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Optimization of Friction Stir Welding Process Parameters of Dissimilar AA2024-T3 and AA7075-T73 Aluminum Alloys by Using Taguchi Method

Muna K. Abbass* **Munthir M. Al-Kubaisy****
Ruqaya Abdulkadhim***

*,**,****Department of Production Engineering and Metallurgy/ University of Technology*
***Email: mukeab2014@yahoo.com
****Email: drmnthr_mm@yahoo.com
*****Email: rukaia1990@yahoo.com

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Abstract

The aim of present study is to determine the optimum parameters of friction stir welding process and known the most important parameter along with percentage contribution of each parameter which effect on tensile strength and joint efficiency of FS welded joint of dissimilar aluminum alloys AA2024-T3 and AA7075-T73 of 3 mm thick plates by applied specific number of experiments using Taguchi method .AA2024 was placed on the advancing side and AA7075 on the retreating side. FSW was achieved under three different rotation speeds (898, 1200 and 1710) rpm, three different welding speeds (20, 45 and 69) mm\min , three different pin profiles (cylindrical, threaded cylindrical and cone) and tool tilt angle 2°. Taguchi method was proposed the orthogonal array of L9 based on the three number of process parameters and the three levels of variation for each parameter , S\N ratio and ANOVA analysis of robust design were applied to the results.

The result of S\N ratio analysis were obtained to find the parameters optimization, which has been of rotation speed equal to 898 rpm, welding speed 45 mm\min, and threaded cylindrical pin profile with joint efficiency (76%). The tensile strength result shows that the welding speed was the most important parameter with a percentage contribution of 66.05 % over the other process parameters.

Keywords: *Friction stir welding, Aluminum alloys, Taguchi method.*

1. Introduction

Friction stir welding (FSW) is a modern solid state welding processes that was invented [1]. It involves a cylindrical shoulder tool with a profiled pin which is rotated and thrust quickly into the area to be joined between two pieces of plate or sheet material. To keep joint faces from separated they have to be securely clamped [2]. Frictional heat is produced between welding tool and the work pieces of material. This heat resulting the work pieces to be soften but it doesn't reach to melting temperature and permits the tool to move along the weld line.The resultant material which has become plasticized is moved from the leading edge to the trailing edge of the tool pin and is forged together by close contact of the tool shoulder and pin profile. Thus creating bond between work pieces [3]. Many industries such as aerospace, ship building, automobile have adopted friction stir welding in their welding operations. This because many advantages over traditional welding methods. Among these advantages are it does not cause much distortion, fume, porosity or spatter, consumables (wire used as a filler). Moreover, it does not need surface treatment and shielding gas [4].

The Taguchi method has been applied in a large scale to engineering analysis and is widely used in designing systems with high quality. Taguchi method, using a special design of orthogonal array to investigate the influence of the entire welding parameters through the small number of experiments [5], thus bringing out the most important factors in the process by employing variance analysis (ANOVA) and signal-to-noise ratio (S/N)".

Palanivel and Mathews [6] focused on the tensile behavior of dissimilar joints of AA6351-T6 and AA5083-H111 of 6mm thickness produced by friction stir welding . Five various of tool pin, like straight square, tapered square, straight hexagon, straight octagon and tapered octagon, with three various welding speeds of 50, 63 and 75mm/min , and speeds of tool rotational of 950 rpm have been used to weld the joints. They found that the straight square pin with 63 mm/min produced tensile strength higher than that of the other tool pin profiles and welding speeds.

Kumbhar and Bhanumurthy [7] described the microstructural development and mechanical properties which are associated with the dissimilar joints of friction stir welding of aluminum alloys AA5052 and AA6061 of 5mm thickness . Friction stir welding was performed at different combinations of speeds of tool rotation of 1120 and 1400 rpm and welding speeds of 60, 80 and 100 mm\min and 3◦ tilt angle of the tool. The tensile test specimens evaluation showed good mechanical properties. The alloying elements interdiffusion and similar orientations development in the nugget zone could help produce the better tensile properties of the friction-stir-welded of specimens of AA5052-AA6061.

Many researchers [8, 9] studied the effect of friction stir welding parameters such as welding speed , speed tool rotational and types of tool pin profile on the microstructural and mechanical properties of dissimilar aluminum alloys AA7075 and AA6061. They found that the tensile strength of the dissimilar joints increases with increasing welding speed and tool rotation speed.

Rajamanickam and Balusamy[10] described the effect of friction stir welding parameters on mechanical properties of 2014 aluminum alloy plate using design of experiments DOE . With 9 experiments, varying process parameters like speed of tool rotation and speed of welding were taken in consideration . ANOVA was used to examine the influence of input parameters on mechanical properties of joints which were welded .The tensile strength, hardness and elongation were used to characterize the samples. It was concluded that increase in speed of welding is proportional to the tensile strength. The sample which was welded with speed of rotation of 1200 rpm and speed of welding of 8mm/min showed the highest elongation, on the other hand the sample welded with the 600rpm and 20 mm/min showed lowest elongation.

Suresha et al. [11] studied the effect of parameters of friction stir welding process on tensile strength and efficiency of FSW joints for two kinds of tool pin profiles namely conical and cylindrical tool heads with grooves. The process parameters of friction stir welding include speed of tool rotation of 900, 1120 and 1400 rpm, speed of welding of 40, 50 and 63 mm\min and depth of plunge of 4.93, 4.96 and 4.99 mm. It has been noted that the speed tool rotational shows more effect on tensile strength in both tools. Better joint efficiency comes from conical profile than from the cylindrical profile tool. ANOVA was used to determine the percentage contribution of these parameters of the process and it was concluded that the speed of tool rotational and speed of welding are the important parameters which contribute to the response.

Krishna et al. [12] used the Taguchi experimental design technique to determine the optimum welding parameters for friction stir welds of different alloys of aluminum "AA2024-T6 and AA6351-T6" for tensile properties. The effect of FSW parameters, speed of rotation, speed of welding and axial force, on tensile strength was evaluated. So as to enhance the productivity and weld quality, best welding conditions to get the highest stensile strength were assessed. A mathematical model based on non-linear regression was developed to establish the relation between the parameters of process and tensile strength. The confirmation tests were made to confirm the results were under the best identified conditions.

The current study aims to obtaining the best parameters of FSW welding which are speed of tool rotation, speed of welding and pin geometry. The identification of the most effective parameters of welding process is made by using L9 Taguchi orthogonal array. Furthermore, ANOVA is used to find out how much each parameter contributes to the process.

2. Experiment Work

2.1. Material Selection

Aluminum alloy plates 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. 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 shown in Table 2.

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 (500)g	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

2.2. Tools Features

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). Three welding tools are designed and machined as shown in Figure 1 and Table 3. The tools were subjected to heat treatment (hardening and tempering) and the each tool has average hardness value of 53-55HRC.

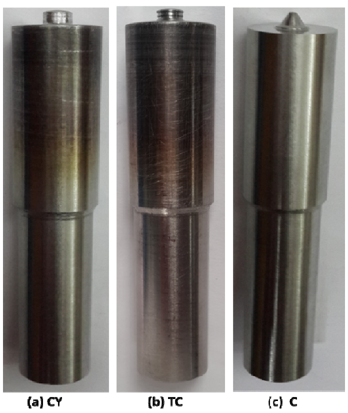
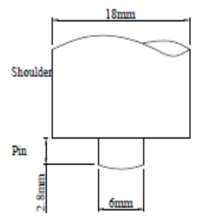
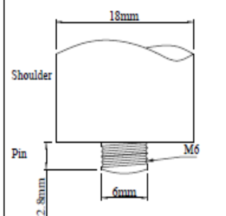
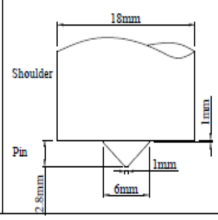


Fig. 1. Tool Design (a) Cylindrical CY (b) Threaded cylindrical TC (c) Cone C.

Table 3,
The welding tools design and details.

Tool Symbol	Tool Design (pin geometry and shoulder)	Details
Model 1		Cylindrical (CY) Shoulder Concavity:0° Shoulder diameter:18mm Pin diameter:6mm Pin length :2.8mm
Model 2		Threaded Cylindrical (TC) Shoulder Concavity:0° Shoulder diameter:18mm Pin diameter:6mm Pin length :2.8mm (M6with 1mm pitch)
Model 3		Cone(C) Shoulder Concavity:0° Shoulder diameter:18mm Pin diameter:6mm Pin Length :2.8mm

2.3. Friction Stir Welding Process

FSW process was carried out by using milling machine (type: Knuth Werkzeugmaschinen GmbH, Germany) to fabricate butt welded joints. For all the dissimilar joints, 2024 plates were placed on the advancing side and 7075 was on the retreating side of the weld. Figure 2 shows friction stir welding steps.

acting step

Fig. 2. Friction Stir welding steps.

2.4. Orthogonal Array Selection

The experimental design suggested by ANOVA covers the use of orthogonal arrays to arrange in order the parameters of welding process and the levels at which they must differ. In terms of the L9 orthogonal array suggested by Taguchi, three experiments were carried out on each set of parameters of process. The three parameters which were used in this experiment were the speed of rotation (rpm), speed of welding and geometry of pin. Table 4 shows the parameters and the levels of the process. The tilt angle (2º) remains constant. A total of nine experimental runs were made, a combination of levels was used for each control factor as given in Table 5.

Table 4,
Parameters and their levels of FSW.

Parameters	Level 1	Level 2	Level 3
Rotation speed RS (rpm)	898	1200	1710
Welding speed WS(mm\min)	20	45	69
Pin Geometry PG	Cylindrical (CY)	Threaded cylindrical (TC)	Cone (C)

Table 5,
Experimental of L9 Orthogonal array.

Experiment No.	RS (rpm)	WS (mm\mim)	PG
1	898	20	CY
2	898	45	TC
3	898	69	C
4	1200	20	TC
5	1200	45	C
6	1200	69	CY
7	1710	20	C
8	1710	45	CY
9	1710	69	TC

2.5. Tensile Test

Transverse tensile tests were 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 [13].

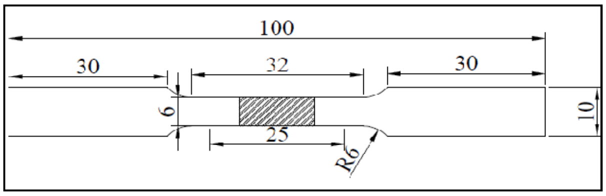


Fig. 3. ASTM- E8M Sub-Size Sample for Tensile Test, all dimensions are mm [13].

2.6. Microstructure Inspection and Microhardness Test

Optical microscope was used to examine the samples which were made from a cross section of the FSW joints and base alloy in sequences steps.

1- 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.
2- The process of polishing was made on the samples using 0.5μm diamond paste and special cloth for polishing and lubricant.
3- 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) [14]. They were washed and dried.
4- Optical microscope is used to provide information about the microstructure of welded samples.
5- 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.

3. Results and Discussion

3.1. Signal to Noise Ratio: (S\N) Ratio

Tensile strength is an important response characteristic taken into consideration in this investigation. It describes the quality of FSW welded joints. So as to estimate the effect of welding parameters on tensile strength, means and S/N ratio for each control factor (speed of tool rotation, the speed, of welding and pin geometry) were calculated. The appropriate S/N ratio was selected using previous knowledge, experience, and process understanding. In this study, the S/N ratio was selected in terms of the standard of the "higher is better", in order to maximize the response. In the Taguchi method, is used to determining the difference of the quality characteristics from the value desired is achieved by using the S/N ratio.

In this study, the tensile strength data were analyzed to decide the influence of FSW parameters. Table 6 shows the three levels of parameters of process as per L9 orthogonal array, the means of tensile strength and corresponding S/N ratio.

Analyzing the mean for each of the experiments will result in better parameter combination level so that tensile strength at high level is made certain in terms of experimental data. The plots as in Figures (4and5) can be used to identify the highest level of process parameter conformity to the highest S/N ratio and tensile strength respectively.The tensile strength is assessed to be the highest with speed of rotation of 898 rpm and speed of welding of 45mm/min and threaded cylindrical pin geometry (TC) which is optimal from the plots obtained.

Table 6,
Tensile strength, joint efficiency and S/N Ratio for experiments.

Experiment No.	RS (rpm)	WS (mm\min)	PG	Mean MPa	Efficiency%	S\N ratio
1	898	20	CY	318	71	50.05
2	898	45	TC	340	76	50.62
3	898	69	C	300	67	49.54
4	1200	20	TC	327	73	50.29
5	1200	45	C	315	70	49.96
6	1200	69	CY	310	69	49.82
7	1710	20	C	311	69.1	49.85
8	1710	45	CY	330	73.3	50.37
9	1710	69	TC	295	66	49.39

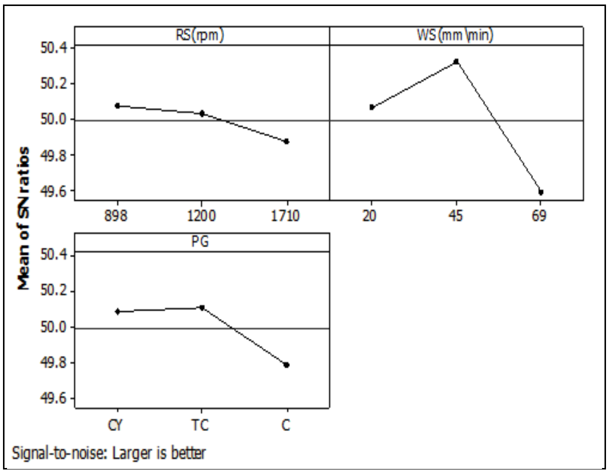


Fig. 4. Main Effect Plot for S/N ratio.

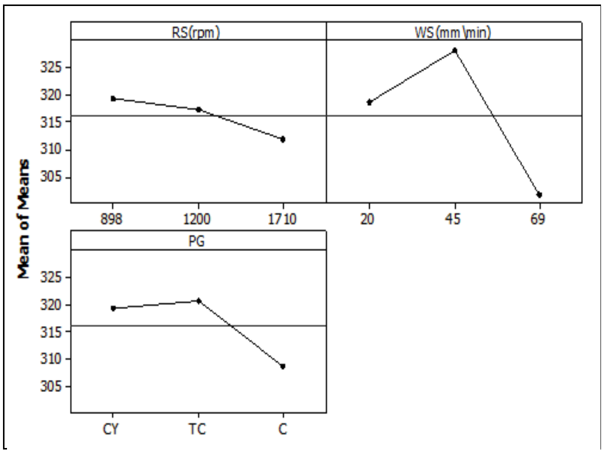


Fig. 5. Main Effect Plot for mean tensile strength.

3.2. Analysis of Variance (ANOVA)

The ANOVA test is used to examine the importance of the parameters of welding process which influence the tensile strength of joints welded with FSW. The F-test named after Fisher can also be utilized to determine which process has important influence on tensile strength. Usually, the difference of the process parameter has a significant influence on the quality characteristics of tensile strength of welded joints , when F is high .The ANOVA test results show that the process parameters considered are very important factors which influence the tensile strength joints welded with FSW in the order of speed of rotation,speed of welding and geometry of pin. It is shown that the ANOVA of tensile result display that the speed of welding is the most effective parameter having a percentage of 66.05 %, followed by geometry of pin of 15.68% and speed of rotation of 5.21%. As shown in Table 7.

Table 7,
ANOVA of tensile strength (Means).

Parameters	DF	Seq SS	Adj SS	Adj MS	F	P_A%
Rotation speed RS (rpm)	2	86	86	43	0.16	5.21
Welding speed WS(mm\min)	2	1093.6	1093.6	546.8	5.84	66.05
Pin Geometry PG	2	260	260	130	0.56	15.68

Note: DF- Degrees of Freedom, Seq SS – Sequential Sum of Squares, Adj SS –Adjusted Sum of Squares, Adj MS – Adjusted Mean Square, , F─Fisher ratio. P_A percentage contribution.

3.3. Tensile Test Results

The tensile strength of all the joints tested were noted to be lower than the tensile strength of the base alloys as shown in Figure 6. In welding, the heat input has a great effect on the weldment mechanical properties. From the experimental results, it was found that the tensile strength is directly proportional to increase in speed of welding in the tested range. It was also noted that the tensile strength increases with increase in speed of tool rotation up to 898 rpm and then decreases. In FSW, it is seen that the increase in speed of the welding and decrease in the speed of tool rotation reduce the required heat input for joining which lead to reducing the thickness of thermomchanically affected zone TMAZ and HAZ which in turn enhances the tensile properties. Other workers reached the same results[10] .

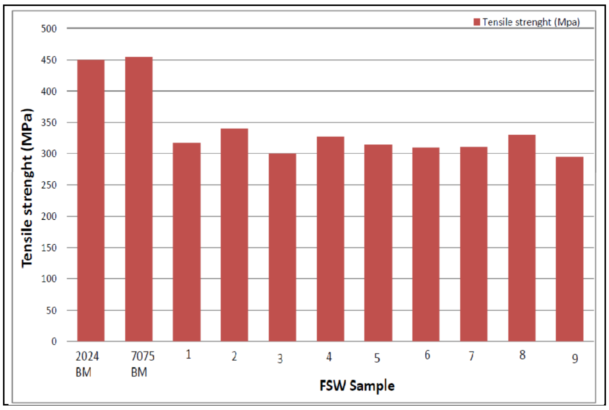


Fig. 6. Tensile strength of base alloys and FSW welded joints.

From Figure 6 it was seen that the increase in the tensile strength is in direct proportion to rotational speed at 898 rpm, after that it reduces . The tensile strength first increases to a maximum value and afterwards show reduce with increasing the rotational speed at a given welding speed or tool pin geometry of the friction stir welded joints. Generally the tensile strength is low at lower rotational speeds because of unsuitable tool stirring action but with the increase of rotational speed for a certain range the strain hardening influence induced by tool stirring action increases tensile strength but the tensile strength lowers significantly with an increase of rotational speed to a rather high value due to increase heat input results in reprecipitation, reduction in dislocation density and coarsening of strengthening precipitates. The variation in tensile strength value at various speed of rotational for a tool pin geometry is because of the different of material flow and frictional heat generated. For a given rotational speed or tool pin geometry, the increase of welding speed increases the tensile strength to a certain value, and further increase of speed of welding results in the reduce in the tensile strength of the friction stir welded joints At lowest (20 mm/min) and highest speed of welding (69 mm/min) lower tensile strengths are observed. The lower speed of welding, which significantly deteriorates the mechanical properties of joints due to larger heat input into the weld samples, however as the welding speed increases, the thermal cycles effect is minimized which leads to an increase in tensile strength. The lower tensile strength at 69mm/min is due to insufficient frictional heat generated. The dissimilar joints fabricated using the threaded cylindrical (TC) tool has maximum tensile strength than that the joints made using other two tools these result are in agreement with research[15].

The tensile strength of the base alloys and dissimilar joints at optimal welding parameters is shown in Figure 7.

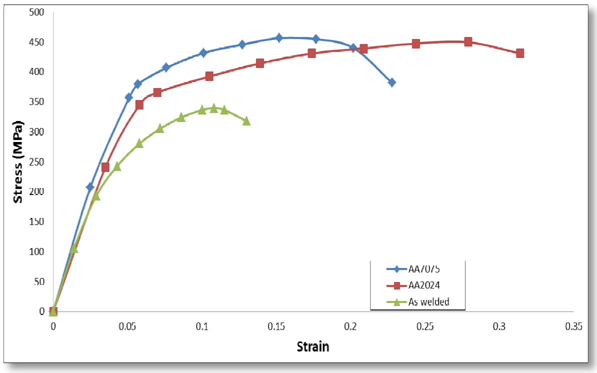


Fig. 7. Stress-strain curves of base alloys (AA2024 and AA7075) and as welded sample at 898 rpm, 45 mm\min and threaded cylindrical pin profile.

3.4. Microhardenss Results

Figure 8 shows the profile of microhardness along the FS weld showing a value of 162 HV in the center weld. It can be obseved the hardness of welded joint is lower in the heat affected zone HAZ as regards both the 2024 and 7075 base alloys. This is related to the classical behavior of FSW welded aluminum alloys. Two main reasons account for the improved hardness of the stir zone(SZ):-

(1) The SZ grain size a lot finer than that of base metal; strengthening of a materials is very much affected by grain refinement because hardness is inversely proportional to grain size decreases.

(2) Hardness is improved by the fine particles of intermetallic compounds and fine precipitates, because the difference in hardness between the HAZ and SZ is due to the refinement of grain in the SZ.

The stirred zone has higher hardness compared with the HAZ and TMAZ because of the smaller grain size at this zone. The HAZ zone experienced thermal cycle without plastic deformation, the over-ageing and coarsening of strengthening precipitates reduced the hardness in HAZ. The over-ageing of precipitates in the HAZ depends on the heat exposure time and temperature, and it controlled by rotational and welding speeds and also the deciding factors for the hardness distribution in HAZ similar results were reported elsewhere [15].

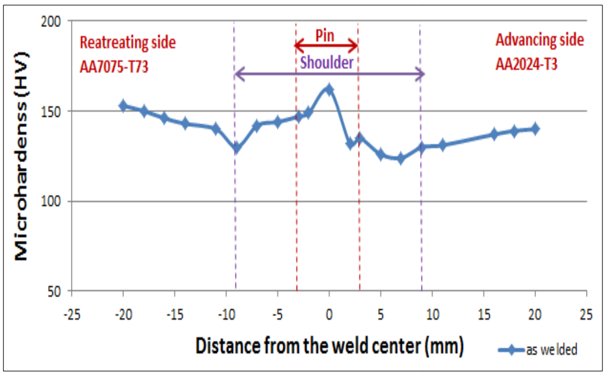


Fig. 8. Microhardness distribution across the transverse cross section of FSW dissimilar Al-alloys AA2024-T3 and AA7075-T73.

3.5. Microstructure Results

Figure 9 shows sample microstructure cross section of joint welded with FSW at best parameters of welding. It is observed that joints welded with FSW do not show any defect and any other imperfection (for example lack of penetration, porosity, etc.) due to sufficient heat generation. Typical microstructural features of FSW such as the SZ, TMAZ and HAZ) have been identified. The parent alloys and HAZ have similar microstructure. The TMAZ region undergoes both heating as well as plastic deformation during FSW because they are characterized by a structure which is deformed and is induced by the tool mechanical stirring . The SZ is made by two regions composed of re-crystallized very small grains made of both 2024 and 7075 Al alloys ,which were composed of fine grains and equiaxed. The higher temperatures and severe plastic deformations result in remarkable smaller grains than that the parent metal, these results are in agreement with those of researcher [16], in terms of all the FSW literature data for aluminum alloys; the initial elongated grains of the original materials are mechanically changed to a new fine grain structure and equiaxed these results are in agreement with those of researcher [17].

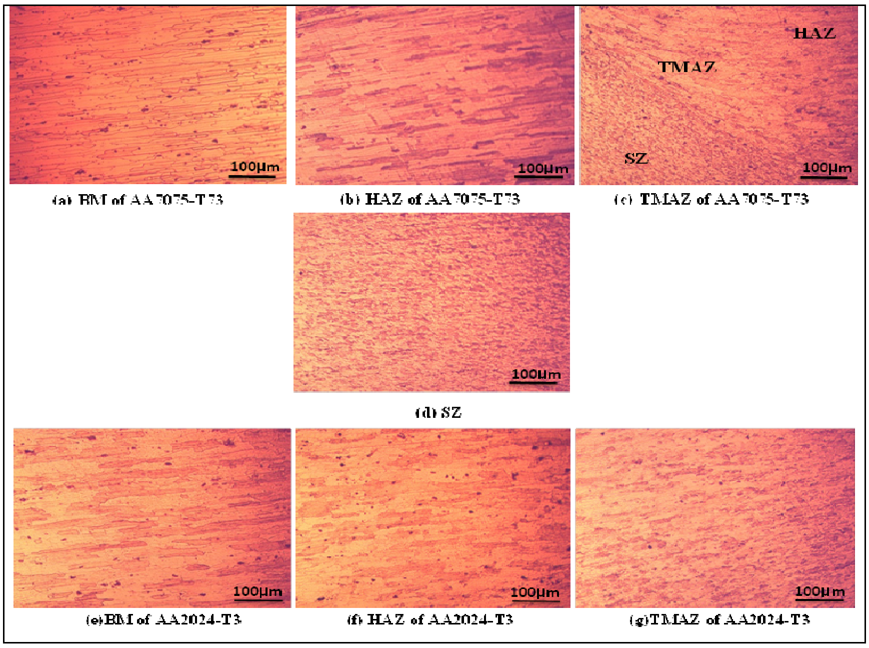


Fig. 9. Microstructures of dissimilar FSW aluminum alloys (AA2024-T3 and AA7075-T73).

4. Conclusions

1- The optimum values of parameters of FSW welding like speed of rotational, traverse speed and geometry of pin are 898rpm, 45 mm\min and cylindrical threaded pin geometry respectively.

2- The contribution percentage of FSW process was evaluated, It was found that the speed of welding, speed of rotation and geometry of pin have 66.05%, 5.21% 15.68% contribution respectively obtained from welded joints.

3- Tensile strength of welded joints increases as the welding speed increases.

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

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أمثلية عوامل عملية اللحام بالخلط الاحتكاكي لسبيكتي الالمنيوم غير المتشابهة (AA2024-T3 وAA7075-T73) بأستخدام طريقة تاكوشي

منى خضير عباس* منذر محمد راضي** رقية عبد الكاظم***

*،**،*** قسم هندسة الانتاج والمعادن/ الجامعة التكنولوجية

*البريد الالكتروني:mukeab2014@yahoo.com

**البريد الالكتروني: drmnthr_mm@yahoo.com

*** البريد الالكتروني: rukaia1990@yahoo.com

الخلاصة

يهدف البحث الحالي الى تحديد العوامل المثلى لعملية اللحام بالخلط الاحتكاكي ومعرفة أكثر عامل يؤثر مع نسبة مشاركة كل عامل على مقاومة الشد وكفاءة الملحومات لسبيكتي الألمنيوم غير المتشابهة (AA2024-T3 وAA7075-T73) من خلال أجراء عدد محدد من التجارب باستخدام طريقة تاكوشي. وضعت السبيكة AA2024 على الجانب المتقدم لعدة اللحام وAA7075 على الجانب المتأخر.

وتم أجراء عملية اللحام بالخلط الاحتكاكي عنده ثلاث سرع دوران مختلفة (898 , 1200 و 1710) دورة| دقيقة وثلاث سرع لحام مختلفة (20 , 45 و69) ملم| دقيقة وباستعمال ثلاثة تصاميم مختلفة للأداة (اسطواني ،اسطواني مسنن ومخروط) وعند زاوية ميل 2° .تم اعتماد طريقة تاكوشي على اختيار مصفوفة متعامدة من L9 استنادا الى ثلاثة أعداد من معاملات العملية وثلاثة مستويات من المتغيرات لكل معامل. تم تطبيق نسبة أل S\N وتحليل أل ANOVA على النتائج.

وقد تم الحصول على نتيجة تحليل نسبة ألS\N لايجاد المعاملات المثلى، والتي كانت سرعة الدوران 898 دورة | دقيقة ، وسرعة اللحام 45 ملم| دقيقة وتصميم الأداة الاسطواني مسنن مع كفاءة الملحومة (76%). وقد وجد من تحليل ANOVA الى أن سرعة اللحام هي أكثر عامل يؤثر على مقاومة الشد مع نسبة مشاركة 66.05% من المعاملات الأخرى.