Effect of Aging Time on the Mechanical Properties of Friction Stir Spot Welding of Al-alloy (AA2024)

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Abstract

A friction stir spot welding process of aluminum alloy (AA2024) is carried out to understand the effect of welding parameters such as rotational tool speed (650 ,750,1000, 1250 and 1500 rpm) and plunging time (30, 60 and 90 sec)on the mechanical properties of welded joints with using special tool steel (X32). Tensile shear force and Vickers hardness tests. were investigated. Solution heat treatment and aging at 190ºC for various times were performed for welded joints at optimum welding conditions It was found the best mechanical properties were for samples welded at rotational tool speed of 750 rpm and plunging time of 60 sec. It was also found that the maximum shear force and hardness of spot welded joints reach maximum values when aging times were 3hr and 5hr respectively at 190ºC.

Keywords: friction stir spot welding, aluminum alloys, mechanical properties aging time

1- Introduction

Friction stir welding (FSW) is a solid state joining process invented at TWI in 1991. This technology makes it possible to join aluminum alloys, which are difficult or impossible to weld by conventional techniques [1-3] .

A Friction Stir Spot Welding (FSSW) is a novel variant of the "linear" FSW process, creates a spot, lap-weld without bulk melting. FSSW can be a more efficient (significant energy and cost savings) alternate process to electric resistance spot welding, TIG spot and Laser spot. FSSW has generated tremendous interests in the automotive industry was used for direct replacement of resistance spot welding of Al alloys as well as performing better than mechanical joining techniques such as riveting [4,5].

As a natural evolution of the FSW process, friction stir spot welding (FSSW) has recently been proposed [6]. In such a process, directly based on the friction stir welding process mechanics, a rotating tool with a probe pin is introduced into the two blanks to be joined, supported by a proper backplate. The rotating tool generates frictional heat inthe specimens and at the same time a material flow is determined. The heated and softened material close to the tool plastically deforms and a bond is made between the surfaces of the upper and lower sheets. No linear movement is allowed to the tool, which is retracted from the workpiece as the stirring process is completed. The published researches about friction stir spot welding are limited.

L Fratini et al [7] [2007] studied the friction stir spot welding (FSSW) of AA6082-T6. In particular, process mechanics is highlighted and joint strength is considered in relation to varying the most relevant process parameters. Furthermore, the results obtained are compared with those derived from the application of traditional mechanical fastening techniques such as clinching and riveting. In this way the effectiveness of FSSW is highlighted.

Tsung-Yu Pan, [8][2007] studied the displacement control spot friction weld process of sheets of 6111-T4 aluminum. 0.94 mm in thickness, in a lap-joint configuration. The pin tool was rotating at a constant speed. Various tool pin plunge depths, from 1.6 to 1.9 mm, were examined. The lap-shear strength of spot friction welded samples started low at the shallowest insertion depth, increased to a maximum value of over 3 KN at about 1.8 mm depth, then dropped to lower strength when the insertion depth was deeper. Test samples showed a failure mode of interfacial separation at shallow insertion depths, to a nugget-pull mode at the highest strength, then changing to a perimeter failure when the insertion was the deepest. A nugget-pull failure mechanism corresponded to the highest lap shear strength.

The effect of welding parameters on the mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding was analysed by **P. Cavaliere et al** [9][2009] . In this study, different samples were produced by varying the advancing speeds of the tool as 80 and 115 mm/min and by varying the alloy positioned on the advancing side of the tool and the rotating speed was fixed at 1600 RPM. Microhardness (HV) and tensile tests performed at room temperature were used to evaluate the mechanical properties of the joints. The fatigue tests were conducted in the axial total stress–amplitude control mode, with R = rmin/rmax = 0.1. In order to analysis the microstructural evolution of the material, the welds' cross-sections were observed optically and SEM observations were made of the fracture surfaces.

Ayad M. Takhakh et al [10] [2011] investigated effect of welding tool shoulder diameter on the mechanical properties of 1200 aluminum plates of 1.5mm thick which were welded by friction stir spot welding. They were used four welding tools diameter (10, 13, 16 and 19 mm) at constant preheating time and plunging time. They concluded that increasing tool shoulder diameter from 10 mm to 19 mm for a fixed welding parameter caused increasing the mechanical properties (hardness and shear force) of the spot welded joints.

The first aim of this work is to study effect of friction stir spot welding parameters such as rotational tool speed and plunging time on the maximum shear force of welds. The second aim is to study the effect of aging time on the mechanical properties , tensile shear force and hardness of friction stir spot welded joints at optimum welding parameters.

Experimental Procedure

1- The used material

The aluminum alloy AA2024 plates of 1.5mm thick , 130 mm long and 25 mm wide have been used in this study , with a nominal chemical composition is indicated in **Table 1**.

2-Welding Process

Friction stir spot welding process of Al-2024 sheets was carried out by using drilling machine type Bohr machine Gewicht as shown in **Figure 1.**

The welding Tool was made from special tool steel X38CrMoV51 (DIN 1.2343) as shown in **Figure 2**. The nominal chemical composition of welding tool used in this study is shown in **Table 2**. A back-plate is utilized on the bottom side of the specimens to support the applied load. The two overlap plates are clamped with carbon steel clamps or fixtures in order to fix these plates and that become rigid and can not separate during welding process. as shown in **Figure 3.** The dimensions of overlap plates to be welded by friction stir spot welding is shown in **Figure 4**

3- FSSW Process Steps

To friction stir weld a lap joint, a specially designed cylindrical tool is rotated and plunged into the joint line or area (in this study). The tool has a small diameter entry probe or pin of 3 mm, and 2.8 mm length with a concentric larger diameter shoulder of 16 mm. When descended to the part, the rotating entry probe contacts the surface and rapidly friction heats and softens a small column or area of metal. As the probe penetrates beneath the surface, part of this metal area is extruded above the surface. The tool shoulder and length of probe control the depth of penetration [11].

Figure 5 friction stir spot welding steps which include plunging step , stirring step and drawing out. **Figure 6** shows the photograph picture of friction stir spot welded joints of Al-2024 alloy which was welded at tool speed of 750 rpm and plunging time of 60 sec.

4- Tests and Inspections

Tensile Shear Test is conducted for all friction stir spot welded samples by using uniaxial tensile testing instrument type (Instron machine 1195) to determine maximum shear force or shear strength of overlap joints according the standard specifications.[12]

Aging Hardening Heat Treatment

Age hardening or precipitation heat treatment included solution heat treatment and aging are made for aluminum base alloy of AA 2024 and welded joints in electric furnace at temperature of 520ºC for 30min. Quenching in water was followed by aging process at 190ºC for various times .The solution heat treatment and aging were carried out only for samples welded at optimum welding variables i.e the best rotational tool speed and plunging time (750 rpm and 60 sec) respectively which give higher tensile shear force than other conditions.

Microstructure Inspection and Hardness Test

Samples Preparation for Microstructure:

The samples made from a cross section of the FSSW joints and base alloy were ground, polished and etched and observed under optical microscope in sequences steps. Wet grinding operation with water was done by using emery paper of SiC with the different grits of (220, 320, 500, and 1000). Polishing process was done to the samples by using diamond paste of size (1µm) with special polishing cloth and lubricant. They were cleaned with water and alcohol and dried with hot air. Etching process was done to the samples by using etching solution which is composed of (99% H_2O+1%HF).Then the samples were washed with water and alcohol and dried. The friction stir spot welded joint samples were examined by optical microscope provided with a digital camera, and computer.

The Vickers hardness test was made by using Vickers hardness tester type (Einsingenbei U/M, Mode Z323). A 300gf load for (10-15)sec was used for hardness over top surface of the friction stir spot weld joint. Five readings for hardness values were taken for each spot weld and the average hardness (VHN) was found .

Results and Discussion

1- Description of FSSW Process

In the FSSW process no linear translation is provided to the tool, which is retracted after the appropriate proper process time or proper plunging time. Generally no nuting angle is given to the tool, which is normal to the specimen surface to be welded. As the rotating tool is inserted into the two overlapped sheets a local backward extrusion is observed and a full contact between the upper sheet and the tool shoulder is reached. Then a heat flux is generated by the work of the friction forces decaying into heat. Observation of the material flow and of the microstructure obtained in the weld area leads to a full understanding of the process mechanics. Considering a top view of the spot joint as shown in **Figure 6**.

Owing to the absence of tool feed rate, no asymmetry in the metal flow (typical of FSW processes) is observed. In particular, the interface surface of the lower specimen is deformed upwards and such material develops the role of a mechanical anchor between the two jointed sheets.

Figure 7 shows a micrograph of the corner locus at the tip of the pin. The typical onion rings morphology of the nugget zone can be clearly seen. Furthermore, as in FSW processes, detailed observation of the material microstructure in the joint section makes it possible to distinguish a few different areas, as shown in **Figure 8**.

Figure 9 indicates a micrograph of the cross section of the spot joint after solution heat treatment and aging at 190ºC for 5hr. **Figure 10** shows a microstructure of the base alloy after heat treatment as mention above .It can be seen a uniform distribution of strengthening phases or precipitates of Al_2Cu in microstructure of spot weld and HAZ and base alloy.

2-Tensile Shear Force Results

Table 3 shows tensile shear force results of friction stir spot welded joints of Al-2024 alloy plates which are welded at different rotational tool speeds and plunging times with constant tool design and preheating dwell time (20 sec). It was seen that maximum shear force increases as tool speed increased until reach to maximum value at 750 rpm and then drop gradually after this value. This is due to increasing of frictional heat and plastic flow of metal which lead to increase the stirring area and metal mixing between two overlap plates also increases , therefore spot welding area and the shear force of welded joint becomes higher. In addition to, as plunging time increases from 30 to 90sec for a given preheating time the tensile shear force of spot weld increases. This is due to increase stirring penetration through the interface between the two plates , it means that the welding depth increases through the upper and lower plates and the welding efficiency improves.

3- Effect of Aging Time on Mechanical Properties of FSSW Joints

Hardness test was carried out on top surface of spot weld in the stir zone and HAZ regions and was taken the average hardness value for all spot joints which are welded at a constant tool rotation speed (750 rpm)and plunging time (60 sec) after solution treated and aged condition at 190ºC for various aging times.

Table 4 summaries the mechanical properties, tensile shear force and Vickers hardness of friction stir spot welded joints after performing solution heat treatment at 520C° and aging at 190ºC in different time. It was seen that the shear force and hardness increase with increasing aging time until reach to maximum value, 3600 N and 116 HV after aging time 5hr and 3hr respectively. This is due to precipitation of second phase particles of Al_2Cu phase (Ɵ) from solid solution (Al-matrix) during aging the alloy at 190ºC. These results are confirmed by XRD analysis inspection as shown in **Figures 11 and 12**. Also precipitation of strengthening phases of (AlCuMg, Al_2Cu) which are coherent with alloy matrix induce internal strain field and cause distortion in alloy matrix that intersect with the moving dislocations and then pinning the dislocations which lead to an increment in stress required to move the dislocation, as results, the alloy strength increases [13]. It was seen that the hardness and shear force of spot welds decrease at longer aging times because of coarsening and /or a dissolution of precipitates of AlCuMg, Al_2Cu the strengthening phases into solution during welding. The hardness of spot weld was slightly higher than the base alloy after 15 hr aging time . Hardening in the spot zone could be due to the formation of GPZ at room temperature after welding. The observed hardness profiles were similar to those of other researchers (Madhusudhan Reddy et al, 2006 and Saad and Shibayanagi, 2007)[14,15].

Muna K. A. et al [16][2011] noticed that after age heat treatment the hardness distribution shows a hardness drop in the HAZ, but 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. .

Conclusions

1-Friction stir spot welding (FSSW) was not succeed at short plunging time of 30 sec at all tool rotational speeds.
2-The optimum welding conditions of FSSW variables are tool rotational speed of 750 rpm and plunging time of 60 sec which give the best mechanical properties.
3-Maximum shear force of FSSW joint increases as plunging time increases at all tool rotational speeds except speed of 750 rpm .
4-The hardness and shear force increase with increasing aging time and reach to their maximum values at 3hr and 5hr respectively at 190ºC.
5-XRD analysis pattern indicated the appearance of the strengthening phases or precipitates of (AlCuMg, Al_2Cu) in the spot weld and base alloy after heat treatment

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Table 1 The chemical composition of Al-alloy AA2024

Element wt%	Cu	Mg	Mn	Si	Zn	Fe	Cr	Ni	Cd	Al
Nominal Value	4.91	1.307	0.5439	0.1456	0.1001	0.311	0.0366	0.0039	0.0041	Rem

Table 2 The chemical composition of welding tool X38

Element wt%	C	Si	Mn	P	Cr	Mo	Co	Fe
Nominal value	0.96	0.45	0.40	0.03	0.03	4.7-2.6	4.5-5.0	Balance

Table 3 Results of tensile shear force of FSSW in Al-2024 alloy

Plunging time (Sec)	Rotational tool speed (rpm)	Tensile shear force (N)
30	650 750 1000 1250 1500	Failed = = = =
60	650 750 1000 1250 1500	2000 2400 1900 1700 1650
90	650 750 1000 1250 1500	2100 2350 2300 2250 2200

Table 4 The mechanical properties results of FSSW after aging at 190ºC

Condition	Aging time hr	Tensile shear force (N)	Hardness HV Kg/mm^2
As weld at 750 rpm and 60sec	–	2400	80.6
S.T. at 520ºC For 30min And aging at 190C°	S.T. 1 3 5 7 10 15	3300 3350 3400 3600* 2700 2600 2300	84 92 116* 106 100 95 87

Figure 1 Milling machine used in FSSW in this study

Figure 2 Welding tool (X38) used in this study

Figure 3 Clamping the Al-alloy plates with fixtures

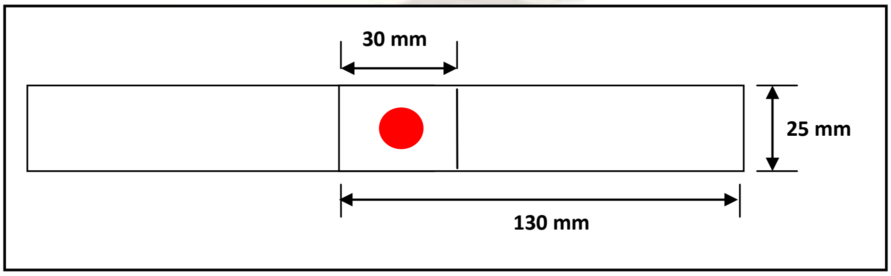

Figure 4 Dimensions of spot weld sample

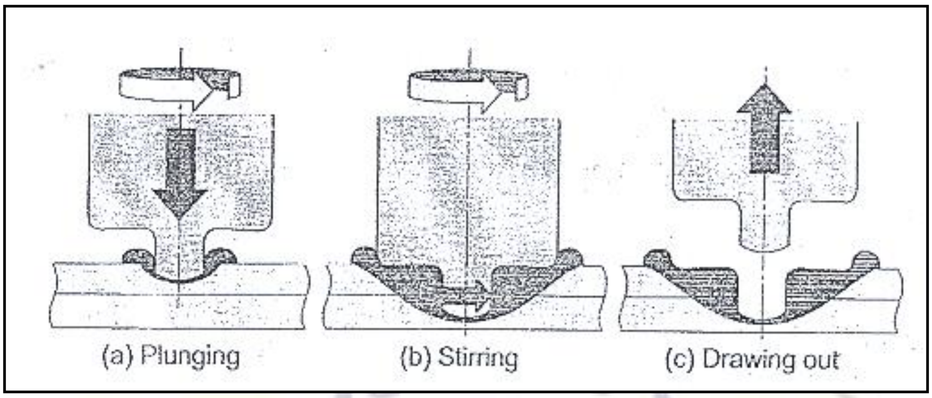

Figure 5 Friction stir spot welding (FSSW) steps

Figure 6 Photograph picture of FSSW welded samples

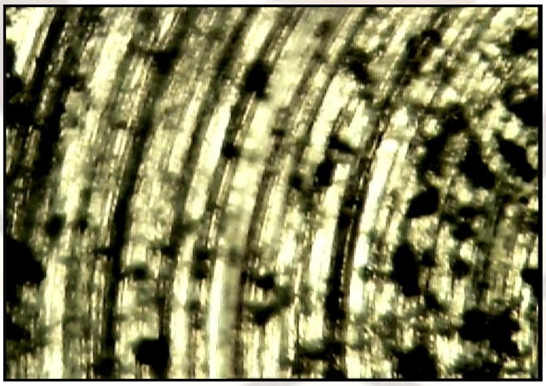

Figure. 7 Onion rings morphology at the tip of the pin of welding tool. Magnification X 63

Figure 8 Micrograph of cross section of FSSW joint at optimum condition (750 rpm and 60 sec) before heat treatment . Magnification X125

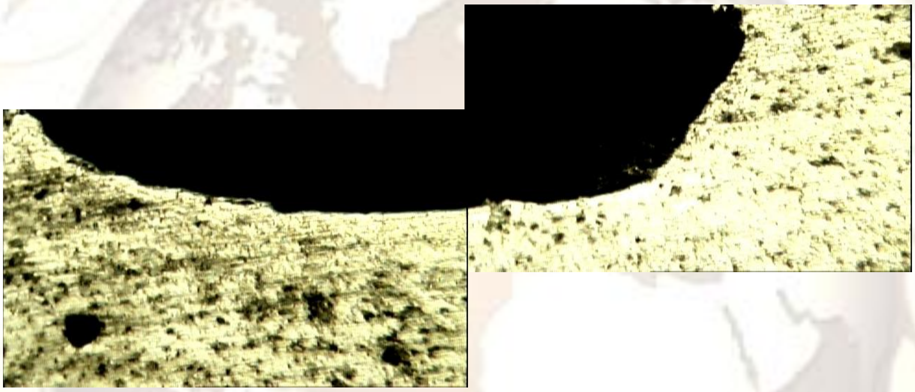

Figure 9 Micrograph of cross section of FSSW joint at optimum condition(750 rpm and 60 sec) after solution heat treatment and aging at 190°C for 5hr. Magnification X125

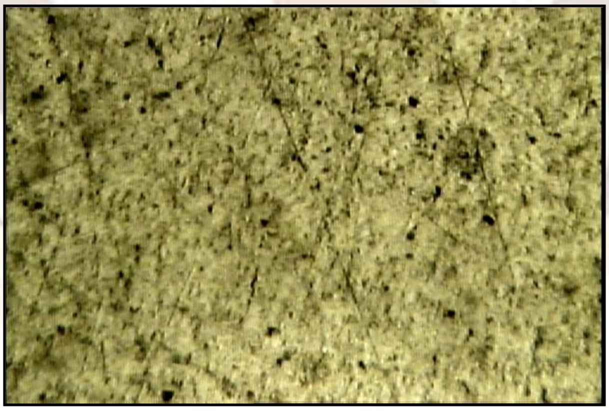

Figure 10 microstructure of base metal after HT and aging at 190°C for 5hr. magnification X125

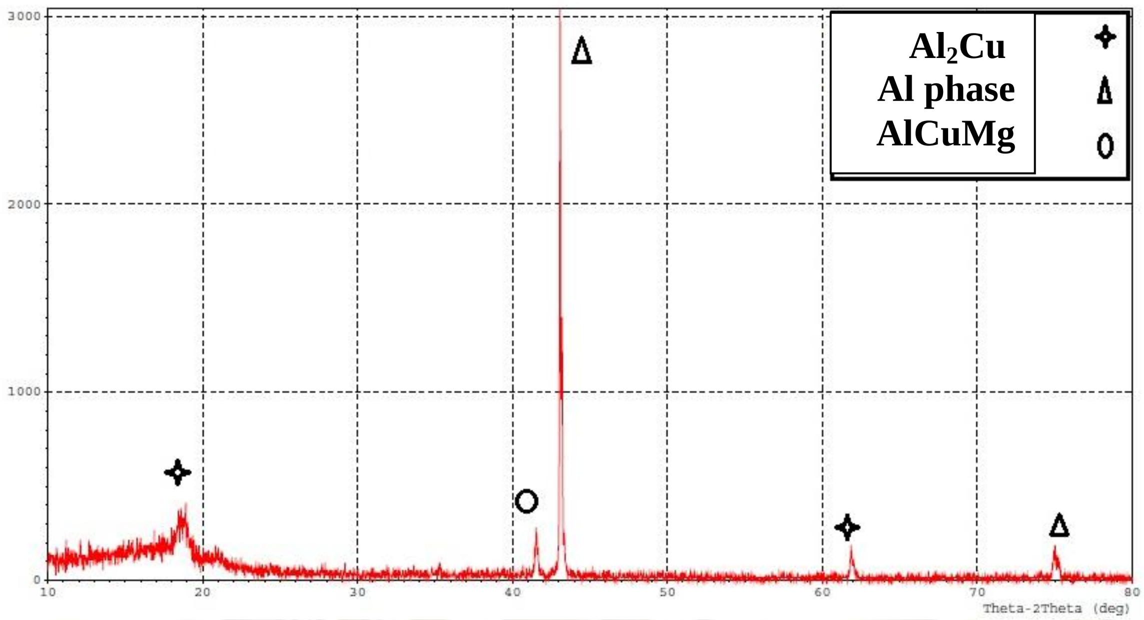

Figure 11 Photograph of XRD analysis pattern of friction stir spot weld before heat treatment (as weld)

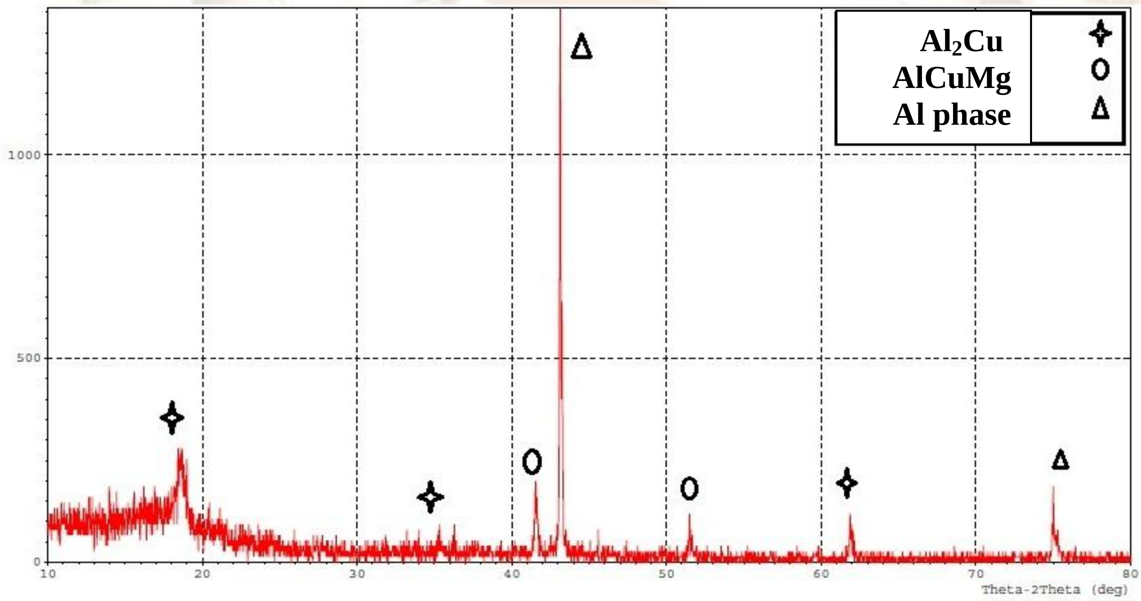

Figure 12 Photograph of XRD analysis pattern of friction stir spot weld after solution heat treatment and aging at 190 ºC for 5hrs.