Egypt. J. Chem. **Vol. 62,** No. 8, pp.1367 - 1375 (2019)

Egyptian Journal of Chemistry
http://ejchem.journals.ekb.eg/

Effect of Friction Stir Welding Process Parameters and Post-Weld Heat Treatment on the Corrosion Behaviour of AA6061-O Aluminum Alloys

Mostafa S. S. El-Deeb[1], Lobna A. Khorshed[2*], Sayed A. Abdallah[3], A. M. Gaafer[3] and T. S. Mahmoud[3]

[1]*Department of Manufacturing Engineering and Production Technology, Modern Academy for Engineering and Technology, Cairo Egypt.*

[2]*Electrochemistry Laboratory, Physical Chemistry Department, National Research Centre, Dokki, Cairo, Egypt.*

[3]*Mechanical Engineering Department, Faculty of Engineering - Shoubra, Benha University, Cairo, Egypt.*

THE aim of the present work is to study the effect of rotation and welding speeds as well as the T4 and T6 post-weld heat treatments (PWHT) on the corrosion behavior of AA6061-O aluminum plates joined using friction stir welding (FSW). The corrosion properties of welded joints were studied by Potentiodynamic polarization and Immersion tests. The results showed that both T4 and T6 PWHT improves the corrosion resistance of stirred zones compared to base alloy. However, joints of T4 showed lower corrosion resistance compared to T6. Increasing welding speed or reducing rotation speed increased the corrosion resistance of joints.

Keywords: Friction stir welding, AA6061 aluminum alloy, Immersion test, Potentiodynamic polarization test.

Introduction

Friction stir welding (FSW) is a relatively new joining technique invented at The Welding Institute (TWI) in 1991 for mainly welding Al alloys [1]. The high quality Al welds produced by this technique encouraged researchers to extend its application to include other alloys such as magnesium, copper, steel and dissimilar alloys. Since FSW is carried out in the solid state, all problems from solidification process are eliminated. Also, compared with the conventional fusion welding processes, the residual stresses and distortion are very low due to low heat input [2-6]. AA6061 is a typical alloy of 6xxx series and includes some alloying elements such as Al-Mg-Si [7].

The corrosion of aluminum alloy FS welds is commonly investigated using methods such as immersion test and potentiodynamic polarization technique. Concerning the corrosion properties of AA6061 FSW welded joints, the stir zones of the joints exhibit susceptibility to local corrosion [8]. In the welding of aluminum alloys by FSW process, it was found that the corrosion properties of welded joints are markedly affected by the welding parameters such as rotational and welding speeds. The effect of the FSW process parameters on the corrosion behavior of FS welded aluminum joints were studied by many workers [9-11]. Nam et al. [9] investigated the effect of welding speed on the corrosion properties of AA6061 FSW welded joints using potentiodynamic polarization test. They observed that the corrosion properties enhanced by increasing the welding speed due to formation of large protected film on the surface of the stir zone. Weifeng Xu et al. [10] investigated the effect of welding and rotational speeds on the corrosion properties of AA2219-O FSW welded joints using cyclic polarization. They observed that by increasing the welding speed from 60 to

*Corresponding author e-mail: lobnakhorshed@yahoo.com
Received 4/2/2019; Accepted 13/3/2019
DOI: 10.21608/ejchem.2019.7946.1624

100 mm/min or rotational speed from 500 to 600 rpm, the corrosion resistance decreases. Mohiedin et al. [11] studied the effect of tool rotational and traveling speeds on the corrosion properties of AA5052 FSW welded joints using potentiodynamic polarization test. They observed that the optimum combination of tool rotational and traveling speeds at 400rpm and 250 mm/min respectively give high corrosion resistant of stir zone.

It has been reported that the corrosion resistance of FS welds can be improved by several treatments after or during the welding [12-13]. Vincent Proton et al. [12] investigated the corrosion behavior of the nugget of a FSW joint employing a 2050 Al–Cu–Li alloy. They used two metallurgical states, the as-welded joint called NHT and a post-welding heat treatment joint called PWHT. The results showed that the post-welding heat treatment significantly modified the corrosion behavior of the nugget. They observed that a susceptibility to intergranular corrosion was shown in the NHT nugget, and both intergranular and intragranular corrosion features were observed in the PWHT nugget. Vijaya et al. [13] studied the effect of post weld heat treatment, viz., peak aging (T6) and retrogression & reaging (RRA), on corrosion behavior of AA7075 aluminum alloy with 8mm thickness. It was observed that in peak aging (T6) condition the weld showed poor corrosion resistance but in RRA the resistance to pitting corrosion was improved.

There are little studies about improving corrosion resistance that have been reported for FSW of AA6061 aluminum alloy, moreover, the use of T4 and T6, as pretreatment, were not used as a process for AA6061 aluminum alloys. Some treatments were done but not on the AA6061 aluminum alloy [14-16]. The present work aims to study the effect of the FSW process parameters, typically, the tool rotational and welding speeds as well as the post weld heat treatment, typically, T4 and T6 heat treatments on the corrosion behavior of friction stir welded AA6061 joints.

Experimental

The materials and welding parameters

AA6061-O aluminum alloy plates having 8 mm thickness were FS welded using conventional vertical milling machine. The chemical composition of the AA6061 alloy is: 0.52% Si, 0.025% Fe, 0.005% Mn, 0.871% Mg, 0.259% Cu, 0.2% Cr, 0.008% Zn, 0.04% Ti, and 98.08% Al. A non-consumable tool with a shoulder having 30 mm diameter and a threaded probe of 12 mm diameter, 1.25 mm pitch and 7.8 mm height was used to weld the AA6061 Al plates. The welding tool is made of H13 alloy steel. FSW was carried out using three different tool rotational speeds of 400, 500 and 630 rpm and two welding speeds of 25 and 40 mm/min. The tool tilt angle was kept constant at 2 degrees. The surface of the plates was cleaned with acetone before welding.

The FS welded plates were heat treated immediately after welding. Half of FS welded plates were heat treated at T4 by heating them in a furnace at 550 ^{o}C for 2 hours followed by quenching in water. Other half of the plates were heat treated at T6 by heating them in a furnace at 550 ^{o}C for 2 hours then quenched in water followed by artificial aging at 177 ^{o}C for 6 hours. After PWHT, all plates were cut using an electric discharge wire cutting machine. Metallographic samples were ground using emery paper of increasing finesse up to 1200 grit followed by polishing using 0.3 µm alumina suspension and then etched using solution of 1 ml HF +1.5 ml HCl +2.5 ml HNO_3 + 95 ml distilled water for 240 s at ambient temperature. Microstructural investigations were carried out using both optical microscope and scanning electron microscope (SEM). The microstructural measurements of the size of the α-Al grains were performed using image analyzing techniques.

Static immersion and Electrochemical measurement

Static immersion and potentiodynamic polarization corrosion tests were used to investigate the surface morphologies of corroded samples and the corrosion behavior of FS welded samples after T4 and T6 heat treatments. In the static immersion tests, the samples were exposed to 3.5% NaCl solution for 15 days and then ultrasonically cleaned for 5 min in distilled water and ethanol. Finally, the surface morphologies of corroded samples were analyzed by field emission scanning electron microscope, 250 model QUANTA. For potentiodynamic polarization tests, the corrosion properties of the samples were measured by using Autolab 302 N potentiostat/galvanostat workstation with NOVA 1.10 software. Conventional three-electrodes configuration with platinum rod as a counter electrode (CE), standard Ag/AgCl electrode as reference electrode (RE), and AA6061 aluminum alloy as working electrode (WE) were used. The electrochemical measurements were carried out at room temperature after rinsed the test samples with double distilled water, degreased with ethanol, connected to a copper wire and sealed with epoxy resin with the exposure area of $1cm^2$. The test solution was also, 3.5% NaCl. Potentiodynamic polarization curves were obtained on the potential range from -2.5 V to 2 V with scan rate of 1.0 mV s^{-1}. Corrosion current density (i_{corr}) and resistance polarization (R_p), which is equivalent to the corrosion rate of the specimens, were estimated by using Tafel extrapolation.

Results and Discussion

Microstructural Observations

Figure 1 shows typical micrographs of the microstructure of the AA6061 Al alloy base metal (BM) after T4 and T6 heat treatments. In both cases, the microstructure of BM consists of elongated α-Al primary grains with an average size of 30±4 µm. Figures 2 and 3 show typical micrographs of the microstructure in the center line of the stir zones FS welded using different tool rotational and welding speeds after T4 and T6 heat treatments, respectively.

It is clear that, the microstructure of the stir zones consists of finer equiaxed grains due to the dynamic recrystallization occurred during FSW. Quantitative analysis of grain size revealed a clear dependence of grain size on the tool rotational and welding speeds. Figure 4 shows the variation of the average grain size at the center of the stirred zones with tool rotational speed at different welding speeds and post-weld heat treatments. The average grain size was found to be increased with increasing rotational speed and/or reducing the welding speed. The stirred zones heat treated at T6 exhibited slightly higher average grain size when compared with those heat treated at T4.

Scanning Electron Microscope (SEM) was also used to investigate the microstructures of the 6061 aluminum alloy base metal and stir zone of welded specimens after T4 and T6 treatments. Examination of the composition of the second phase particles in the stir zones shows that most of precipitates are AL_2O_3 and Mg_2Si.[17].

Corrosion Behaviour

Static Immersion Tests

Figure 5 shows SEM micrographs of the corroded surfaces morphologies of AA6061 base alloy after T4 and T6 heat treatments. It can be noted that the surface of the AA6061-T4 base alloy showed only local corrosion (pits) (see Fig. 5a), while the AA6061-T6 base alloy showed that beside the pitting corrosion, a general corrosion (see Fig. 5b) were taken place. Such results indicated that AA6061-T6 base alloy have higher corrosion resistance than the AA6061-T4 base alloy.

Figure 6 and 7 shows typical SEM micrographs for the corroded surfaces of the stirred zone FS welded using tool rotational speed of 400 rpm and different welding speeds for FS joints heat treated at T4 and T6 conditions. Examination of the corroded surfaces revealed that the stirred zones have higher corrosion resistance compared with the AA6061 base alloy. However, the corrosion resistance of stirred zone heat treated at T6 condition is found to be higher than those heat treated at T4 condition.

Potentiodynamic Polarization Measurements.

Figure 8 shows the polarization curves for the AA6061 base alloy as well as stirred zones FS welded at different tool rotational and welding speeds and heat treated at T4 and T6 conditions. Table 1 and 2 list the electrochemical

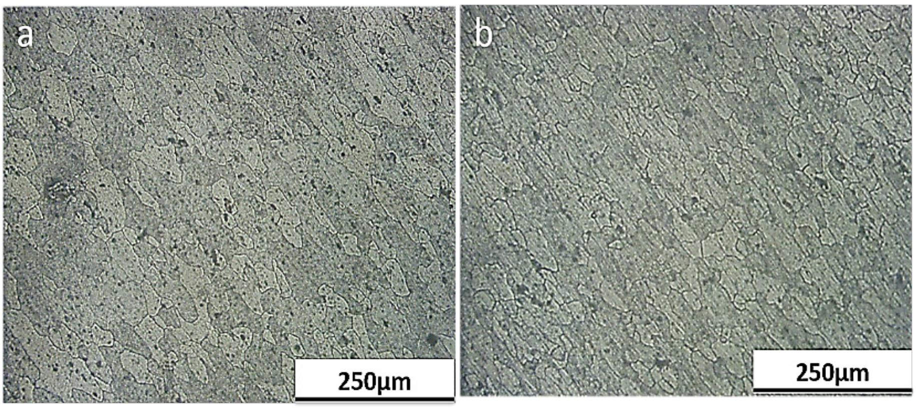

Fig. 1. Microstructure of base metal after (a) T4 and (b) T6 heat treatments.

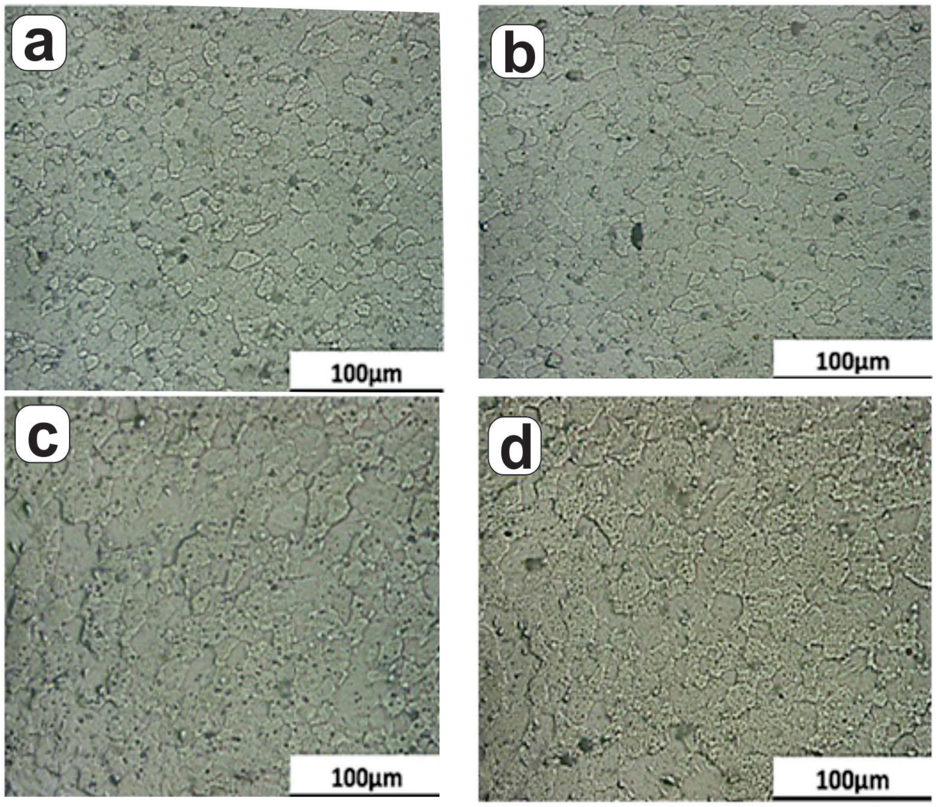

Fig. 2. Microstructures at the centers of the stir zones of joints after T4 heat treatment.

The joints FS welded using tool rotational and welding speeds of (a) 400 rpm and 25 mm/min (b) 400 rpm and 40 mm/min, (c) 630 rpm and 25mm/min and (d) 630 rpm and 40 mm/min.

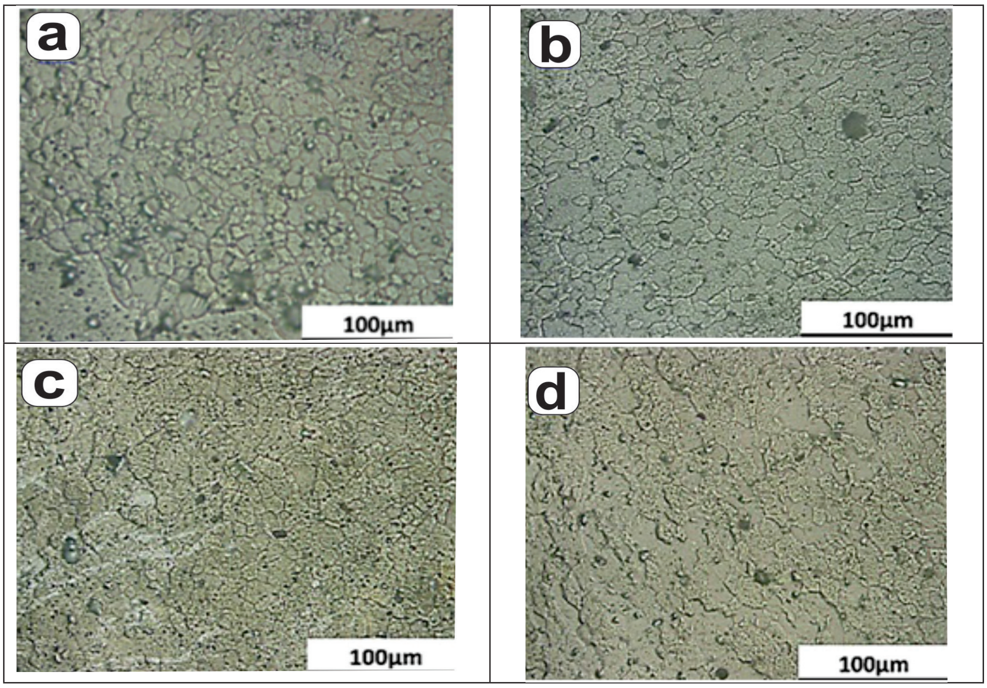

Fig. 3. Microstructures at the centers of the stir zones of joints after T6 heat treatment.

The joints FS welded using tool rotational and welding speeds of (a) 400 rpm and 25 mm/min (b) 400 rpm and 40 mm/min, (c) 630 rpm and 25 mm/min and (d) 630 rpm and 40 mm/min.

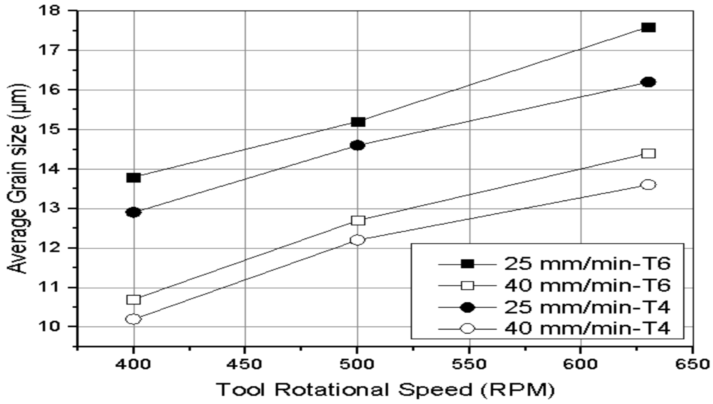

Fig. 4. Variation between the average grain size at the center of the stirred zone with the tool rotational speed at different welding speeds and post-weld heat treatments.

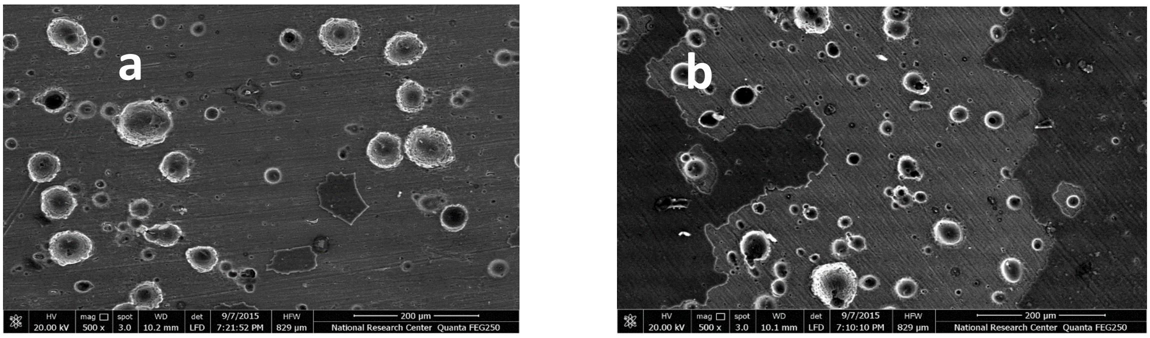

Fig. 5. SEM of the base alloy after immersion in 3.5% NaCl solution for 15 days (a) AA6061-T4and (b) AA6061-T6.

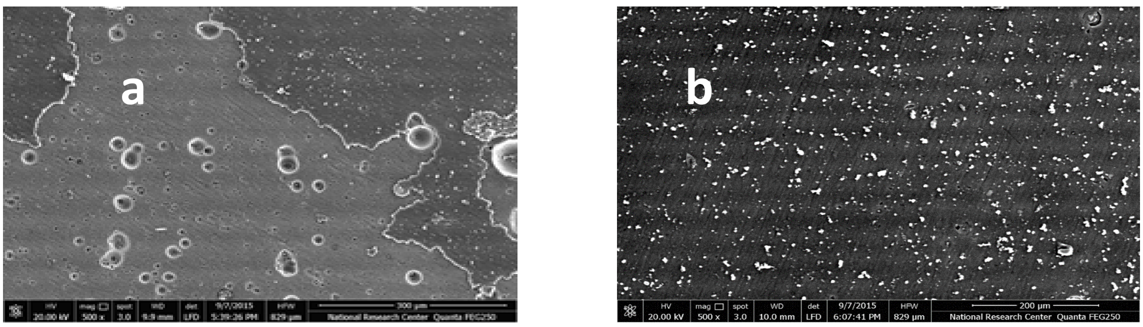

Fig. 6. SEM micrographs of the corroded surfaces at the center of the stirred zones for joints FS welded at 400 rpm and 25 mm/min and heat treated at (a) T4 and (b) T6.

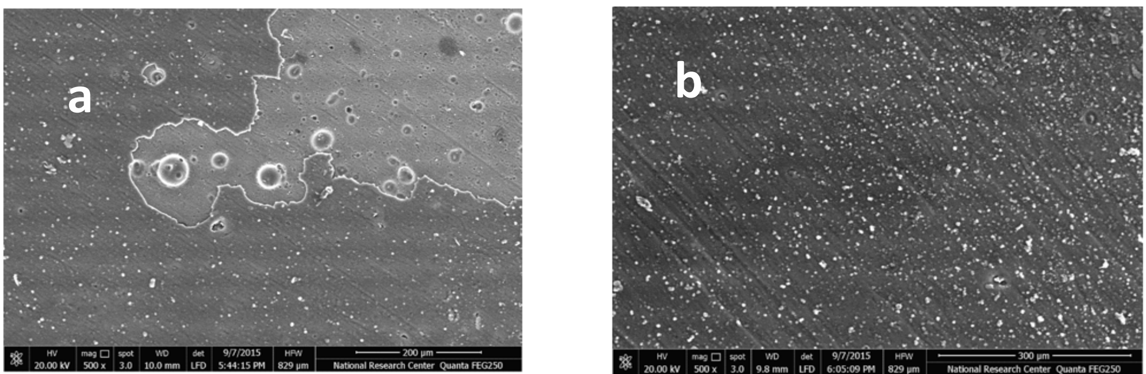

Fig. 7. SEM micrographs of the corroded surfaces at the center of the stirred zones for joints FS welded at 400 rpm and 40 mm/min and heat treated at (a) T4 and (b) T6.

parameters obtained from potentiodynamic polarization measurements for the base alloy as well as stirred zones after T4 and T6 heat treatments, respectively. The results revealed that AA6061-T4 base alloy exhibited higher corrosion rates than AA6061-T6 base alloy. The AA6061-T4 and AA6061-T6 base alloys exhibited corrosion rates of 123.554 and 79.511 µm/year, respectively. At constant FSW process parameters, the stirred zones exhibiter better corrosion resistance than the base alloys. However, the stirred zones heat treated at T6 condition showed better corrosion resistance in 3.5% NaCl solution than that heat treated at T4 condition at the same welding parameters. For example, stirred zone FS welded using 400 rpm and 40 mm/min exhibited corrosion rates of 16.382 and 5.326 mm/year when heat treated at T4 and T6 conditions, respectively.

The results revealed also that reducing the tool rotational speed and/or increasing the welding speed increase(s) the corrosion resistance of the stirred zones. For example, for stirred zones heat treated at T6 and FS welded using welding speed of 25 mm/min, increasing the tool rotational speed

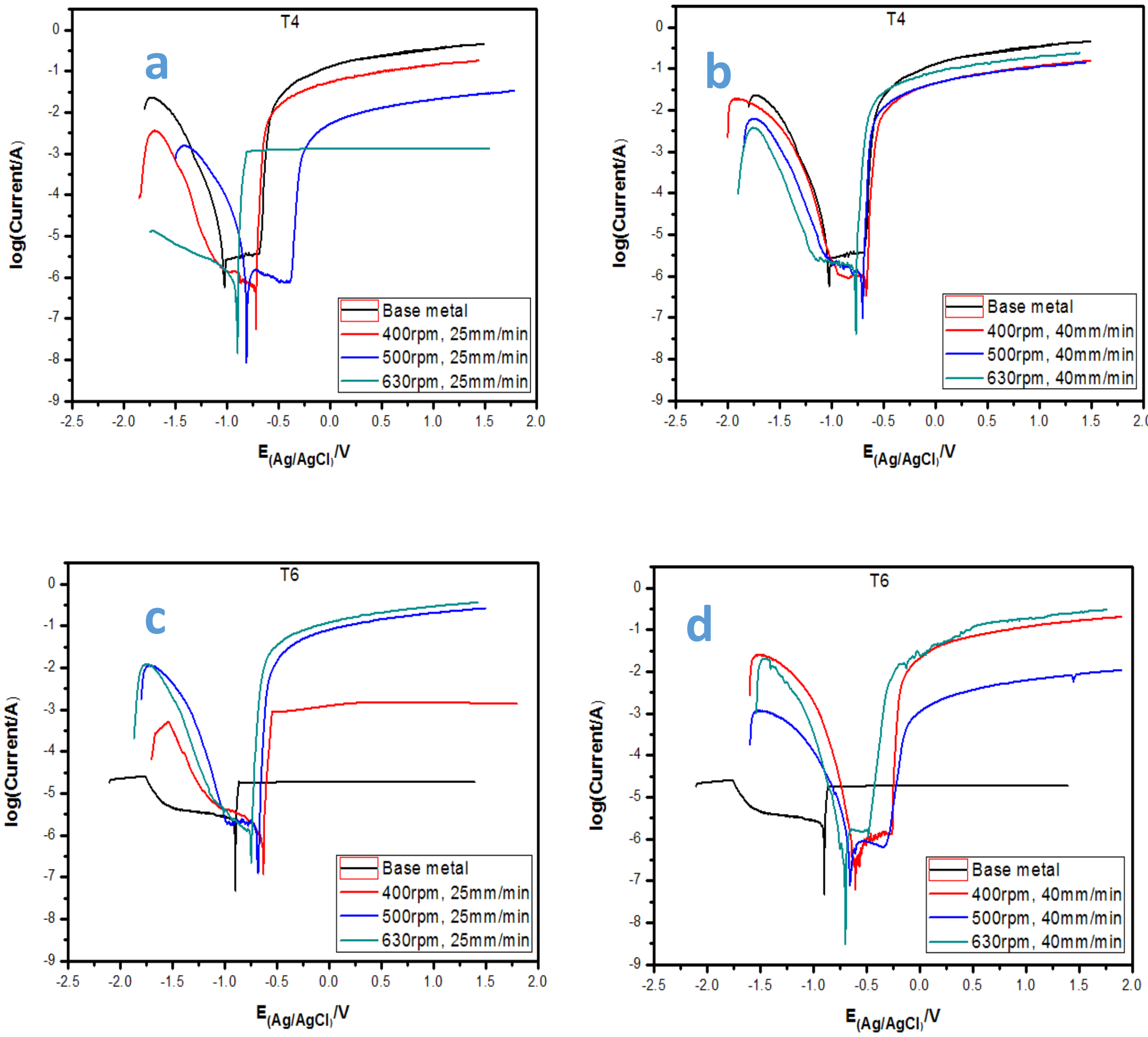

Fig. 8. Potentiodynamic polarization curves of the AA6061-O base metal and stir zones of joints FS welded at different tool rotational and welding speeds and post-weld heat treatment at T4 (a, b) and T6 (c, d).

TABLE. 1. Electrochemical parameters obtained from potentiodynamic polarization measurements for AA6061-T4 base alloy and stirred zones FS welded using different tool rotational and welding speeds.

Welding speed (mm/min)	Rotational speed (rpm)	β_a (V.dec^{-1})	-β_c (V.dec^{-1})	-E_{corr} (V)	j_{corr} (µA. cm^{-2})	Corrosion rate (µm/ year)	Polarization resistance (kΩ)
Base metal		0.180	0.179	1.0262	11.342	123.554	3.436
	400	0.122	0.163	0.714	3.176	34.596	9.539
25	500	0.128	0.070	0.820	3.744	40.785	5.248
	630	0.129	0.078	0.895	4.812	52.422	4.386
	400	0.209	0.050	0.651	1.504	16.382	11.650
40	500	0.175	0.054	0.704	1.863	20.295	9.618
	630	0.149	0.041	0.765	2.416	24.148	5.668

TABLE 2. Electrochemical parameters obtained from potentiodynamic polarization measurements for AA6061-T6 base alloy and stirred zones FS welded using different tool rotational and welding speeds.

Welding speed (mm/min)	Rotational speed (rpm)	β_a (V.dec^{-1})	$-\beta_c$ (V.dec^{-1})	-E_{corr} (V)	j_{corr} (µA. cm^{-2})	Corrosion rate (µm/ year)	Polarization resistance (kΩ)
Base metal		0.179	0.132	0.897	7.299	79.511	4.520
	400	0.100	0.250	0.631	2.900	31.590	10.695
25	500	0.090	0.139	0.679	3.245	35.349	7.310
	630	0.127	0.100	0.745	3.336	36.341	7.282
	400	0.171	0.089	0.607	0.489	5.326	51.987
40	500	0.164	0.097	0.649	0.519	5.650	50.99
	630	0.101	0.116	0.697	0.549	5.980	42.703

from 400 rpm to 630 rpm increases the corrosion rate from 31.590 to 36.341 mm/year, respectively. While, for stirred zones heat treated at T6 and FS welded using tool rotational speed of 400 rpm, increasing the welding speed from 25 rpm to 40 mm/mm reduces the corrosion rate from 31.590 to 5.326 mm/year, respectively. The lowest corrosion rate (i.e. best corrosion resistance) of 5.326 mm/year was observed for stirred zone FS welded using tool rotational speed of 400 rpm, welding speed of 40 mm/min and post-weld heat treated at T6 condition.

By increasing FSW speed from 25-40 mm/min, the microstructure had smaller grains, refined microstructure and increased homogeneity which lead to an enhancement in the corrosion resistance [18]. It was observed from potentiodynamic polarization measurements an increase of the tool welding speed from 25–40 mm/min at the same post weld heat treatment improves the corrosion resistance due to shift in positive corrosion potential and reduced corrosion current density in the high welding speed 40mm/min compared to the low welding speed 25mm/min as listed in tables 1, 2, this is due to insoluble corrosion product film formed (protective aluminum oxide passive film) on a surface can block the surface from further attack and significantly reduce the corrosion rate. These results are in good agreement with *N.D. Nam* [9], and observed that the corrosion resistance in T6 treatment is higher than T4 due to the shift in positive corrosion potential and reduction in corrosion current density at the same welding parameters as listed in tables 1, 2.

The corrosion resistance of T6 is higher than T4 condition in base metal and stir zones in the static immersion tests due to the rapid growth of dense adherent oxide film on the samples with T6 treatment, this film acts as a barrier between the metal surface and solution, but a breakdown in the film took place in T4 treatment and appeared local corrosion (pits), these results are in good agreement with SEM micrograph shown in Fig. 5, 6.

Conclusion

From the analyses, we can summarize the results as follows:

1. Both T4 and T6 post-weld heat treatments enhance the corrosion resistance of the stirred zones when compared with the base alloy. However, joints post-weld heat treated at T4 showed lower corrosion resistance at the stirred zones when compared with post-weld heat treated at T6.
2. For AA6061 joints post-weld heat treated at T6 or T4 conditions, increasing the welding speed and/or reducing the tool rotational speed increase(s) the corrosion resistance of the stirred zones. The welding speed showed higher influence on the corrosion resistance of the stirred zones than the tool rotational speed.
3. The best corrosion resistance was observed for stirred zones of joints FS welded using the lowest tool rotational speed (i.e. 400 rpm), highest welding speed (i.e. 40 mm/min) and post-weld heat treated at T6 condition due to insoluble corrosion product film formed (protective aluminum oxide passive film) on a surface can block the surface from further attack and significantly reduce the corrosion rate.

Acknowledgments

The authors acknowledge the Faculty of Engineering at Shoubra - Benha University for providing facilities and the National Research Centre, Cairo, Egypt for the performing potentio-dynamic polarization measurements and for helpful advice. Many thanks and appreciation to Dr. Saad Abd Elmohsen Khodir, doctor at Central Metallurgical Research and Development Institute who helped me much in achieving this work.

References

1. Thomas W., Nicholas E., Needham J. C., Murch M., Templesmith P. and Dawes C., Friction stir welding. *International Patent Application No. PCT/GB92102203 and Great Britain Patent Application,* 9125978.8, (1991).
2. Xue P., Ni D., Wang D., Xiao B. and Ma Z., Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al–Cu joints. *Materials Science and Engineering: A,* **528**,(13-14), 4683-4689(2011).
3. Mishra R. S. and Ma Z., Friction stir welding and processing. *Materials Science and Engineering: R: Reports,* **50**(1-2), 1-78(2005).
4. Yong-Jai K., Seong-Beom S. and Dong-Hwan P., Friction stir welding of 5052 aluminum alloy plates. *Transactions of Nonferrous Metals Society of China,* **19**, s23-s27(2009).
5. Cabibbo M., Forcellese A., Simoncini M., Pieralisi M. and Ciccarelli D., Effect of welding motion and pre-/post-annealing of friction stir welded AA5754 joints. *Materials & Design,* **93**, 146-159(2016).
6. Yong Y., Zhang D.-T., Cheng Q. and Zhang W., Dissimilar friction stir welding between 5052 aluminum alloy and AZ31 magnesium alloy. *Transactions of Nonferrous Metals Society of China,* **20**, s619-s623(2010).
7. Nikseresht Z., Karimzadeh F., Golozar M. and Heidarbeigy M., Effect of heat treatment on microstructure and corrosion behavior of Al6061 alloy weldment. *Materials & Design* (1980-2015), **31**(5), 2643-2648(2010).
8. Paglia C. and Buchheit R., A look in the corrosion of aluminum alloy friction stir welds. *Scripta Materialia,* **58**(5), 383-387(2008).
9. Nam N., Dai L., Mathesh M., Bian M. and Thu V., Role of friction stir welding–Traveling speed in enhancing the corrosion resistance of aluminum alloy. *Materials Chemistry and Physics,* **173**,

7-11(2016).

10. Xu W., Liu J. and Zhu H., Pitting corrosion of friction stir welded aluminum alloy thick plate in alkaline chloride solution. *Electrochimica Acta,* **55**(8), 2918-2923(2010).

11. Hariri M. B., Shiri S. G., Yaghoubinezhad Y. and Rahvard M. M., The optimum combination of tool rotation rate and traveling speed for obtaining the preferable corrosion behavior and mechanical properties of friction stir welded AA5052 aluminum alloy. *Materials & Design,* **50**, 620-634(2013).

12. Proton V., Alexis J., Andrieu E., Delfosse J., Lafont M.-C. and Blanc C., Characterisation and understanding of the corrosion behaviour of the nugget in a 2050 aluminium alloy friction stir welding joint. *Corrosion Science,* **73**, 130-142(2013).

13. Kumar P. V., Reddy G. M. and Rao K. S., Microstructure, mechanical and corrosion behavior of high strength AA7075 aluminium alloy friction stir welds–Effect of post weld heat treatment. *Defence Technology,* **11**(4), 362-369(2015).

14. Vacchi G.S., Plaine A.H., Silva R., Sordi V.L., Suhuddin U.F.H., Alcantara N.G., Kuri S.E., Rovere C.A.D., Effect of friction spot welding (FSpW) on the surface corrosion behavior of overlapping AA6181-T4/Ti-6Al-4V joints, *Mater. Des.,* **131**, 127-134(2017).

15. Gharavi F., Matori K.A., Yunus R., Othman N.K., Fadaeifard F., Corrosion evaluation of friction stir welded lap joints of AA6061-T6 aluminum alloy, *Trans. Nonferrous Met. Soc. China,* **26**, 684-696(2016).

16. Gharavi F., Matori K.A., Yunus R., Othman N.K., Fadaeifard F., Corrosion behavior of Al6061 alloy weldment produced by friction stir welding process, *J. Mater. Res. Technol-JMRT,* **4**, 314-322(2015).

17. El-Deeb M.S., Khodir S., Abdallah S.A., Mahmoud A.G.T., Effect of Friction Stir Welding Process Parameters and Post-Weld Heat Treatment on the Microstructure and Mechanical Properties of AA6061-O Aluminum Alloys, *Journal of American Science,* **12**, 106-115 (2016).

18. Kim W., Nam N., Kim J. and Lee J., Effect of strontium on corrosion properties of AZ91 magnesium alloy. *Electrochemical and Solid-State Letters,* **14**,(11), C21-C24(2011).

تاثير المعاملات والمعالجات الحرارية (T4,T6) على سلوك التآكل لسبيكة الألومنيوم 6061 الملحومه بطريقه اللحام التقليبى الإحتكاكى

مصطفى سمير سيد الديب[1]، لبني عبد العزيز فؤاد خورشيد[2]، سيد عبدالونيس عبدالله[3]، أحمد محمد جعفر[3]، تامر سمير محمود[3]

[1]قسم هندسة الانتاج وتكنولوجيا التصنيع بالاكاديمية الحديثة بالمعادى.

[2]قسم الكيمياء الفيزيقية - المركزالقومي للبحوث - القاهرة - مصر.

[3]قسم الهندسة الميكانيكية بكلية الهندسة بشبرا - جامعة بنها.

الهدف من البحث هو دراسه تأثير السرعة الدورانية وسرعة اللحام والمعالجات الحراريه ((T4,T6 على سلوك التآكل لسبيكة الألومنيوم 6061 الملحومه بطريقة اللحام التقليبى الإحتكاكى. تم إختبار سلوك التآكل بإستخدام طريقتين الأولى طريقة الغمر دون التأثير بأى جهد والطريقة الثانية بإستخدام إختبار الإستقطاب البوتنشيوديناميكى كلا فى محلول كلوريد الصوديوم. أظهرت النتائج أن كلا المعالجتين (T4,T6) بتحسن من مقاومة التآكل للمنطقة الملحومة مقارنة بالمعدن الأصلى وأظهرت النتائج أيضا أن الوصلات بالمعالجة T6 تتمتع بمقاومة أعلى للتآكل مقارنة بالوصلات المعالجة T4. وأظهرت النتائج أيضا أن بزيادة سرعة اللحام أو بتناقص السرعة الدورانية تزداد مقاومة التآكل للوصلات الملحومة.