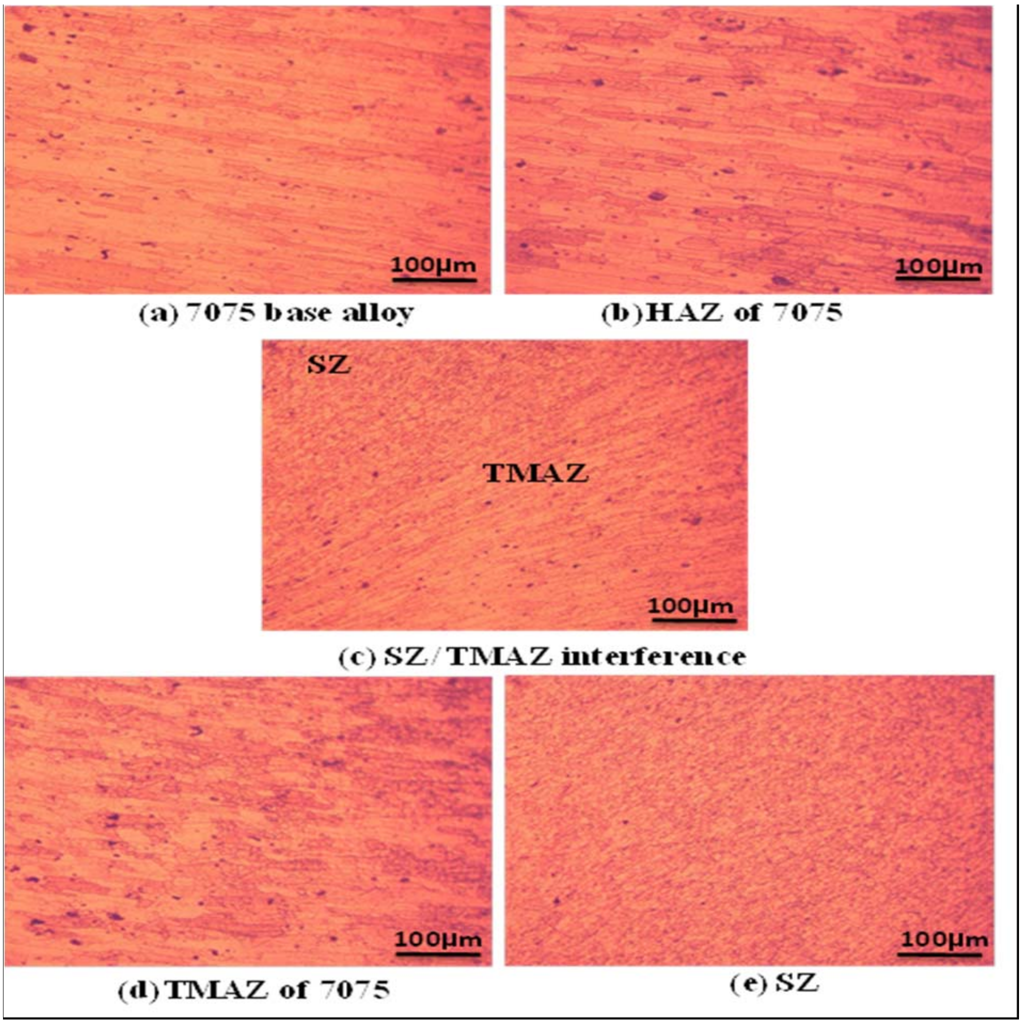


Figure (11) Microstructure of similar welded joints of Al 7075T73 alloy.

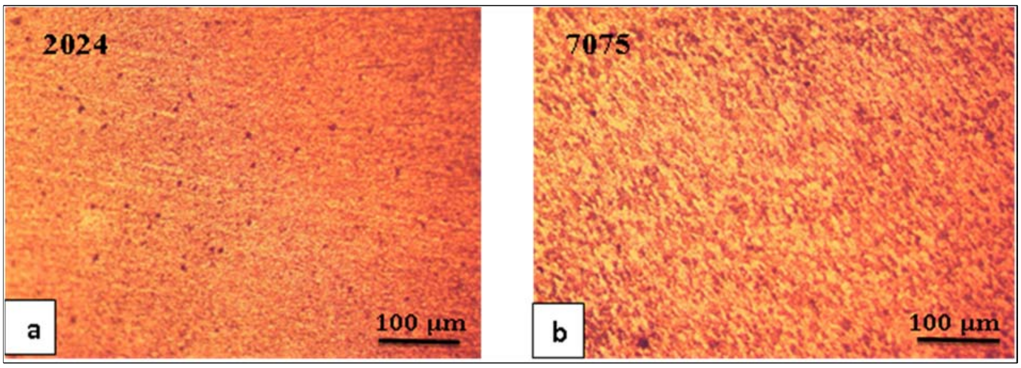


Figure (12) Microstructure of similar welded joints at stir zone of (a) Al 2024 and (b) Al 7075.

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