Eng. & Tech. Journal ,Vol.32, Part (A), No.11, 2014

Determination of Optimum Tool Design for FSW AA2024-T351

Zuhair Sadeed Al- Tahir
Mechanical Engineering Department, University of Technology / Baghdad
Dr. Samir Ali Al- Rubaii
Mechanical Engineering Department, University of Technology / Baghdad
Dr. Qasim Abbas Atiah
Mechanical Engineering Department, University of Technology / Baghdad

Received on: 15/12/2013 & Accepted on: 7/8/2014

ABSTRACT

Friction stir welding is a relatively new joining process, which involves the joining of metals without fusion or filler materials. In this study, the effect of tool pin profile on the mechanical properties of aluminum alloys AA2024-T351 joints produced by FSW was investigated. Four different tool pin profiles were developed, (straight cylindrical, taper cylindrical, triangular, and square) to weld the joints. All the welds were produced perpendicularly to the rolling direction for aluminum alloys. Tensile and bending tests were performed to evaluate the mechanical properties by using computerized universal testing machine. Among the four tools, square pin profile gives better tensile strength (265 MPa), elongation (4.9), maximum bending force (1450 N), and maximum welding efficiency (61%) in terms of tensile strength.

Keywords: Friction stir welding, Tool design, AA2024-T351, Tensile and bending tests, Joint efficiency.

إيجاد التصميم الامثل لعدة لحام الخلط الاحتكاكي لسبيكة الالمنيوم (AA2024-T351)

الخلاصة

اللحام بالخلط الاحتكاكي هو عملية لحام جديدة نسبيا ، والذي يستلزم لحام المعادن بدون استخدام الانصهار او المواد المالئة. في هذه الدراسة، تم التحقق من تاثير شكل وتد الاداة على الخواص الميكانيكية لسبائك الالمنيوم (AA2024-T351) الملحومة بطريقة لحام الخلط الاحتكاكي. أربعة اشكال وتد الاداة تم تهيئتها ، (اسطواني مستقيم ، اسطواني مسلوب ، مثلث، ومربع) من اجل إجراء عملية اللحام. جميع الوصلات الملحومة تم لحامها بشكل عمودي على اتجاه سحب سبائك الالمنيوم. تم اجراء اختبارات الشد والانحناء لتقييم الخواص الميكانيكية باستخدام ماكنة اختبار مبرمجة عامة. من بين الادوات الاربعة، شكل الوتد المربع يعطي مقاومة الشد الافضل(265 ميكا باسكال)، أقصى قوة إنحناء (1450 نيوتن)، وأقصى كفاءة لحام (61%) بدلالة مقاومة الشد.

INTRODUCTION

Friction stir welding (FSW) is a new solid-state joining technology invented at the welding institute (TWI) in 1991. It has been proven to be a very successful joining technology for aluminum alloys. Compared to the conventional

https://doi.org/10.30684/etj.32.11A.4
2412-0758/University of Technology-Iraq, Baghdad, Iraq

welding processes, FSW can produce superior mechanical properties in the weld zone. This new technique is attracting more and more research interest. During the FSW process, the tool penetrates into the work piece, and then moves along the joint line at a constant speed (see Figure 1). The material in front of the rotating tool pin is plastically deformed and stirred back to the trail edge of the tool pin in the welding[1].

The tool serves three primary functions, that is, heating of the work piece, movement of material to produce the joint, and containment of the hot metal beneath the tool shoulder. Heating is created within the work piece both by friction between the rotating tool pin and shoulder and by severe plastic deformation of the work piece. The localized heating softens the material around the pin and, combined with the tool rotation and translation, leads to movement of material from the front to the back of the pin, thus filling the hole in the tool wake as the tool moves forward. The tool shoulder restricts the metal flow to a level equivalent to the shoulder position, that is, approximately to the initial work piece top surface.

As a result of the tool action and influence on the work piece, when performed properly, a solid state joint is produced, that is no melting. Because of various geometrical features on the tool, material movement around the pin can be complex, with gradients in strain, temperature, and strain rate. Accordingly, the resulting nugget zone microstructure reflects these different the rmomechanical histories, and is not homogeneous [1].

A lot of researches have been already done towards understanding the effect of process parameters on the material flow behavior, microstructure formation and mechanical properties of friction stir welded joints. But, a few research works have focused on the influence of FSW tool profiles and tool dimensions from the design point of view. The reform, the aim of this paper is to study the effects of FSW tool profiles on the mechanical properties (elongation, tensile strength, and maximum bending force) for Aluminum alloy (AA2024-T351). Thus, this research work presents the relation between the FSW tool profile and elongation, tensile strength, and maximum bending force in the friction stir welded AA2024-T351 [2-6].

EXPERIMENTAL WORK

Aluminum Alloy Selection and Specimens Preparation

The base material used in this investigation is 2024-T351 which was obtained from a local market with a thickness of (3.2 mm). AA2024-T351 aluminum alloy is Al-Cu-Mg grade alloy of 2xxx series heat treatable of medium strength alloys. A piece of this alloy was analyzed to find its chemical composition by spectra device, as shown in Table 1 with the standard material according as ASTM B209M for comparison purpose and the standard mechanical properties of AA2024-T351 aluminum alloy as ASTM E8 [7], [8], as given in Table (2).

The base material (BM) was cut into required size (200mm *100mm *3.2mm) by power saw cutting matching for FSW, and the plate edge was ground to ensure that there is no gap exists between the two plates that make the required butt joint design.

Design and Manufacturing of Welding Tools

The design of the tool is the key to the successful application of the process to a greater range of material and over a wider range of thickness.

In order to obtain an optimal tool design, four different tools with pin profiles (straight cylindrical, taper cylindrical, triangular and square) and straight cylindrical shoulder were used, see Figure 2. The friction stir welding tools were manufactured by CNC turning and milling machines, these friction stir welding tools were fabricated from tool steel labeled as X12M (density ρ = 7800 kg/m^3, specific heat C_p = 500J/kg.^{o}C and the thermal conductivity k = 40 W/m.^{o}C). The tool heat treatment includes heating the metal to 1020°C for 30 min and then air cooling to room temperature, which gives a hardness of 58 HRC [9],its chemical composition is tabulated in Table 3 together with the standard tool material. All designed and manufactured FSW tools dimensions are presented in Table (4).

Selecting the Optimum Tool Design

To obtain high quality of friction stir welded joints with high mechanical properties, i.e., high welding efficiency, the main welding parameters (rotational speed and welding speed) must be carefully selected to balance the effect of each parameter on the amount of heat input during welding.

The rotational and welding speeds were chosen according to the self-optimized parameter suggested in previous work [10], therefore the tool rotational speed was kept constant at 980 rpm, and the welding speed was also kept constant at 20 mm/min (see Table 5). The FSW trials were carried out on a vertical milling machine with a square butt joint configuration.

Welding Procedure

A plate was fixed at a predetermined location on the backing plate and clamped into place. This same location was used for all plates in this research work. The tool was then positioned directly over the plunge location, and the pin was brought into contact with the top surface of the work piece.

Each tool plunges slowly between the two sheets that are required to be welded until the shoulder of the tool touches the sheet surface. The tool was then allowed to dwell for 30-40 sec to allow the shoulder to preheat the work piece during welding. After the dwell, the tool began to traverse along the welding line with the selected tool. When a full weld has been made, the pilot hole will be welded over, and the pin was parked above the weld. When the tool was parked, it was dragged, and a park hole was left. This procedure is used to fabricate one butt joint for each FSW experiment, using a certain tool design. 10 experiments were carried out to obtain the optimum tool design (from EXP1 to EXP10) using different designed and manufactured tools (from FST1 to FST10), with 20 mm/min welding speed and 980 rpm rotational speed for all experiments.

Mechanical Tests

Tensile tests

Tensile test was carried out on samples taken in a perpendicular direction to the welding to determine the tensile properties of the welding joints for both welding processes. The shape and dimensions of the transverse tensile specimens according to the standard are shown in Figure 3 [8]. All tensile tests were carried out at room temperature and constant loading rate (5 mm/min) by computerized universal testing machine (Hydraulic Tunis Olsen), which has a maximum capacity of (1000 kN). Then, the average of three specimens was taken to evaluate the tensile behavior of each welded joint.

Bending tests

Three point bending test was carried out to determine the maximum bending force of the welded joints. Bending tests were conducted with former diameter equal to 30 mm. The shape and dimensions of the transverse bending specimens according to the standard are shown in Figure 4 [11]. The bending test was carried out at room temperature by universal testing machine (Hydraulic LARYEE testing machine).

RESULTS AND DISCUSSION

Determination of Optimum Tool Design

Tensile and bending test results

After carrying out the experiments, the welded joints were visually examined and the welds with good surface appearance were chosen and machined into the standard test specimens for the mechanical testing [8], [11].

Tensile and bending tests were carried out, and the results have been divided according to the tool pin profile. It should be noted that the testing values of the base metal are (438MPa tensile strength) and (1520 N maximum bending force), respectively at welding speed of 20 mm/min and rotational speed of 980 rpm.

Tool profiles results

For discussion and comparison purposes, the tool profiles were classified according to their types into the following series (from F1-series to F4-series):

1- Straight cylindrical pin profile (F1-series):

F1-series are characterized by changing in pin diameter from 4 mm to 5 mm and shoulder diameter from 10 mm to 15 mm, which means that the first tool with d_p=4 mm, D=10 mm, $\frac{\mathrm{D}}{\mathrm{dp}} = 2.5$, L_p=2.7 mm, and the second tool with d_p=5 mm, D=15 mm, $\frac{D}{\mathrm{dp}} = 3$, L_p=2.7 mm.

In (F1-series), the plastic material flows around the pin. In EXP1, using of the first tool produces weld with the highest ultimate tensile strength compared to EXP2 that used the second tool. The increase in weld strength with the first tool is attributed to increasing heat generation and material plastic flow. Also, bending stress reaches maximum value in this series with the first tool. Table 6 shows that the tensile strength, bending stress, and efficiency of the weld joint increase in EXP1 [12].

2- Taper cylindrical pin profile (F2-series):

F2-series are characterized by changing in pin diameter from 4 mm to 5 mm and shoulder diameter from 12 mm to 15 mm, which means that the third tool with d_p=4 mm, D=12 mm, $\frac{\mathrm{D}}{\mathrm{dp}} = 3$, pin angle=8°, L_p=2.7 mm, and the forth tool with d_p=5 mm, D=15 mm, $\frac{D}{\mathrm{dp}} = 3$, pin angle=8°, L_p=2.7 mm.

In case of tapered cylindrical pin profiles, much of the materials movement takes place by simple extrusion, and it seems to have no vertical motion of the material which is apparently necessary to stabilize the rotational zone and to provide sufficient deformation of material to obtain sound weld.

In EXP3, using of the third tool produces weld with the highest ultimate tensile strength compared to EXP4 that used the forth tool. Also, bending stress reaches

maximum value in this series with the third tool. Table 7 shows that the tensile strength, bending stress, and efficiency of the weld joint (ratio of tensile strength of the welded work piece to tensile strength of base metal) increase in EXP3 [12].
Comparing this series with F1-series, it is found that there is a high increasing in mechanical property due to the effect of tapered shape.

3- Triangular pin profile (F3-series):

F3-series are characterized by changing in pin diameter from 4 mm to 5 mm and shoulder diameter from 12 mm to 15 mm, which means that the fifth tool with d_p=4 mm, D=12 mm, $\frac{D}{dp} = 3$, L_p=2.7 mm, and the forth tool with d_p=5 mm, D=15 mm, $\frac{D}{dp} = 3$, L_p=2.7 mm.

In triangular pin profiled tool, the frictional area between the probe side and the welding material is limited to near three sharp edges, which is very smaller than that of other tools. Additionally, the pin bottom area of the triangular is smaller than that of the cylindrical pin tools. Since larger frictional area will generate larger amount of friction heat, the friction heat generated by the triangular probe might be smaller than that by the column tools. Consequently, for the triangular pin, the bottom surface temperature is always lower than the others, due to lack of stirring in the friction stir processing zone.
In EXP5, using of the fifth tool produces weld with the highest ultimate tensile strength compared to EXP6 that used the sixth tool. Also, bending stress reaches maximum value in this series with the third tool. Table 8 shows that the tensile strength, bending stress, and efficiency of the weld joint increase in EXP5 [13].
Comparing this series with F1-series and F2-series, it is noted that there is an increasing in mechanical property due to the effect of tapered shape.

4- Square pin profile (F4-series):

F4-series are characterized by changing in pin diameter from 4 mm to 5 mm and shoulder diameter from 10 mm to 15 mm, which means that the seventh tool with d_p=4 mm, D=10 mm, $\frac{D}{dp} = 2.5$, L_p=2.7 mm, and the eighth tool with d_p=5 mm, D=15 mm, $\frac{D}{dp} = 3$, L_p=2.7 mm, and the ninth tool with d_p=5 mm, D=15 mm, $\frac{D}{dp} = 3$, L_p=2.85 mm, and the tenth tool with d_p=5 mm, D=15 mm, $\frac{D}{dp} = 3$, chamfered edge inclined angle with 8°, L_p=2.85 mm.

During stirring, square profile tool sweeps a large amount of metal from the plasticized zone and results in an inhomogeneous structure.
In EXP8, using of the eighth tool produces weld with the highest ultimate tensile strength compared to EXP7 that used the seventh tool, EXP9 that used the ninth tool, EXP10 that used the tenth tool. Also, bending stress reaches maximum value in this series with the eighth tool. Table 9 shows that the tensile strength, bending stress, and efficiency of the weld joint increase in EXP8 [14].
Comparing this series with F1-series, F2-series and F3-series, it is noted that there is an increasing in mechanical property due to the effect of squared shape.
The joint welded by square pin profiled tool exhibits high tensile strength when compared to other joints. The joint fabricated by straight cylindrical pin profiled tool

has the least tensile strength. The tensile strength of the joints, welded using straight cylindrical, taper cylindrical and triangular pin profiled tools do not change significantly. This is due to the difference in dynamic orbit created by the eccentricity of the rotating tool of the FSW process [14].

CONCLUSIONS

The following conclusions have been made from the above investigation:

- Aluminum alloy (2024-T351) is weld able using different (FSW) tool geometries and different (FSW) parameters giving different welding joints efficiencies.

- The shape of the straight cylindrical pin profile has a small effect on the mechanical properties (tensile and bending), while the shape of the square cylindrical pin profile has a significant influence on the mechanical properties.
- The maximum weld strength obtained in this study was (265 MPa) or (61%) weld joint efficiency with (4.9%) elongation recorded in the weld using the square pin profiled tool and 5 mm rotation diameter, with welding parameters (rotational speed of 980 rpm and welding speed of 20 mm/min).
- The maximum bending force obtained in this study was (1450 N) recorded in the weld using the square pin profiled tool and 5 mm rotation diameter, with welding parameters (rotational speed of 980 rpm and welding speed of 20 mm/min).

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Table 1: Standard and experimental chemical compositions of aluminum alloy AA2024-T351 (wt%)

wt% / Material	Si	Fe	Cu	Mn	Mg	Cr	Zn
Standard [7]	≤0.500	≤0.500	3.800-4.900	0.300-0.900	1.200-1.800	≤0.100	≤0.250
Experimental	0.121	0.265	3.800	0.511	1.370	0.009	0.134

Table 2: Standard and experimental mechanical properties of aluminum alloy AA2024-T351

Property / Material	σy (Mpa)	σu (Mpa)	EL. (%)
Standard [8]	≥290	≥435	≥15
Experimental	327	438	17.3

Table 3: Chemical composition of tool steel X12M

Element	C	Si	Mn	P	S	Cr	Cu	Ni	V
Standard [9]	1.800 - 2.400	≤0.400	≤0.600	≤0.030	≤0.030	12.000 - 15.000	≤0.250	≤0.500	≤0.300
Actual	1.870	0.278	0.270	0.009	0.001	12.440	0.079	0.200	0.023

Table 4: FSW tools dimensions (designed and manufactured in the present study)

Description of the pin	FSW Tool No.	Rotation diameter (mm)	Shoulder Diameter (mm)	Shoulder surface	Pin Length (mm)
Straight cylindrical	FST1	4	10	Flat	2.7
	FST2	5	15	Flat	2.7
Taper cylindrical	FST 3	4	12	Chamfered edge inclined angle with 8º	2.7
	FST 4	5	15	Chamfered edge inclined angle with 8º	2.7
Triangular	FST 5	4	12	Flat	2.7
	FST 6	5	15	Flat	2.7
Square	FST 7	4	10	Flat	2.7
	FST 8	5	15	Flat	2.7
	FST 9	5	15	Flat	2.85
	FST10	5	15	Chamfered edge inclined angle with 8º	2.85

Table 5: FSW experiments used to obtain the optimum tool design at suitable rotational and welding speeds of FSW

Experiment No.	FSW Tool No.	Welding Speed (mm/min)	Rotational speed (rpm)
EXP1	FST1	20	980
EXP2	FST2	20	980
EXP3	FST3	20	980
EXP4	FST4	20	980
EXP5	FST5	20	980
EXP6	FST6	20	980
EXP7	FST7	20	980
EXP8	FST8	20	980
EXP9	FST9	20	980
EXP10	FST10	20	980

Table 6: Tensile and bending testing results of (F1-series)

FSW Exp.	Modulus of Elasticity (GPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Welding Efficiency (%)	Maximum Bending Force (N)
BM	63.6	438	17.3	-	1520
EXP1	69.6	87.4	3.8	20	1020
EXP2	19.5	31.1	4.4	7	105

Table 7: Tensile and bending testing results of (F2-series)

FSW Exp.	Modulus of Elasticity (GPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Welding Efficiency (%)	Maximum Bending Force (N)
EXP3	71	234	6	53	1430
EXP4	65.5	183.4	4.5	42	1120

Table 8: Tensile and bending testing results of (F3-series)

FSW Exp.	Modulus of Elasticity (GPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Welding Efficiency (%)	Maximum Bending Force (N)
EXP5	66	250	4.9	57	1370
EXP6	68.4	212	4.8	48	1040

Table 9: Tensile and bending testing results of (F4-series)

FSW Exp.	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Elongation (%)	Welding Efficiency (%)	Maximum Bending Force (N)
EXP7	68	220	5.1	50	1400
EXP8	71	265	4.9	61	1450
EXP9	92.1	173.1	5	40	1400
EXP10	89.8	109	5.6	25	1040

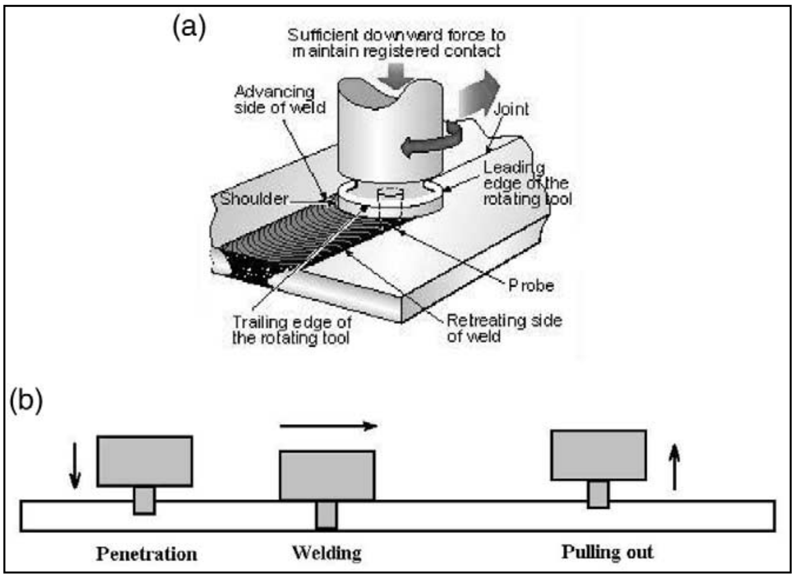

Figure 1: Schematic diagram of FSW. [1]

Figure 2: Image of FSW tools used in the present work

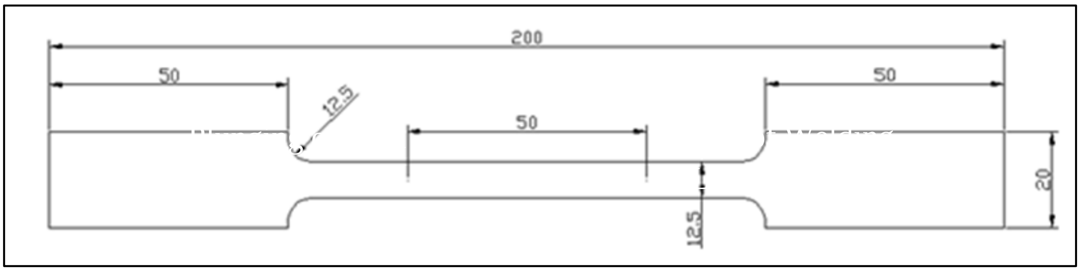

Figure 3: Tensile test specimen (all dimensions in mm) [8]

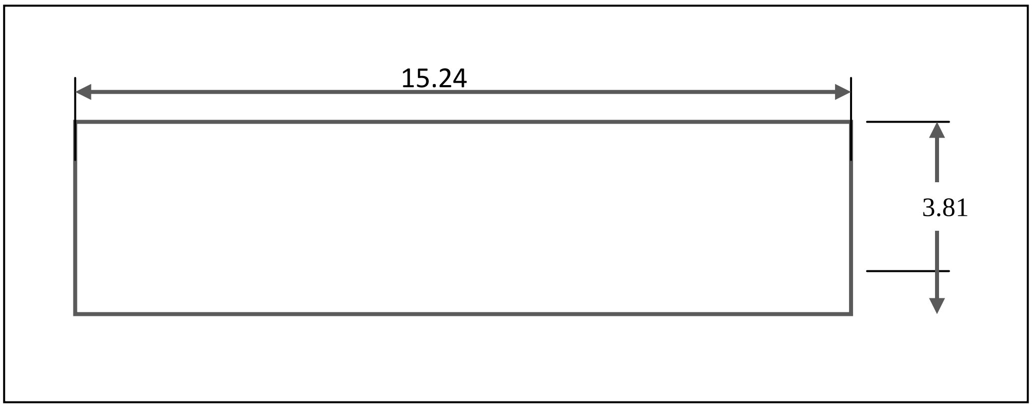

Figure 4: Bending test specimen (all dimensions in cm) [11]