Study the Effect of Reverse Rotation Friction Stir Processing on the dissimilar aluminum alloys

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Abstract

Friction stir welding (FSW), a solid-state welding process, it's involve a welding by friction between two metals or alloys, and also using for the joining of dissimilar materials due to the lower processing temperature over conventional fusion welding, it's include only one pass of welding. Friction Stir Processing (FSP) is a recent outgrowth of the Friction Stir Welding (FSW) process and relies on solid-state deformation to modify the structure of the workpiece, it's involve two pass or more of welding and applied either on the base metal(BM) or to join the two alloys/metals. In this paper the new method used, namely reverse rotation friction stir processing (RFSP), this research aims to study the effect of (RFSP) technique on the mechanical properties of welded alloys. (FSW) includes a single pass of the welding line but the second method (RFSP) involves two pass of welding (forth and back) but the 1st pass with a rotation speed in clockwise and the 2nd pass in counter-clockwise. The alloys used of dissimilar AA 2024 and AA6061 aluminum alloys of (3mm) thickness, the parameters used in this research include different rotational speed (1600, 1800, 2000 and 2200) RPM and one feed speed (25) mm/min. In the tensile test the results of reverse rotation friction stir processing (RFSP) was higher than friction stir welding (FSW) for all rotation speeds of welding except (1800 RPM). In the microhardness measurement the values of hardness for all samples at the nugget zone is higher than the basemetal of 6061-T6 and lower than the basemetal of 2024-T3. The efficiency of ultimate tensile strength reaches to about (72 %) for (RFSP) as compare with value of (FSW) and it's about (44%) at rotation speed (1600 RPM).The only exception of welding was when the rotational speed of (1800 RPM), where the (FSW) is better than (RFSP), efficiency was approximately (77%) for the (FSW) compared with the results of (71%) (RFSP).

Keywords: friction stir welding (FSW), friction stir processing (FSP), reverse rotation friction stir processing (RFSP), Microhardness, Microstructure, efficiency

1. Introduction

Aluminum alloys, AA2024-T3 and AA6061-T6, are widely used in many fields such as aerospace industry and marine industry in the construction of frames, pipelines and storage tanks as high strength-to-weight ratio materials. Dissimilar joining process is considered as a difficult when compared to the similar welding process, due to variation in chemical composition and mechanical properties of the base materials [1], so the Friction Stir Welding (FSW) and Friction Stir Processing (FSP) techniques are used for welding the dissimilar aluminum alloys. Friction stir welding (FSW), a solid-state welding process patented by The Welding Institute (TWI) in 1991, is a potential candidate for the joining of dissimilar materials due to the lower processing temperature over conventional fusion welding [2]. Friction Stir Processing (FSP) is a recent outgrowth of the Friction Stir Welding (FSW) process and relies on solid-state deformation to modify the surface of the working surface/materials as shown in figure (1). FSP has been shown to locally eliminate casting defects and to refine the microstructure of alloys to improve their mechanical properties. Such improvements have important implications for manufactured components for a variety of automotive and other industrial applications [3].

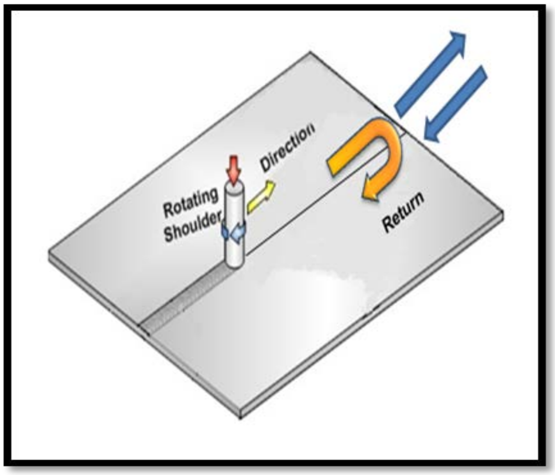

Figure 1: Schematic of friction stir processing (FSP) for plates.

2. Experimental

Aluminum alloys used in this study are AA2024-T3 and AA6061-T6, the plates of AL alloys with a dimension of (200 x 100) mm and (3 mm) thickness, chemical compositions and mechanical properties has been obtained by make a tests for 2024 and 6061 base metals (BM) are shown below in Tables **(1)** and **(2)**. The aluminum plates are prepared using a press and grinding machine. The joint was fabricated in the single pass for (FSW) and double pass for (RFSP), to weld the plates by (FSW)and (RFSP) process the two aluminum plates are fixed in the milling table by used a clamping fixture, the work was done with a MITSUBISHI CNC M70V milling machine Figure (2), and tool is fixed on the spindle. CNC program is prepared as per the input parameter. Before beginning the process must get stratification for two plates by using the Dial Gage to give a good welding line, the friction stir welding and processing procedure of dissimilar AA2024 and AA6061 aluminum alloys is shown in Figure (3).

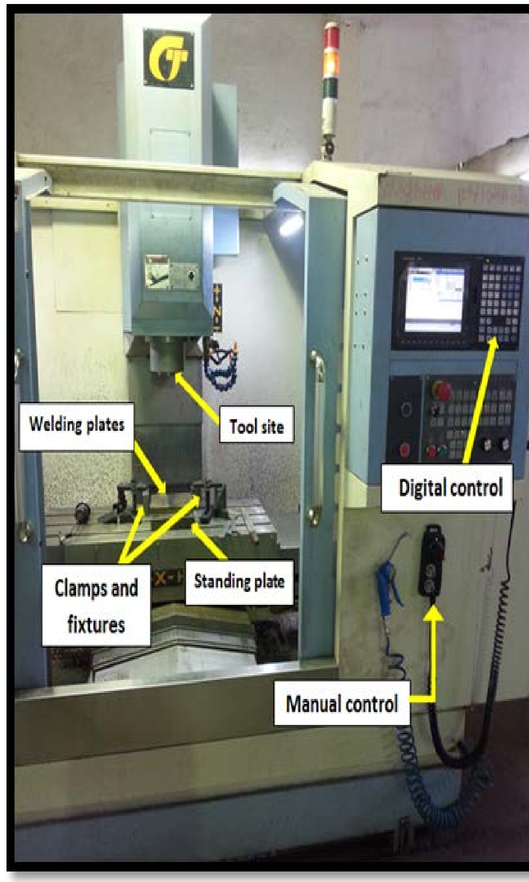

Figure 2: MITSUBISHI CNC M70V milling machine.

Table 1: Chemical composition of the two aluminum alloys.

Element	WT % 6061	WT % 2024	Standard of 6061[4]	Standard of 2024[4]
Mg	0.885	1.25	0.8-1.2	1.2-1.8
Si	0.641	0.087	0.4-0.8	Max 0.5
Cu	0.328	5.75	0.15-0.4	3.8-4.9
Mn	0.096	0.535	Max 0.15	0.3-0.9
Ti	0.018	0.014	Max 0.15	Max 0.15
Cr	0.208	0.008	0.04-0.35	Max 0.1
Zn	0.112	0.103	Max 0.25	Max 0.25
Fe	0.463	0.193	Max 0.7	Max 0.5
Al	**Balance**	**Balance**	**95.8-98.6**	**90.7-94.7**

Table 2: Mechanical properties of base materials.

Aluminum Alloys		Yield strength (MPa)	Ultimate tensile strength, (MPa)	Modulus of elasticity (GPa)
2024-T3	Standard [5]	345	483	73.1
	Measured	352.61	490.43	74.41
6061-T6	Standard [6]	276	310	68.9
	Measured	287.4	320	69.23

The AA2024-T3 alloy sheet was located on the advancing side and AA6061-T6 on the retreating side as shown below.

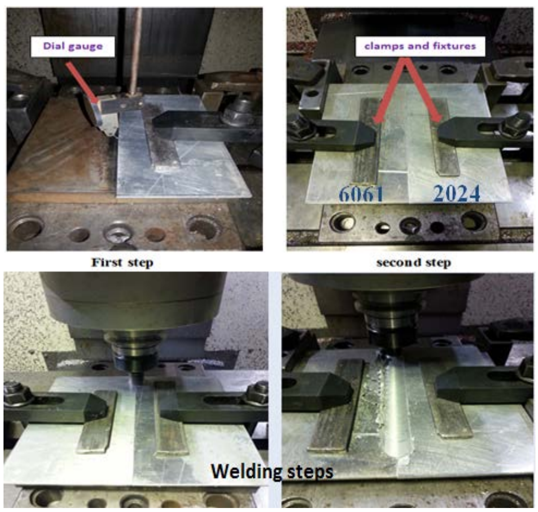

Figure 3 : Matching and welding process for two plates.

FSW and FSP parameters and tool dimension used in this study were listed in Table (3).

Table 3: Welding Parameters and Tool Dimensions.

No.	Process Parameters	Values
1	Rotational Speed(rpm)	1600,1800,2000,2200
2	Welding Speed(mm/min)	25
3	Pin Length(mm)	2.9
4	Tool shoulder Diameter(mm)	18
5	Diameter of Taper pin(mm)	D1=4, D2=3.5

The tool which used for welding is made from tool steel X38 ,the chemical composition of tool after tested as shown in table (4), the tool design plays an important function in the welding process and it's a taper tool with (18 mm) shoulder diameter ,(4×3.5 mm) taper pin diameter and the length of the pin was equal to the depth of the plunged in the plate and it was(2.9 mm) as shown in figure (4).

Table 4: Chemical composition of welding tool [7].

C	Si	Mn	P	Cr	Ni	Mo	Co	Fe
0.88-0.96	0.16	0.40	0.03	0.03	-	4.7-2.0	4.5-5.0	Balance

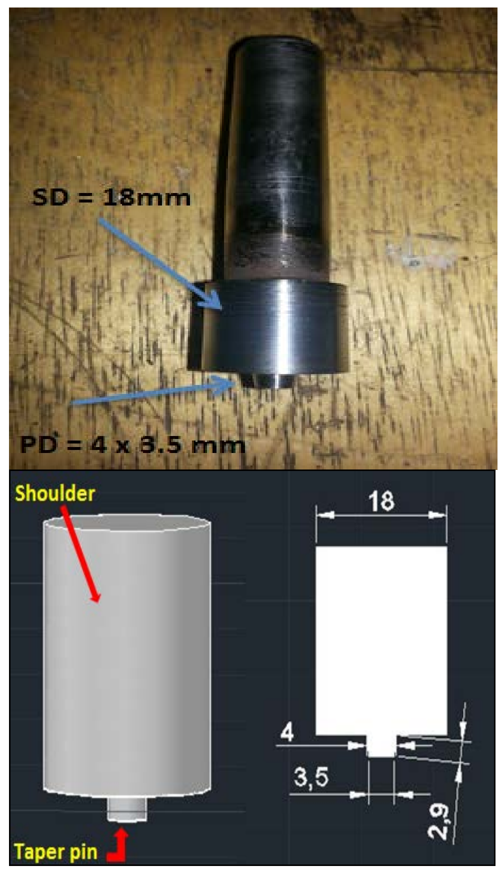

Figure 4: FSW, FSP and RFSP tool.

3. Experimental work

Tensile strengths of the welded joints and base metals were measured using flat samples were prepared as per ASTM E8M. The specimens were cut by using a C-TEK milling machine.

The tensile test has been carried out with tensile test device, at speed of test (1 mm/min) for test the specimens of dissimilar 2024-T3,6061-T6 aluminum alloys for every method of welding.

Microstructure

The grain structure and morphologies were evaluate by use an optical microscope type MEIJI, for the selected cross section of welded specimens, the preparation of specimens was done by make a grinding with a different emery papers [8]. The etching solution involve using a killer's etchant (2 ml HF, 3 ml HCL, 5ml HNO3 and 190 ml H2O) according to ASTM E407-76 and test was carried out on the cross section in order to analysis the different zones, these zones include NZ, HAZ, TMAZ and BM.

Micro Hardness Test

A micro hardness testing machine, type INNOVA, the hardness test is done to evaluate the resistance of material to indentation and scratching. The test was carried out at the NZ,HAZ,TMAZ,BM[7] with a (1.5 mm) distance between micro hardness tests, and the load used is (200 gm) .

4. RESULT AND DISCUSSIONS

4.1 Results Of Friction Stir Welding (FSW) And Friction Stir Processing (FSP)

The two plates of AA are show in figure (5). The welding line for friction stir welding (FSW) and friction stir processing (RFSP) of 2024-T3, 6061-T6 dissimilar aluminum alloys are shown in Figure (6),(7).

Figure 5: base metal of two type of AA

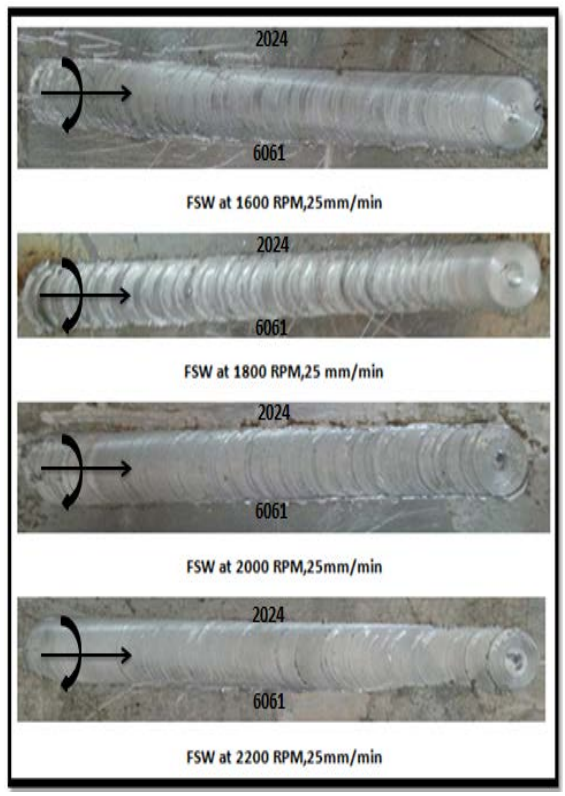

Figure 6: surface of welding line for all (FSW) specimens.

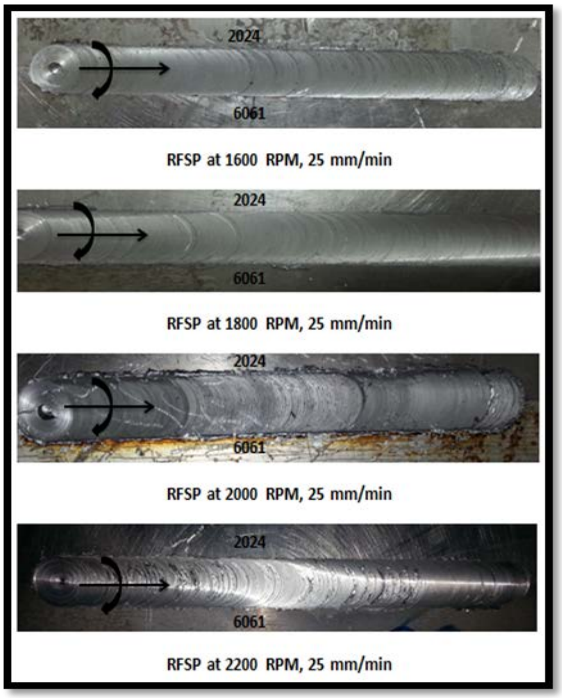

Figure 7: surface of welding line for all (RFSP) specimens

The bottom lines of welded alloys are show below in the figure (8).

Figure 8: The bottom lines of welding for some welded alloys

The figure (6) and figure (7) show a good welding quality without any defect through the cross sections of weld joints when used recent welding methods such RFSP as compared with FSW that has some defects during the joints cross section.

4.2 Tensile Test Result

The tensile test has been carried out and the result for two methods friction stir welding and reverse rotation friction stir processing process as shown in the table (5) and (6) .

Table 5: Results of tensile specimens of FSW.

samples	Type of welding	Average of ultimate tensile strength (MPa)
A1,2	FSW(1600RPM,25mm/min)	135
A3,4	FSW(1800RPM,25mm/min)	239
A5,6	FSW(2000RPM,25mm/min)	175
A7,8	FSW(2200RPM,25mm/min)	189

Table 6: Results of tensile specimens of RFSP.

samples	Type of welding	Average of ultimate tensile strength (MPa)
H1,2	RFSP(1600RPM,25mm/min)	222
H3,4	RFSP(1800RPM,25mm/min)	221
H5,6	RFSP(2000RPM,25mm/min)	172
H7,8	RFSP(2200RPM,25mm/min)	213

From the table (5), (6) the results of reverse rotation friction stir processing (RFSP) method were higher than friction stir welding (FSW) for all speeds except (1800RPM, 25mm/min) speed. The welding efficiency for RFSP (the welding efficiency is proportional of the ultimate stress of the welded specimen to the ultimate stress of the base material) [9]. Table (7) show modulus of elasticity and extension for FSW, RFSP at different speeds.

Table 7: Modulus of elasticity and extension for FSW

Speeds (rpm)	Modulus E (Gpa) for FSW	Extension % for FSW	Modulus E (Gpa) for RFSP	Extension % for RFSP
1600	3.33	7.5	9.46	6.7
1800	8.01	9	10.57	9
2000	4.8	6.15	4.93	10
2200	5.58	5	5.76	5

The behavior of ultimate tensile strength for FSW and RFSP at different rotation speeds as shown in the figure (9) .

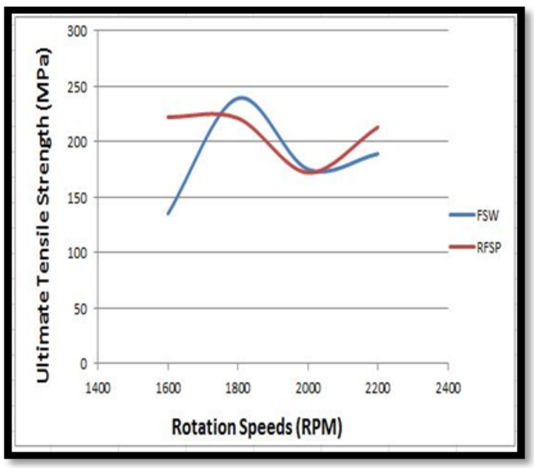

Figure 9: Tensile results for FSW and RFSP at different rotation speeds

4.3 Microstructure Results

From the macro-graphic, different regions of weldments are identified and it represents the effective stir of both the base material in the nugget zone Fig. (10). Metallographic examinations of cross sections of the dissimilar 2024,6061 joints at 1600 RPM, 25 mm/min and 1800 RPM, 25 mm/min are shown in figure (11) and figure (12) respectively.

RFSP

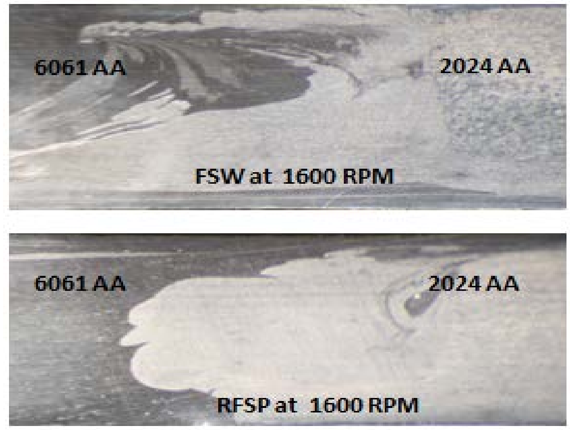

Figure 10: Macrostructure, FSW and RFSP

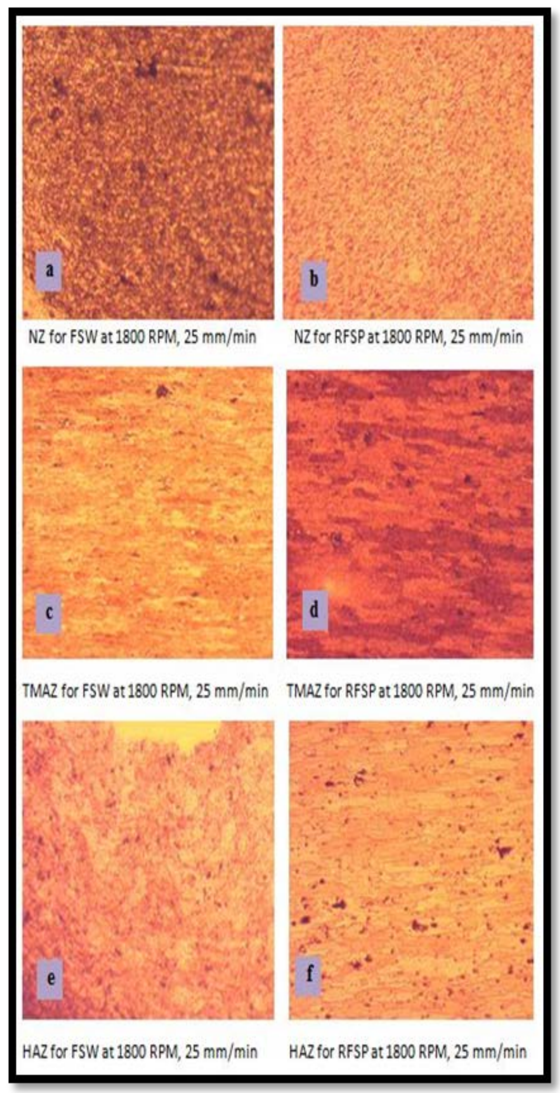

Figure 11: The microstructure of the welding zones in FSW and RFSP for dissimilar joints at 1600 RPM, 25 mm/min

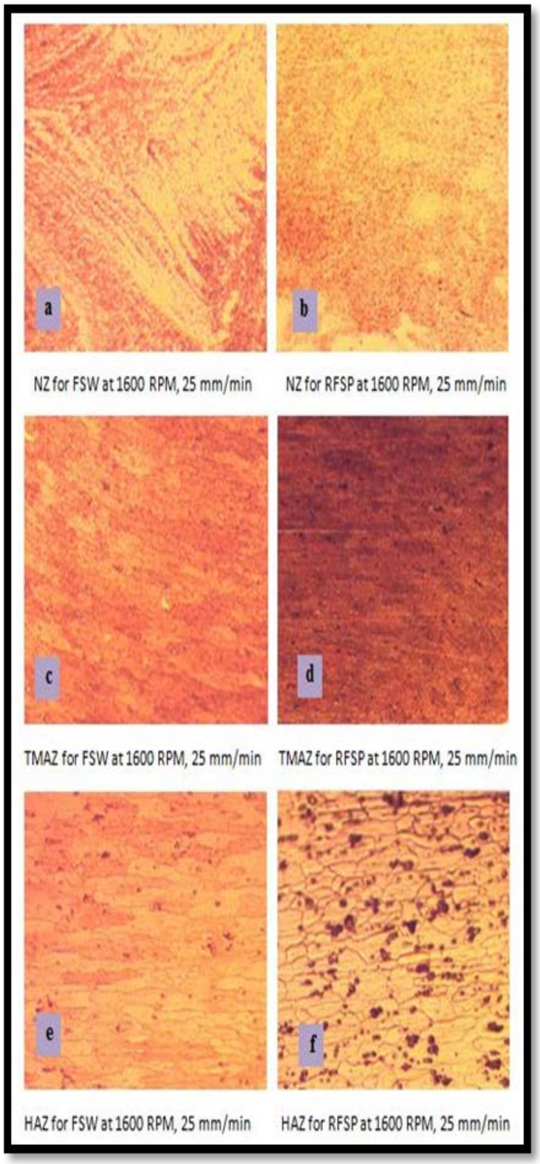

Figure 12: The microstructure of the welding zones in FSW and RFSP for dissimilar joints at 1800 RPM, 25 mm/min

Figure (11) and figure (12) shows the microstructure of the weld zones include nugget zone (NZ), the thermomechanical affected zone (TMAZ), and the heat affected zone (HAZ) from photo (a to e). The microstructure of the weld nuggets was characterized by the presence of fine equiaxed recrystallized grains of the two welded alloys. The grain structure of welded section for RFSP at 1600 RPM been much finer as compare with weld zones of FSW this is due to the FSP soften the material and subjected to a stirring action resulting in homogenous mixing and refined grain structures, but at 1800 RPM the reverse is true that's mean the grain size in weld zones of FSW as shown in the figure (12) include (a, c and e) smaller than that of RFSP and this is an exception in this technique. This is due to the effect of heat generated at RFSP being lower than FSW at (1800 RPM) and that's leads to obtain a coarse grains .

4.4 Micro Hardness Result

The hardness test was done for all specimens of both methods and the best result has been obtained at (1600 RPM, 25 mm/min) and (1800 RPM, 25 mm/min), figure (13) and figure (14) respectively show the micro hardness readings for different zones .

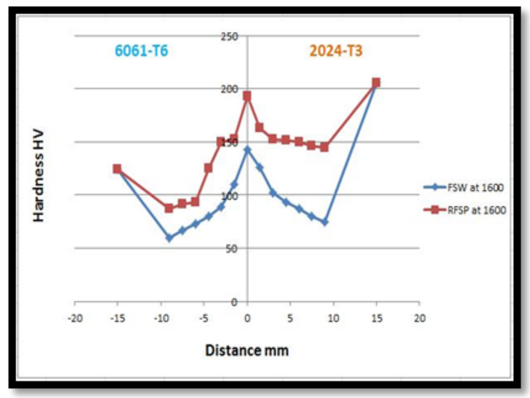

Figure 13: Hardness profiles of FSW and RFSP at (1600 RPM, 25 mm/min).

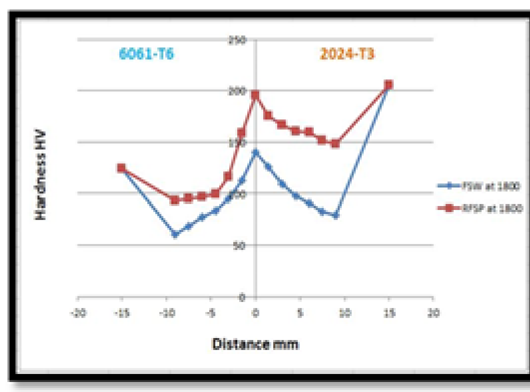

Figure 14: Hardness profiles of FSW and RFSP at (1800 RPM, 25 mm/min).

Figure (13) and figure (14) shows the Vicker's hardness tests for (FSW) and (RFSP) at 1600 rpm, 25 mm/min and 1800 rpm, 25 mm/min. Higher hardness value was observed at NZ region and slow down at TMAZ, HAZ for all type of welding. From figure (13) and figure (14) at the side of 6061-T6 there are a decline in the values of hardness for welded samples by (RFSP), this is due to the roughness of granules in

The heat-affected zone (HAZ) which leads to decrease in hardness values unlike to the other side, hardness in the NZ, TMAZ and HAZ regions were slightly lower in comparison to that of the base metals. The values of hardness for every process of welding (FSW and RFSP) respectively were 136.2 HV and 174.3 HV at 1600 rpm, the values of 139.8HV and 195.6 HV at 1800 rpm. The higher hardness measured in the RFSP at rotation speed 1800 rpm as described above, The hardness of weld nugget was considerably higher than that of AA6061 base material (BM) and (TMAZ). On the other hand the hardness is comparatively lower than AA2024.

Friction stir welding gives coarse grains and that causes to decreasing of the micro hardness. In this process tool rotation and feed rate cause dynamic recrystallization and dynamic recrystallization causes to new fine grains [10]. The results show in this figure that the friction stir processed area has a higher Vickers hardness value than friction stir welded because of FSP is caused to grain refinement and according to the Hall-Petch relationship the hardness increases as the grain size decreases [11].

5. Conclusion

1. Using reverse rotation friction stir processing (RFSP) to weld the dissimilar 2024-T3, 6061-T6 Al-alloys is better than friction stir welding (FSW) at some rotating speeds.
2. The best efficiency of FSW and RFSP for dissimilar joining were founded at rotation speed (1800 RPM) and weld speed (25mm/min), efficiency reaches to (77 % and 71 %) of the ultimate tensile stress for FSW and RFSP respectively.
3. The RFSP method is effective, it will give long life welds because of RFSP enhanced the mechanical properties and modification of microstructure leads to increase the mechanical properties.
4. The values of micro hardness were variable from weld line distance due to change in micro structural properties, the result show the value of hardness at the nugget zone for reverse rotation friction stir processing is higher than friction stir welding due to RFSP caused a grain refinement more than that in FSW.
5. Concluded from this research when using reverse rotation friction stir processing (RFSP) has been getting a good distribution of the grains when most of the rotation speeds used in the present work.

Nomenclature

AA ……………..Aluminum Alloy

FSW ……………Friction Stir Welding

FSP ……………..Friction Stir processing

RFSP ……………Reverse Rotation Friction Stir processing

TWI ……………..The Welding Institute

BM ………………Base metal

NZ ………………..Nugget zone

HAZ ……………...Heat affected zone

TMAZ……………Thermo mechanically affected zone

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تأثير متغيرات المزج الاحتكاكي العكسي على سبائك الالمنيوم المختلفة

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الخلاصة:

طريقة لحام المزج الاحتكاكي(FSW) وهي عملية لحام الحالة الصلبة، والتي تتضمن الحام بواسطة الاحتكاك بين معدنين او سبيكتين، و أيضا تستخدم للحام المواد المختلفة نظرا لدرجة حرارة المعالجة المنخفضة بالمقارنة مع طرق لحام الانصهار التقليدية. اما طريقة المعالجة بالمزج الاحتكاكي (FSP)تعتبر من الطرق الحديثة لتحسين خصائص المعادن وانها مشتقة من طريقة لحام المزج الاحتكاكي (FSW) وتعتمد على تشويه الحالة الصلبة والتي تعمل على تعديل بنية قطعة الشغل. في الدراسة الحالية الطريقة الجديدة المستخدمة هي طريقة المعالجة بالمزج الاحتكاكي العكسي(RFSP) ، ويهدف هذا البحث إلى دراسة تأثير تقنية (RFSP) على الخواص الميكانيكية للسبائك الملحومة. وكانت النتائج التي تم الحصول عليها جيدة باستخدام هذه الطريقة بالمقارنة مع طريقة لحام المزج الاحتكاكي (FSW) الذي يتضمن مسار واحد من خط لحام ولكن (RFSP) يتضمن تمريرتين من خط الحام (ذهابا وعودة) ولكن مرور الأول مع سرعة دوران في اتجاه عقارب الساعة ومرور الثاني في عكس اتجاه عقارب الساعة. تم استخدام سبيكة المنيوم نوع 2024 وسبيكة المنيوم نوع 6061 وبسمك (3 ملم), المتغيرات المستخدمة في هذه البحث تشمل سرع دورانية مختلفة (1600 , 1800, 2000, 2200 دورة في الدقيقة (و استخدمت سرعة تغذية واحدة (25) ملم / دقيقة. في اختبار الشد كانت نتائج طريقة المعالجة بالمزج الاحتكاكي العكسي (RFSP) أعلى من طريقة لحام المزج الاحتكاكي (FSW) لجميع سرعات الدوران باستثناء (1800 دورة في الدقيقة)، في قياس الصلادة الدقيقة قيم الصلادة لجميع العينات في منطقة (NZ)أعلى من المعدن الاساس لسبيكة 6061 T6– وأقل من المعدن الاساس لسبيكة .T32024–

كفاءة مقاومة الشد تصل إلى حوالي (72٪) ل (RFSP) وتم مقارنتها مع قيمة (FSW) وانها حوالي (44٪) في سرعة دوران (1600 دورة في الدقيقة). وكان الاستثناء الوحيد ل الحام عندما كانت كفاءة سرعة دوران (1800 دورة في الدقيقة) ل (FSW)أفضل من (RFSP) وتصل حوالي (77٪) ل (FSW)مقارنة مع نتيجة (71٪) ل(RFSP) .