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EFFECT OF WELDING PARAMETERS ON THE MECHANICAL PROPERTIES OF DISSIMILAR ALUMINUM ALLOYS 2024-T3 TO 6061-T6 JOINTS PRODUCED BY FRICTION STIR WELDING

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ABSTRACT

The use of fusion welding process for 2024-T3 and 6061-T6 alloys is not preferred because of the heat generated from the thermal cycle of the welding which can affect the heat treatments of base metals. Therefore, solid state nature of friction stir welding (FSW) process is generally used in order to join these dissimilar alloys. This experimental study presents the effect of variable rotational and traverse speeds on hardness, bending, and tensile properties of 2024-T3 and 6061-T6 alloys joints produced by FSW. Experimental results have shown that defect free friction stir welded joints of good quality successfully produced from 3 mm thick sections of these alloys.

Keywords: Friction stir welding, dissimilar aluminum materials welding, aluminum alloy, mechanical properties.

KAYNAK PARAMETRELERİNİN SÜRTÜNME KARIŞTIRMA KAYNAĞI İLE BİRBİRİNE KAYNAKLANMIŞ 2024-T3 6061-T6 ALUMİNYUM ALAŞIMLARININ MEKANİK ÖZELLİKLERİ ÜZERİNDEKİ ETKİLERİNİN İNCELENMESİ

ÖZET

Ergitme kaynak metodları 2024-T3 ve 6061-T6 alaşımlarının birbirlerine kaynatılması için önerilmemektedir, çünkü kaynak esnasında oluşan ısı kaynak bölgesinin ısıl işlem özelliğini etkilemektedir. Bundan dolayı bu alaşımların birleştirilmesinde, katı hal kaynak yöntemlerinden biri olan sürtünme karıştırma kaynağının (friction stir welding -FSW) kullanılması tercih edilmektedir. Bu çalışma farklı iki malzeme olan 2024-T3 ve 6061-T6 aluminyum alaşımlarının sürtünme karıştırma kaynağı ile birleştirilmesi üzerine yapılan deneysel bir çalışmadır. Bu çalışma kapsamında kaynak pimi açısal hız ve ilerleme hızının, sertlik dağılımı, eğilme ve çekme özellikleri üzerindeki etkilerini incelenmiştir. Deneysel sonuçlara göre kusursuz bir sürtünme karıştırma kaynağı işlemi ile 3 mm kalınlığındaki bu alaşımların (2024-T3 ve 6061-T6) oldukça başarılı bir şekilde kaynaklanabildiği gözlenmiştir.

Anahtar Kelimeler: Sürtünme karıştırma kaynağı, farklı aluminyum alaşımlarının kaynakla birleştirilmesi, aluminyum alaşımları, mekanik özellikler.

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1. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining process that has been invented at The Weld Institute (TWI, United Kingdom), and patented in 1991 by Wayne Thomas under research funded by in part by the National Aeronautics and Space Administration (NASA) [1] . It is an adaptation of the friction welding process. FSW is a continuous process that involves plunging a portion of a specially shaped rotating tool between the butting faces of the joint [2]. The relative motion between the tool and the substrate generates frictional heat that creates a plasticized region around the immersed portion of the tool [3,5]. The shoulder prevents the plasticized material from being expelled out of the weld. The tool is moved relatively along the joint line, forcing the plasticized material to coalesce behind the tool to form a solid–phase joint [4, 10]. Since its invention, the process has received world-wide attention, specialized companies from Europe, Japan and USA are using the technology in production [6]. It can be used also for welding aluminum alloys of different alloy groups or yet dissimilar materials, metal matrix composites and plastics [9].

Other materials such as magnesium, copper, zinc, titanium and even steel can be welded with this process. The process presents several advantages when compared with conventional arc welding processes, mainly in the welding of aluminum alloys. Difficulties related to sensitivity to solidification cracking, gas porosity caused by the hydrogen absorbed during welding and thermal distortion, very common in fusion welding process; do not happen in this process [7]. Other benefits of the process include good strength and ductility along with minimization of residual stress and distortion, no consumables required, improved safety due to the absence of toxic fumes or the spatter, can operate in all positions (horizontal, vertical, etc.), easily automated on simple milling machines — lower setup costs and less training [11]. Friction Stir Welding has found various applications in a number of areas. Potential applications are space shuttle fuel tanks, aluminum decking for car ferries, manufacturing of compound aluminum extrusions and automotive structural components. The ever growing list of FSW users includes Boeing, Airbus, Eclipse, NASA, US Navy, Mitsubishi and Kawasaki [12]. FSW technique can be applied effectively to a variety of joints configurations like butt joints, lap joints, T butt joints and even fillet joints [3]. In a FSW process, advancing side (AS) is the side where the direction of the tool rotation and traverse movement direction are the same and the side where the velocity vectors (of tool rotation and traverse movement) are opposite is referred to as retreating side (RS) [13].

Heat treatable aluminum alloys (as such 2024 and 6061) are specially produced for critical applications with advanced mechanical properties of high strength and ductility but unfortunately sometimes with the disadvantage of unsuitability to conventional welding processes. Therefore in critical applications of aerospace and similar, those special heat treatable alloys (not suitable for conventional welding processes) need to be friction stir welded. Although friction stir welding of the same (or similar) aluminum alloys have been studied largely in literature [14-19] not much study have been found regarding FSW of dissimilar aluminum alloys [20,22], in particular of 2024-T3 to 6061-T6 alloys. Two specific articles [23,24] have studied material flow and microstructural evolution associated with the FSW of 2024 and 6061 aluminums but neither of two alloys has studied the mechanical properties of the dissimilar material FSW joint. Not much, even almost no study and experimental results are available regarding mechanical properties of FSW of 2024 and 6061 aluminums. In this paper, friction stir weldability and also the mechanical properties of the joint produced by FSW of specific dissimilar aluminum alloys (2024-T3 alloy to 6061-T6) are studied and experimental results are provided as new/novel results.

2. EXPERIMENTAL PROCEDURE

2.1. Material Used

Dissimilar 2024-T3 and 6061-T6 aluminum alloys of 3 mm thick plates were friction stir butt welded. The chemical composition for 2024 alloy was as follows: Si 0.1255, Fe 0.272, Cu 4.19, Mn 0.6144, Mg 1.26, Cr 0.012, Ni 0.010, Zn 0.165, Ti 0.018, Pb 0.0099, balance Al, and the chemical composition for 6061 alloy was: Si 0.673, Fe 0.590, Cu 0.326, Mn 0.066, Mg 1.03, Cr 0.196, Ni 0.013, Zn 0.108, Ti 0.015, Pb 0.009, balance Al (All in mass %). 2024 is an aluminum alloy with copper (Al-Cu) of the 2xxx series with a temper condition of solution heat treated, cold worked, and naturally aged. It is usually used where good machinability and high strength are required such as aircraft structures, especially wing and fuselage structures under tension. AA6061 is a precipitation hardening aluminum alloy, containing magnesium and silicon as its major alloying elements, Al-Mg-Si grade alloy of the 6xxx series. It is with a temper condition of solution heat treated and artificially aged [8]. The chemical composition of the base metals was tested by spectrometer device and analyzed according to ASTM standard B209. The tensile properties of the base metals are listed in Table 1.

Table 1. Mechanical properties of 2024-T3 and 6061-T6 base metals

Material	Yield strength MPa	Ultimate tensile strength (UTS) MPa	Percentage of elongation %
2024-T3	380	464	16
6061-T6	295	342	10

2.2. Friction Stir Welding

Friction stir welding of dissimilar aluminum alloys 2024-T3 and 6061-T6 were carried out using a tool made of high speed steel (HSS) consisting of 18mm diameter shoulder and 6 mm diameter cylindrical pin with an overall height of 2.8 mm making it slightly shorter than the plate thickness as it is illustrated in Figure 1. Tool tilting angle used during all the tests was 1 degree. Tilting angle is the angle between axis of the tool itself and the axis which is vertical to the plates being welded.

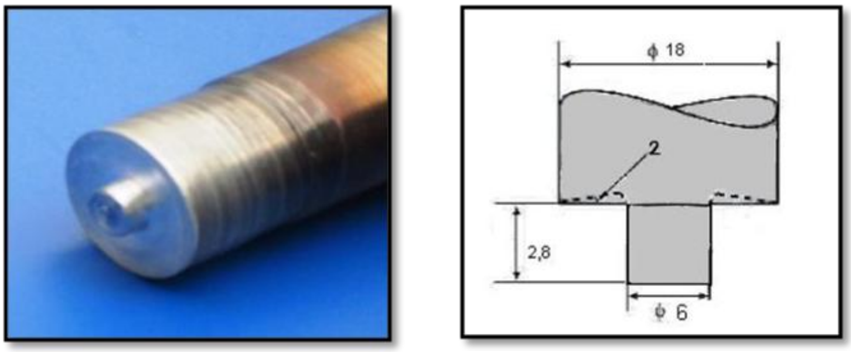

Figure 1. FSW tool used in the current study

All welding experiments were carried out using a vertical milling machine. The welding plates are located on backing plate which in turn is fastened onto the milling machine table. The welding plates are held fixed in position by the specially designed mechanical clamps as shown in Figure 2 which illustrate the overall geometry of friction stir welding process.

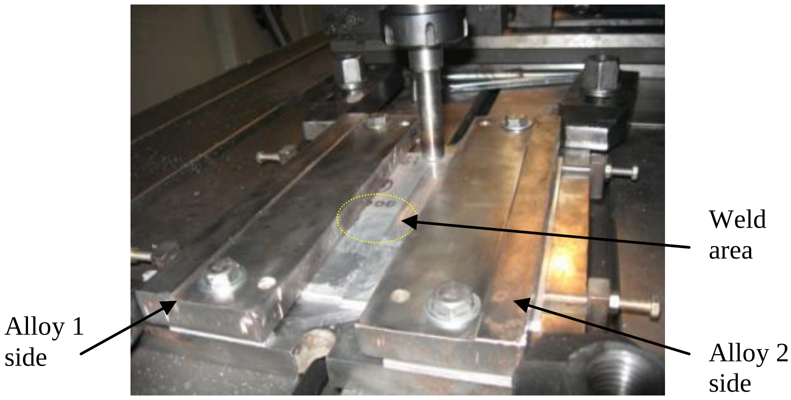

Figure 2. A close-up view of friction stir butt welding

Variable rotational and traverse speeds were used during tests. For the first set of tests, rotational speeds used were 600, 800, 1000, and 1200 rpm while keeping the traverse speed constant at 50 mm/min. In the second set, rotational speed was kept constant at 1000 rpm and traverse speed were set at 25, 75, and 100 mm/min. During FSW, in the first set (varying rotational speeds) advancing side is aluminum alloy 2024-T3 and retreating side is aluminum alloy 6061-T6 for one case. Whereas advancing side is alloy 6061-T6 and retreating side is alloy 2024-T3 for the second case. For the second set (varying traverse speed) advancing side is alloy 6061-T6 and retreating side is alloy 2024-T3. Table 2 and Table 3 summarize welding conditions adopted in the current study.

Table 2. First set of tests with process parameters used to fabricate the joints

Sample number	Traverse speed mm/min	Rotational speed rpm	Direction of weld
1	50	600	2024 on advancing side & 6061 on retreating side
2		800	
3		1000	
4		1200	
5	50	600	6061 on advancing side & 2024 on retreating side
6		800	
7		1000	
8		1200	

Table 3. Second set of tests with process parameters used to fabricate the joints

Sample number	Rotational speed rpm	Traverse speed mm/min	Direction of weld
9	1000	25	6061 on advancing side & 2024 on retreating side
10		75	
11		100	

2.3. Mechanical Tests

Before implementing the mechanical tests the weldments were characterized by the visual inspection and qualitative analysis of the weld roots and crowns. X-ray inspection tests of welded specimens were also carried out to check that no defects or discontinuities were present within the welds. Radiographic unit was operated for 1 min at 150 kV, 2 mA for the inspection.

Tensile properties of each joint were evaluated at room temperature using the computerized Tinus Olsen universal tensile testing machine. All tensile tests were carried out at a constant crosshead speed of 10 mm/min and the average of three specimens was taken to evaluate the tensile behavior of each welded joint.

The configuration and dimension of the transverse tensile specimens were specified according to ASTM (E8M-04) as it is shown in Figure 3. Multiples of specimens are cut from welded plates with the condition that loading axis of the tensile test specimens is transverse (perpendicular) to the welding direction of the plates.

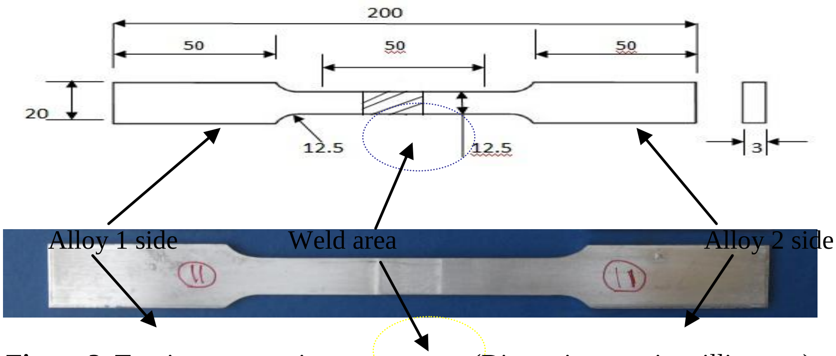

Figure 3. Tension test specimen geometry. (Dimensions are in millimeters)

Face and root bending tests were carried out at room temperature by universal testing machine as it is illustrated in Figure 4. The welded joints were machined into standard test specimen dimensions according to the ASTM (E 190-92) as it is shown in the Figure 5. Microhardness testing of the welded joints was accomplished using the Vickers hardness tester. According to the ASTM, Vickers hardness measurements were taken 1 mm below the top surface of the specimen perpendicular to the welding direction across the weld nugget zone (NZ), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ), TMAZ/HAZ interface zone and the base materials using a diamond pyramid indenter with a load of 20 kg and loading within 15sec.

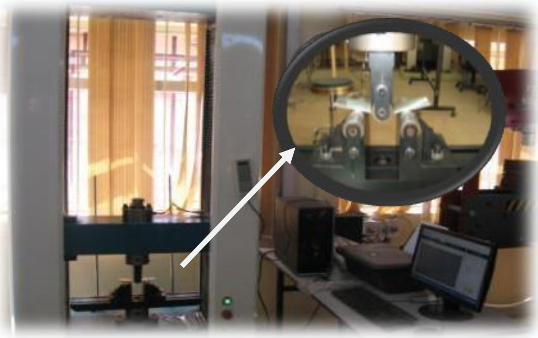

Figure 4. Bending setup.

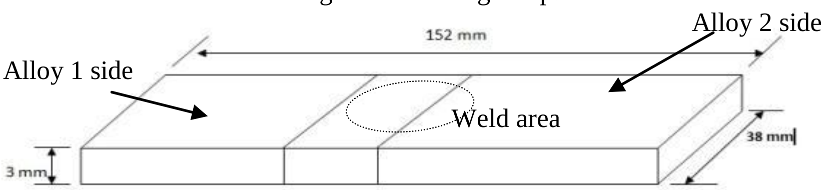

Figure 5. Schematic of bending test specimen according to ASTM. (E 190-92)

3. RESULTS AND DISCUSSIONS

Regarding the joint performance, the weldments indicated no visible defects; weld surface is even and uniform. It can be seen from the Figure 6 and 7 that better surface appearance has been obtained for all the rotational and traverse speeds used. Also the exit hole at the end of the weld was 100% complete which is an indication of good quality weld. In all the joints of this work there was a flash extending from the beginning to the end of the weld. Also X-Ray radiographic inspection was carried out and indicated a good quality weld without any pores and discontinuities at weldment.

Figure 6. Appearance of the weld using cylindrical pin and variable rotational speed of:
(a) 600 rpm. (b) 800 rpm. (c) 1000 rpm. (d) 1200 rpm at traverse speed of 50mm/min

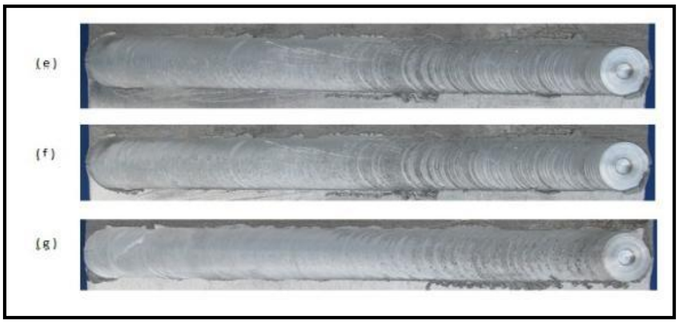

Figure 7. Appearance of the weld using cylindrical pin and variable traverse speed of:
(e) 25 mm/min. (f) 75 mm/min. (g) 100 mm/min at rotational speed of 1000 rpm

Regarding the literature provided in introduction for mechanical properties of FSW of 2024-T3 and 6061-T6 aluminums, not enough even almost no experimental results are available to compare with the experimental results obtained below. Therefore results obtained in this article are discussed with no reference to literature.

3.1. Tensile Strength of Joints

Tensile properties and fracture locations of joints welded at different welding conditions are summarized in Table 4, 5 and 6. From the investigation, the better tensile strength results obtained in the case of locating aluminum alloy 6061-T6 at the advancing side. The reason for this is, material was pushed downward on the advancing side and moved toward the top at the retreating side within the pin. This indicates that the ‘‘stirring’’ of material occurred only at the top of the weld where the material transport was directly influenced by the rotating tool shoulder that moved material from the retreating side around the pin to the advancing side. Also, the amount of vertical displacement of the retreating side bottom was inversely proportional to the weld pitch (welding speed/rotation rate). The yield strength of the joints reached about 179 MPa compared to 295 MPa of the base alloy, the ultimate tensile strength reached values of 220 MPa compared to 342 MPa of the base alloy. The highest value of the ultimate tensile strength obtained at a rotational speed of 1000 rpm and traverse speed of 50 mm/min. The fracture occurred in the TMAZ/HAZ interface region of the 6061-T6 alloy (weaker of the two) as it is shown in Figure 8.

Table 4. Tensile test results for the case of 2024 on advancing side

Traverse speed mm/min	Rotational speed rpm	AA 2024-T3 Located on advancing side				
		Yield strength MPa	Tensile strength UTS MPa	Elongation %	Fracture location	Welding eff.%
50	600	165	195	8	At the NZ/TMAZ of 6061	57
	800	148	184	8.8	At the NZ/TMAZ of 6061	53
	1000	160	193	7.6	At the NZ/TMAZ of 6061	56
	1200	144	193	8.5	At the NZ/TMAZ of 6061	56

Table 5.Tensile test results for the case of 6061 on advancing side

Traverse speed mm/min	Rotational speed rpm	AA 6061-T6 Located at advancing side				
		Yield strength MPa	Tensile strength UTS MPa	Elongation %	Fracture location	Welding eff.%
50	600	172	218	7	At TMAZ/HAZ of 6061	64
	800	176	212	8	At TMAZ/HAZ of 6061	62
	1000	179	220	6	At TMAZ/HAZ of 6061	64
	1200	176	215	7.5	At TMAZ/HAZ of 6061	63

Table 6. Tensile test results for the case of variable traverse speed

Traverse speed mm/min	Rotational speed rpm	AA 6061-T6 Located at advancing side				
		Yield strength MPa	Tensile strength UTS MPa	Elongation %	Fracture location	Welding eff.%
25	1000	144.5	190.3	6.1	At TMAZ/HAZ of 6061	56
75		154.2	206	4.4	At TMAZ/HAZ of 6061	60
100		150.7	206	4.3	At TMAZ/HAZ of 6061	60

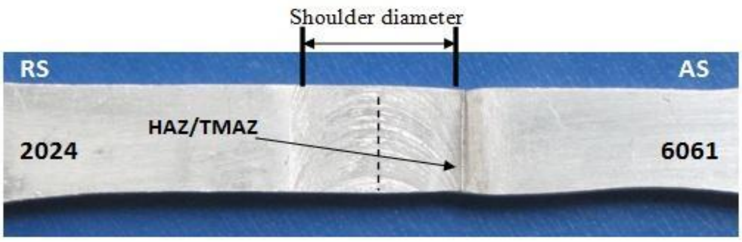

Figure 8. Tensile fracture location for the case of 6061 alloy on advancing side

In the case of locating the aluminum alloy 2024-T6 on the advancing side, lower ultimate tensile strength was recorded. The fracture occurred in the SZ/TMAZ interface region of the 6061-T6 aluminum alloy as illustrated in Figure 9.

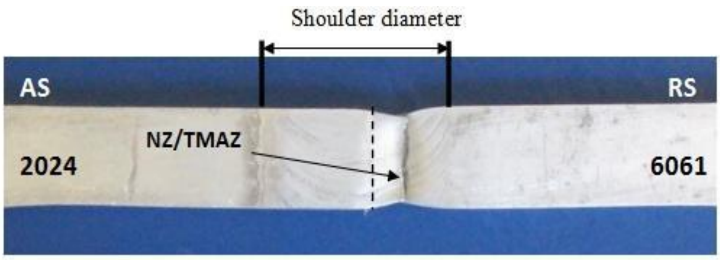

Figure 9. Tensile fracture location for the case of 2024 alloy on advancing side

In order to increase the range of the parameters we used variable traverse speeds of 25, 75, and 100 mm/min with a rotational speed of 1000 rpm (which is representing the better rotation speed of the previous cases). The location of aluminum alloy 6061-T6 at advancing side again. The yield strength and the ultimate tensile strength of the joints reached to a maximum value of about 154 MPa and 206 MPa respectively at traverse speed of 75 mm/min compared to ultimate tensile strength of the base alloy of 342 MPa. The fracture occurred in the TMAZ/HAZ interface region of the 6061-T6 (weaker of the two again) as it is shown in Figure 10.

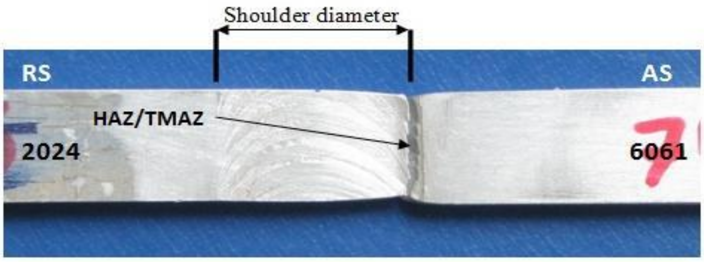

Figure 10. Tensile fracture location for the case of variable traverse speed of 25, 75, and 100 mm/min at a constant rotational speed of 1000 rpm

In general the fracture path of the FSW joints is consistent with the distribution of the lowest hardness. In this study, all the tensile specimens failed roughly along the low hardness zones, and the tensile strength of the welds corresponded well with the hardness values along the low hardness zones.

Tensile properties of FSW butt joints of 2024-T3 plate and AA 6061-T6 plate depends mainly on welding defects and hardness of the joint. Fractures occurred at the variation in tensile strengths at different tool rotation speed was due to different material flow behavior and frictional heat generated.

3.2. Bending Results

Most of the welds presented good ductility and no cracks were observed (during bending tests) for all of the rotational (600, 800, 100, and 1200 rpm) and traverse (25, 50, 75, and 100 mm/min) speeds used. It is illustrated from the bending results that locating the aluminum alloy 6061 on retreating side and 2024 on advancing side present low bending properties and low ductility, the specimens bent to failure at lower bending angles of degree as it is shown in Figure 11a. Whereas, with the change of the location of alloys i.e. locating the aluminum alloy 6061-T6 on advancing side and 2024-T3 on retreating side, the bending angle increases gradually and good bending properties were recorded. It is shown by tests that 180° bending angle (U shape) can be reached and no cracks were observed as it is shown in the Figure 11b. Also, the same good results were observed for variable traverse speeds with keeping the location of alloy 6061 on advancing side. These results were in good agreement with the tensile test results regarding the position of alloys (being at advancing or retreating side).

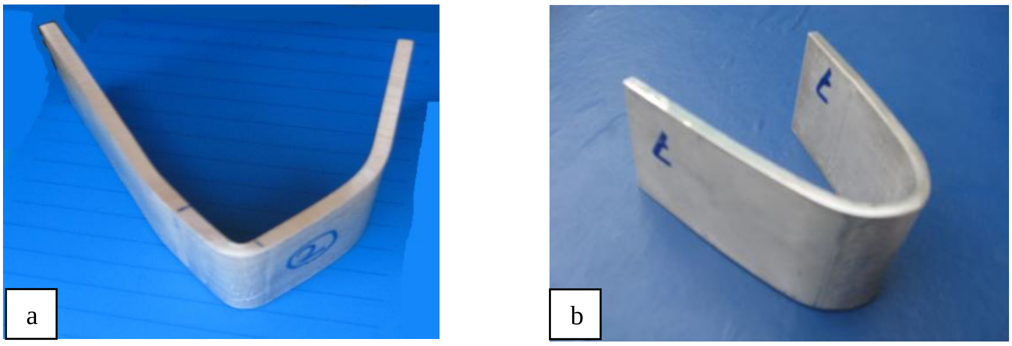

Figure 11. (a) Bending test specimens for the case of 6061-T6 on retreating side. (b) Bending test specimens for the case of 6061-T6 on advancing side

3.3. Microhardness

The microhardness values in all welding areas are reduced compared with that of base metals. Figure 12 and 13 shows the Vickers hardness profile across the centerline of friction stir weldments for the case of using rotational speed (600, 800, 1000 and 1200rpm) at constant traverse speed of 50 mm/min and for the case of using variable traverse speeds 25, 75, and 100 mm/min at a constant rotation speed of 1000 rpm, for both cases aluminum alloy 6061-T6 located at advancing side. It's clearly observed that the maximum hardness across the centerline of all the weldments is found to be at the HAZ/TMAZ interface zone of the aluminum alloy 2024-T3, while there is a significant hardness decrease at the HAZ/TMAZ interface zone of the aluminum alloy 6061-T6. Generally the hardness of the nugget zone did not show a significant decrease compared to the base alloys. The hardness of the base alloy of 2024-T3 was recorded to be about 136HV20 while the hardness of the base alloy of 6061-T6 was recorded to be about 95HV20. The minimum hardness for the HAZ/TMAZ interface region was recorded at rotational speed of 1200 rpm which was 52 HV20 and the maximum hardness recorded at rotational speed of 1000 rpm which was 63 HV20. The nugget zone for the specimens of rotation speed 600, 800, 1000, 1200 rpm showed an increase in the hardness as the tool rotation increased while keep the traverse speed constant at 50 mm/min except. On the other hand, the nugget zone for the traverse speeds of 25, 75, and 100 mm/min showed an increase in the hardness as the tool traverse speed decreased while keep the rotational speed constant at 1000 rpm. The better condition was recorded on rotational speed of 1000 rpm and traverse speed of 50 mm/min which is showing a maximum hardness values across the centerline of the weldment.

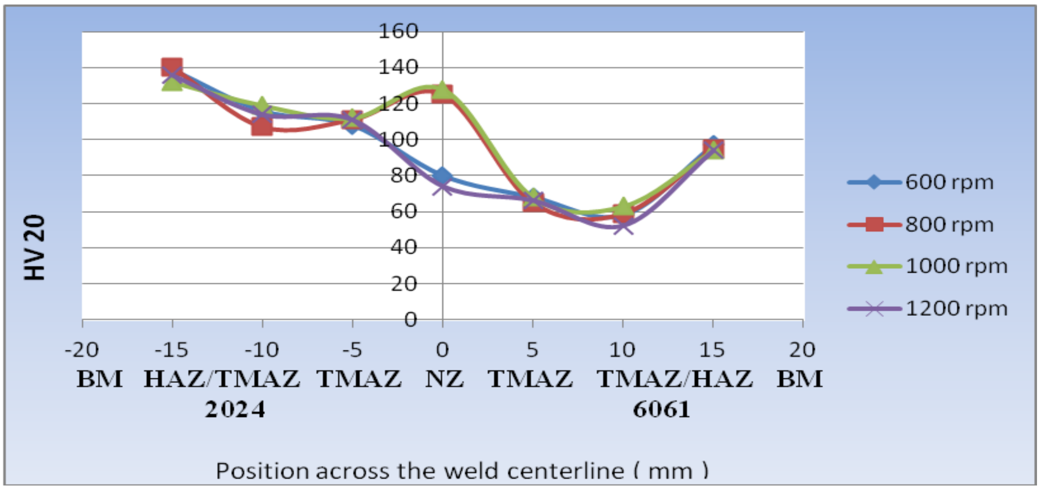

Figure 12. Vickers hardness profile across the weld centerline of friction stir welded Al alloy for different tool rotational speeds at constant traverse speed of 50 mm/min.

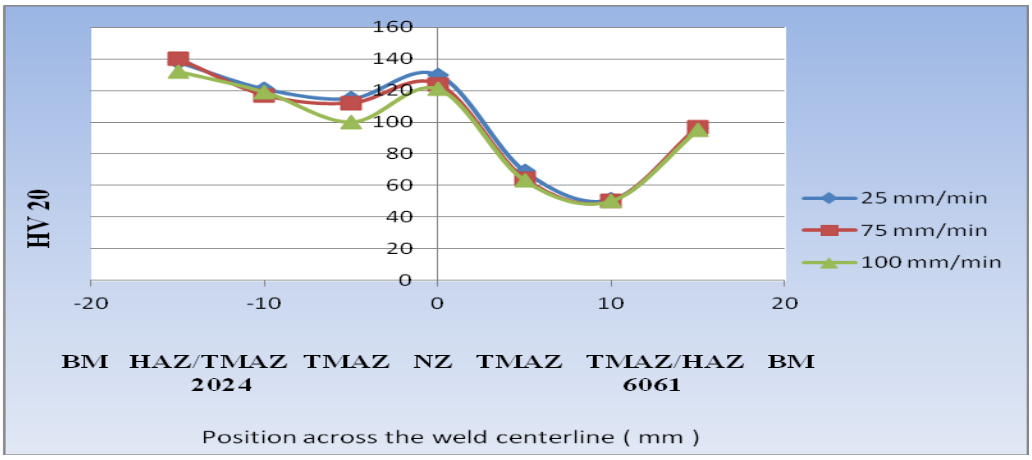

Figure 13. Vickers hardness profile across the weld centerline of friction stir welded Al alloy for different traverse speeds and constant rotational speed of 1000 rpm

The hardness of the weld nugget depends on the grain size of the nugget zone as well as on the dissolution of strengthening precipitation during the thermal cycle of the FSW. Increasing tool rotational speed leads to an increase of the nugget zone temperature and consequently dissolution of the strengthening precipitates will take place for more regions, then after, re-precipitation and natural ageing take place during the cooling of the weld leading to the recovery of the hardness in the weld area and the adjacent areas where dissolution temperature has reached.

4. CONCLUSION

In this study, friction stir welding of dissimilar aluminum alloys 2024-T3 to 6061-T6 was studied by using a vertical milling machine with a variable rotational and traverse speeds to evaluate the effect of process parameters on the mechanical properties. Following conclusions are made:

1. The weldments indicated no visible defects, weld surface is even and uniform with better surface appearance and without any pores and discontinuities for the interior portion.
2. The better condition of FSW for a 3 mm thick of dissimilar aluminum alloys 2024-T3 to 6061-T6, which produces 64 % welding efficiency, at 1000 rpm rotational speed and 50 mm/min traverse speed are determined.
3. The best strength of the weldments (220 MPa) is achieved when the aluminum alloy 6061-T6 is located on the advancing side using rotational speed of 1000 rpm and traverse speed of 50 mm/min.
4. For all of the process parameters, fracture occurred on the side of the aluminum alloy 6061-T6 due to the lower ultimate tensile strength of the aluminum alloy 6061-T6 compared with that of aluminum alloy 2024-T3.
5. When the aluminum alloy 6061-T6 was located on the retreating side, fracture occurred at the NZ/TMAZ interface. When it was located on the advancing side, fracture occurred at the HAZ/TMAZ interface.
6. Low bending properties i.e. lower ductility was observed when the aluminum alloy 6061 located at the retreating side, while better bending properties and higher ductility achieved when the aluminum alloy 6061 located at the advancing side which is showing 180 degree bending.
7. For the hardness distribution, the maximum value for the nugget zone and TMAZ/HAZ interface of aluminum alloy 6061-T6 were 128 HV20 and 63 HV20, respectively representing the optimum welding condition of 1000 rpm for rotational and 50 mm/min for traverse speeds.

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NOMENCLATURE

FSW	Friction Stir Welding
TWI	The Weld Institute
2xxx	Aluminum-Copper (Al-Cu) Alloy Series
6xxx	Aluminum-Magnesium-Silicon (Al-Mg-Si) Alloy Series
T3	Solution Heat Treatment, Cold Worked, and Naturally Ageing
T6	Solution Heat Treatment, and Artificial Ageing
NZ	Nugget Zone
TMAZ	Thermo-Mechanically Affected Zone
HAZ	Heat Affected Zone
BM	Base Metal
HSS	High Speed Steel
ASTM	American Society for Testing and Materials
AS	Advancing Side of the Weld
RS	Retreating Side of the Weld
UTS	Ultimate Tensile Strength

6. REFERENCES

[1] WAYNE, T. and VILACA P., Friction Stir Welding Technology. Springer-Verlag Berlin Heidelberg, 2011.
[2] MATHERS, G., The Welding of Aluminum and Its Alloy, Woodhead Publishing Ltd., 161-165, 2002.
[3] MISHRA, R.S., "Friction Stir Welding and Processing", Journal of Center for Friction Stir Processing, Department of Materials Science and Engineering, University of Missouri, Rolla, MO 65409, USA, 2005.
[4] AKINLABI and TITILAYO, E., Characterization of Dissimilar Friction Stir Welds between 5754 Aluminum Alloy and C11000 Copper. Nelson Mandela Metropolitan University, 2010.
[5] KHALED, T., An Outsider Looks at Friction Stir Welding, Report: ANM-112N-05-06, Ph.D. Chief Scientific / Technical Advisor, Metallurgy Federal Aviation Administration 3960 Paramount Boulevard. Lakewood, CA 90712, 562, 627-5267, 2005.
[6] DAWES, C. J., Friction Stir Welding. The Welding Institute, Abington Hall, Cambridge adapted for TALAT by Roy Woodward, Birmingham and Christian Leroy, EAA. Copyright TWI, 1999.
[7] LI, Y.," Flow Visualization and Residual Microstructures Associated with the Friction-Stir Welding of 2024 Aluminum to 6061 Aluminum", Materials Science and Engineering, A271, 213–223, 1999.
[8] ASTM. Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate. Annual Book of ASTM Standards, Vol 02.02 , 2000.
[9] NAKATA K., KIM Y. G., USHIO M., HASHIMOTO T., JYOGAN, S., Weldability of High Strength Aluminum Alloys by Friction Stir Welding, Joining and Welding Research Institute, Osaka University, Mihogaoka, Ibaraki, Osaka 567-0047 Japan. ISIJ International, 40, 15-19, 2000.
[10] RAI, R., DE, A., BHADESHIA H. K. D. H., DEBROY, T., "Review: Friction Stir Welding Tools", Science and Technology of Welding and Joining, 16, 4, 2011.
[11] NORBERTO PIRES J., LOUREIRO A., BÖLMSJO G., Welding Robots Technology, System Issues and Applications. PhD Thesis © Springer-Verlag Lon don Limited, 2006.
[12] BLIGNAULT. C., Design, Development and Analysis of the Friction Stir Welding Process. Msc Thesis, Electrical, Industrial & Mechanical Engineering Port Elizabeth Technikone, 2002.
[13] KUMAR, K., SATISH V. , KAILA, S., The Role of Friction Stir Welding Tool on Material Flow and Weld Formation. Ph.D. Dissertation, Civil Engineering Department, Colorado State University, Fort Collins, Colorado, USA, 2007.
[14] BAHEMMAT P., RAHBARI A., HAGHPANAHI M., BESHARATI M.K., Experimental Study on the Effect of Rotational Speed and Tool Pin Profile on AA2024 Aluminum Friction Stir Welded Butt Joints, ASME Early Career Technical Conference, Miami, Florida, USA, 2008.
[15] SUTTON, M. A., YANG, B, REYNOLD, A.P, TAYLOR, R., "Microstructural Studies of Friction Stir Welds in 2024-T3 Aluminum", Materials Science and Engineering, 323,160–166, 2002.
[16] AYDIN, H., BAYRAM, A., UĞUZ, A., AKAY, K.S., "Tensile Properties Of Friction Stir Welded Joints Of 2024 Aluminum Alloys In Different Heat-Treated-State", Materials & Design, 30(6), 2211-2221, 2009.
[17] Lee W.B., YEON Y.M., JUNG S.B., "Mechanical Properties Related to Microstructural Variation of 6061 Al Alloy Joints by Friction Stir Welding", Materials Transactions, 45(5), 2004.
[18] ABDELRAHMAN, M. A., GHONEIM M.M., ABDELAZIM M.E., EL-KOUSS M.M.R., ABDELRAHEM N.A., "The Effect of FSW Tool Geometry on AA6061-T6 Weldments", Arab Journal of Nuclear Sciences and Applications, 45(2), 407-418, 2012.
[19] CAVALIERE, P., "Effect of Welding Parameters on Mechanical and Microstructural Properties of Dissimilar AA6082–AA2024 Joints Produced by Friction Stir Welding", Materials and Design, 30 ,609–616, 2008.
[20] VURAL M., OGUR A., CAM G., OZARPA C., "On the Friction Stir Welding of Aluminium Alloys EN AW 2024-0 and EN AW 5754-H22", International Scientific Journal, 28, 2007.
[21] SAAD and TOSHIYA, "Microstructure and Mechanical Properties of Friction Stir Welded Dissimilar Aluminum Joints of AA2024-T3 and AA7075-T6", Materials Transactions, 48(7), 2007.
[22] LI, Y., MURR, L., MCCLURE, J.C., "Flow Visualization and Residual Microstructures Associated with the Friction-Stir Welding of 2024 Aluminum to 6061 Aluminum", Materials Science and Engineering, A271, 213–223, 1999.

[23] OUYANG, J. H., and KOVACEVIC, R., "Material Flow and Microstructure in the Friction Stir But Welds of the Same and Dissimilar Aluminum Alloys", Journal of Materials Engineering and Performance, 11(1), 2001.