# Corrosion behavior of the pre-heated friction stir welded AA2024 alloy reinforced with AA7075 in 3.5% NaCl solution

Aliaa Abdelfatah<sup>1</sup>, Mohamed Abu-Okail<sup>2</sup>, Lamiaa Z. Mohamed<sup>3,\*</sup>

<sup>1</sup> Corr. and Surface Treatment Lab., Dept. of Metallurgy, Faculty of Engineering, Cairo University, Egypt.

<sup>2</sup> Manufacturing Engineering and Production Technology Department, Modern Academy for Engineering and Technology, P.O. Box 11571, Cairo, Egypt.

<sup>3</sup> Mining, Petroleum, and Metallurgical Engineering Depart. Faculty of Engineering, Cairo University, Egypt.

\*E-mail: <u>lamiaa.zaky@cu.edu.eg</u>

Received: 2 September 2020 / Accepted: 7 November 2020 / Published: 30 November 2020

The corrosion resistance of friction stir welded (FSW) AA2024 base material (BM) reinforced with different AA7075 weld material (WM) with different width namely 1.0, 1.5, 2.0, 2.5, and 3.0 mm as a compensation layer were studied. The effect of pre-weld heat treatment on the corrosion resistance of BM, WM, and heat affected zone (HAZ) were investigated. Both AA2024 and AA7075 alloys were pre-weld treated under different heat treatment conditions, the first condition was annealed (O), while the second condition was solution heat treated followed by artificial aging (T6). The welded samples were examined for corrosion resistance using potentiodynamic measurements in 3.5% NaCl solution for the two heat treatment conditions (O and T6). Then, the corroded zones for the two conditions after welding were examined using scanning electron microscopy (SEM), energy dispersion x-ray analysis (EDAX), and mapping of the elemental distribution. It was found that WM-T6 has a higher corrosion rate than WM-O with a uniform corrosion, localized pitting and local galvanic cells formation. After welding, both alloys were highly susceptible to corrosion, and AA2024 alloy had higher susceptibility to corrosion than AA7075 alloy.

Keywords: Friction Stir Welding; Corrosion behavior; NaCl Solution; AA2024 Alloy; AA7075 Alloy

# **1. INTRODUCTION**

7xxx alloys are commonly used as traditional structural materials in the transport industries, such as civil and military vehicles, high-speed trains and ship structures, because of their high specific strength. 2xxx Al alloys have an excellent structural properties thus their typically used in some parts, along with 7xxx Al alloys of higher strength such as the aircraft industry [1-3]. Friction Stir Welding

2

(FSW) is a solid-state joining process that can join almost any kind of metal, including some previously unweldable alloys 2xxx and 7xxx series [1, 4, 5, 6], such as manufacturing process with several applications including aerospace, automotive, electronics and shipbuilding [1, 2, 3, 7, 8, 9]. Because of its low energy consumption and low heat input, FSW is the most widely used for joining lightweight alloys [3]. Many investigators examined the impact of pre-weld heat treatment conditions of base material (BM) on FSW Al alloys' microstructural and mechanical properties, but few studied their effects on corrosion resistance [9-14].

To obtain a good balance of strength and corrosion resistance, a considerable deal of effort was made to achieve improved corrosion resistance with the least loss of strength [15]. However, several manuscripts concentrated on alloys such as aluminum alloy (AA) 7075 with high Cu and low Zn material [16-18]. The FSW-induced variation in precipitation and grain morphology significantly affects the corrosion resistance of the welded plate [6, 19]. The action of anodic polarization has been affected by the precipitate chemical composition, as the alloy elements have different effects on the potential for corrosion. Zn and Mg in the solid solution move the corrosion potential in the active direction, but Cu shifts the corrosion potential to the noble direction [20-22]. This region is also generally susceptible to corrosion because of the alteration of the precipitate composition [23]. It is well documented that when there are the constituent particles, the corrosion resistance of high strength Al alloys will deteriorate. The presence of Al<sub>2</sub>CuMg precipitates and coarse constituent particles makes AA2024 susceptible to localized corrosion which occurs intergranularly in 7xxx Al alloys according to a non-uniform distribution of MgZn<sub>2</sub> [3, 24]. Alloying Al with other metals contributes to the formation of local galvanic cells, which can act as either anode or cathode sites in relation to the Al matrix. Therefore, Al is more corrosion resistant than alloys AA2024-T3 or AA7075-T6. Aggressive ions such as chloride lead to powerful, localized alloy attacks, i.e. pitting, intergranular, galvanic or crevice corrosion, as they facilitate aluminum oxide film breakdown [21, 24].

Owing to its hardness and low density AA2024 alloy is commonly used in the aeronautical and automotive industries. However, under some specified conditions, the alloy AA2024 is susceptible to exfoliation corrosion, which would significantly reduce its mechanical properties and decrease its optimized service life. Many researchers reported the effect of aging treatment on high-resistance, Al alloy exfoliation corrosion behavior [25-26]. Most of them also assumed that the precipitated phases of alloys were achieved in different ageing treatment conditions playing a significant role in exfoliation corrosion, including phase type, shape/size and phase distribution [26]. Because AA2024 contains Cu, however, it experiences extreme corrosion in aggressive media such as saline or low Earth orbit environments [25]. AA2024 is a high strength alloy with a complex microstructure that contains the Al matrix as well as numerous intermetallic particles. Numerous articles attempted to characterize the resulting alloy microstructure and the intermetallic particle composition [27]. The most popular intermetallic particles in the microstructure of AA2024 are the S-phase particles (Al<sub>2</sub>CuMg). Adding additional alloying elements creates scattered particles such as Al<sub>6</sub> (Cu, Fe, Mn), Al7Cu<sub>2</sub>Fe, and (Al, Cu) <sub>6</sub>Mn [28]. Due to its strong mechanical properties, AA7075-T6 is commonly used in the engineering industry as a high-specific resistance equivalent to high-strength steel [29-35]. It offers the opportunity for substantial weight loss, which is important in some applications [29, 30, 32]. However, two main factors restrict the wider use of AA7075-T6: susceptibility to localized corrosion and poor tribological properties due to relatively low durability and strong propensity for adhesion [36]. Al<sub>7</sub>Cu<sub>2</sub>Fe and (Al,Cu)<sub>6</sub>(Fe,Cu) are the main intermetallics in AA7075-T6 that are electrochemically less active than the matrix, and can thus dissolve the surrounding areas [37]. Finally, parameters of thermal treatment, such as temperature, length and cooling rate, may change the form, quantity, size and distribution of intermetallic particles that are both soluble and insoluble. The resistance to certain types of corrosion depends on the alloy and final temper [38]. Also, the media for the corrosion may be aggressive especially in chlorine ions (Cl<sup>-</sup>) such as sea water which broken the protective oxide layer that contain on the Al alloys [39]. Scientific researchers have until now carried out extensive analysis and evaluation on the FSW of 2000 series and 7000 series Al alloy at home and abroad [40].

The purpose of this research was to examine the corrosion resistance of both AA2024 (BM) and AA7075 as a welded material (WM) with different WM widths joined by FSW. Moreover, the effect of pre-heat treatment on the corrosion behavior which studied through corrosion rates and the microstructures of the samples (O and T6).

## 2. EXPERIMENTAL WORK

The AA2024-AA7075 friction stir welded samples used for this work were prepared by previous work [1, 41, 42]. The chemical composition of the AA2024 and AA7075 alloys are listed in Table 1. The samples were welded using friction stir welding (FSW) where AA2024 aluminum alloy was the base material (BM) and AA7075 aluminum alloy was the welding material (WM). The AA7075 alloy weldment had five different WM widths of 1.0, 1.5, 2.0, 2.5, and 3.0 mm as shown in Fig. 1. The samples were pre-heat treated before welding in two conditions, the first case was annealing heat treatment (O) and the second case was solution heat treated with artificial aging (T6). Solution heat treatment with artificial ageing (T6) was performed by means of a combination of solution treatment at 470 °C for a soaking time of 1 h, finally quenching at room temperature in water and subsequent artificial ageing at 165 °C for 6 h [1, 41]. Annealing heat treatment consisted of initial heating to 435 °C, soaking for 2 h, accompanied by air cooling and reheating for 4 h at 230 ° C, eventually air cooling progressively until ambient temperature was reached [1, 42]. The FSW technique was used to join these alloys after natural ageing of the alloys for about 2 months.

Chemical compositions	Cu	Mn	Zn	Mg	Fe	Si	Cr	Ti	Al
BM AA2024	3.8	0.75	0.02	1.3	0.15	0.1	0.006	0.06	Bal.
WM AA7075	1.5	0.01	5.6	2.6	0.15	0.1	0.22	0.12	Bal.

Table 1. The chemical composition of BM (AA2024) and WM (AA7075) in wt.%

Accordingly, the samples studied in this work consists of two groups, the first group included annealed (TO heat treatment condition), friction stir welded samples and the second group included T6 heat treated friction stir welded samples. Both groups were subjected to corrosion testing applied on all three parts. For the annealed condition the three parts are base material with annealing heat treatment (BM-O), welding material with annealing heat treatment (WM-O) and heat affected zone with annealing heat treatment (HAZ-O). For the T6 condition, the three parts are the base material with artificial aging (BM-T6), welding material with artificial aging (WM-T6) and heat affected zone with artificial aging (HAZ-T6).



Figure 1. Welding joint configuration

The corrosion of both groups of samples were investigated in 3.5% NaCl solution. Measurements of linear polarization were conducted out using samples with a surface area of 1 cm<sup>2</sup> and 3.5 mm in width. The working electrodes were cut into three samples (WM, HAZ, and BM) with wire cutting instruments. Each working electrode was prepared for metallographic investigation by grinding with different grades of silicon carbide paper, 100, 240, 360, 500, 600, 800 and 1000 grit, polishing with 0.3  $\mu$ m alumina paste, then polishing to 1 $\mu$ m using a diamond paste, and were finally rinsed with de-ionized water and dried with acetone before electrochemical analysis. This study was carried out at room temperature with PGZ 100 potentiostat with a corrosion cell containing 500 ml of 3.5% NaCl. A platinum electrode was used as the auxiliary electrode, the calomel electrode (mercury and mercury chloride) was used as the reference electrode, and the samples were used as the working electrode while the steady-state open circuit potential (OCP) was noted. The potentiodynamic investigations were made from -1 mV versus OCP to +1 mV versus OCP at a scan rate of 0.333 V/s, and the corrosion currents was recorded. The corrosion current density (icorr), and corrosion potential (E<sub>corr</sub>) were determined from

the Tafel plots of potential versus logarithm of corrosion current density i.e. applied current (log I). The corrosion rate (CR) was calculated from Eq. (1) [43, 44] as follows:

$$CR (mm/yr) = (0.00327 * icorr * eq.wt.) /D$$
 (1)

Where  $i_{corr}$  is the current density in  $\mu$ A/cm<sup>2</sup>, D is the specimen density in g/cm<sup>3</sup>, and eq.wt. is the specimen equivalent weight in grams. The surface microstructure of the two group of samples after corrosion in 3.5% NaCl solution were examined using scanning electron microscope (SEM), FEI inspects S-Netherlands linked with energy dispersion x-ray analysis (EDAX), Bryker AXS-flash detector Germany. The mapping of the corroded samples was investigated at TO and T6, with microstructures investigation for BM, WM, and HAZ.

# **3. RESULTS AND DISCUSSION**

#### 3.1 Corrosion results for Group 1 (TO) case

Conditions	514	Different WM widths							
	BM	1 mm	1.5 mm	2 mm	2.5 mm	3 mm			
E(i=0), mV	-951	-869	-772	-807	-776	793			
i corrosion, mA/cm <sup>2</sup>	46	0.02	0.12	0.01	0.07	0.15			
Rp, ohm.cm <sup>2</sup>	574	1930	132	2990	257	137			
CR, mm/Y	476	0.18	1.42	0.17	0.82	1.80			

Table 3. The corrosion behavior of HAZ-O for different WM widths in 3.5% NaCl solution

Conditions	Different WM widths								
	1 mm	1.5 mm	2 mm	2.5 mm	3 mm				
E(i=0), mV	-744	-770	-767	-761	-757				
i corrosion, mA/cm <sup>2</sup>	0.1	9.6	45	15	15				
Rp, ohm.cm <sup>2</sup>	140	390	773	1230	2510				
CR, mm/Y	531	185	175	112	1.2				

The corrosion polarization curves of BM-O, WM-O and HAZ-O for different widths of WM samples in 3.5% NaCl are provided in Fig. 2. Table 2 illustrates the results for the potentiodynamic polarization curves of BM-O and WM-O in 3.5% NaCl. The corrosion rate values of BM-O and WM-O were studied corresponding with values of the corrosion current and polarization resistance. The WM-

O with WM width 2 mm showed the lowest corrosion rate and the highest polarization resistance compared with other WM and BM-O as given in Fig. 2(a). The corrosion potential  $E_{corr}$  for different WM widths were shifted to more positive values from BM-O (-951mV). Corrosion behavior of HAZ-O at a different WM width are shown in Fig. 2(b) and Table 3. The HAZ-O with WM width 3 mm showed the lowest corrosion rate compared with other WM widths.



**Figure 2.** The corrosion behavior for different WM widths in 3.5% NaCl solution of (a) BM-O and WM-O, and (b) HAZ-O

Both BM-O and WM-O showed significant pitting corrosion over the corroded surfaces. In 7000 series alloys, pitting corrosion has been shown to occur near Cu and Fe containing intermetallic particles because Cu and Fe are more cathodic than the Al matrix which leads to the formation of a galvanic interaction [45]. Figs. 3 and 4 provide the microstructure of the corroded surface of the BM-O, HAZ-O and WM-O at a different WM widths. EDAX analysis of the corroded BM-O showed 24.16%O, 2.27%Na, 0.05%Si, 0.27%Cl, 7.41%Fe, 2.31%Cu, 2.95%Zn and 60.59%Al as noted from Fig. 3(b), where EDAX results for WM-O with different WM widths are presented in Fig. 5 and Table 4. It is shown from the EDAX results that BM-O corrosion was higher than the WM-O corrosion which was also confirming with the potentiodynamic data. Fig. 6 gives the mapping of HAZ-O at a different WM widths.

WM widths,		Elemental analysis, wt.%								
mm	0	Na	Cl	Cu	Zn	Mn	Mg	Al		
1	11.8	0.6	0.0	2.9	0.0	0.6	0.0	Bal.		
1.5	18.8	0.4	0.1	3.1	1.1	0.3	2.0	Bal.		
2	10.4	0.2	0.7	2.9	0.4	0.7	1.8	Bal.		
2.5	15.5	0.0	0.0	3.3	1.4	0.0	2.1	Bal.		
3	16.7	0.4	0.0	3.5	0.9	0.0	2.2	Bal.		

Table 4. EDAX results of corroded WM-O for different WM widths in 3.5% NaCl solution



Figure 3. The corroded BM-O in 3.5% NaCl solution (a) SEM image and (b) EDAX analysis



**Figure 4.** The SEM image of corroded HAZ-O in 3.5% NaCl solution with different WM widths (a) 1 mm, (b) 1.5 mm, (c) 2 mm, (d) 2.5 mm and (e) 3 mm and corroded WM-O in 3.5% NaCl solution with different WM widths (f) 1 mm, (g) 1.5 mm, (h) 2 mm, (i) 2.5 mm and (j) 3 mm



**Figure 5.** The EDAX analysis of corroded WM-O in 3.5% NaCl solution with different WM widths (a) 1 mm, (b) 1.5 mm, (c) 2 mm, (d) 2.5 mm and (e) 3 mm



**Figure 6.** Mapping of the corroded HAZ-O in 3.5% NaCl solution with different WM widths (a) 1 mm, (b) 1.5 mm, (c) 2 mm, (d) 2.5 mm and (e) 3 mm

For both the BM-O and WM-O for different WM widths, only pitting corrosion was observed with no apparent intergranular corrosion. It is noticeable from Fig. 3 that the weld nugget is relatively free from pitting corrosion in comparison to BM-O region. The BM-O also has an inhomogeneous distribution of pitting relegating the majority of damage to the outer surfaces. The HAZ-O regions suffered a slight increase in pitting corrosion compared with the adjacent BM-O and WM-O regions. This effect was more pronounced on the advancing edge side of the weld but was also observed on the retreating side after careful analysis [46].

## 3.2 Corrosion results for Group 2 (T6) case

The corrosion polarization curves of BM-T6 and WM-T6 for different WM widths in 3.5% NaCl are illustrated in Fig. 7(a).

Conditions	BM	Different WM widths							
		1 mm	1.5 mm	2 mm	2.5 mm	3 mm			
E(i=0), mV	-685	-667	-732	-680	-684	-670			
i corrosion, mA/cm <sup>2</sup>	42	0.07	0.01	0.03	25	0.09			
Rp, ohm.cm <sup>2</sup>	165	981	1400	3650	1220	414			
CR, mm/Y	495	0.78	0.32	0.15	1.04	294			

Table 5. The corrosion behavior of BM-T6 and WM-T6 for different WM widths in 3.5% NaCl solution

Table 6. The corrosion behavior of HAZ-T6 for different WM widths in 3.5% NaCl solution

Conditions	Different welding widths								
	1 mm	1.5 mm	2 mm	2.5 mm	3 mm				
E(i=0), mV	-697	-798	-671	-733	-650				
i corrosion, mA/cm <sup>2</sup>	15	0.22	0.01	0.01	19				
Rp, ohm.cm <sup>2</sup>	289	318	2310	4360	884				
CR, mm/Y	183.9	2.5	0.11	0.08	223.8				



**Figure 7.** The corrosion behavior in 3.5% NaCl solution with different WM widths of (a) BM-T6 and WM-T6, and (b) HAZ-T6



**Figure 8.** The corroded BM-T6 in 3.5% NaCl solution (a) SEM image and (b) EDAX analysis

WM widths,	Elemental analysis, wt.%									
mm	0	Na	Cl	Cu	Zn	Mn	Mg	Al		
1	13.0	0.4	0.1	6.9	0.0	1.8	1.7	Bal.		
1.5	24.1	1.3	0.0	3.1	0.0	0.3	1.5	Bal.		
2	11.8	0.6	0.0	2.9	0.0	0.6	0.0	Bal.		
2.5	28.7	3.1	0.1	2.0	0.0	0.4	1.8	Bal.		
3	18.0	1.0	0.1	4.8	0.0	0.2	1.3	Bal.		

Table 7. EDAX results of corroded WM-T6 for different WM widths in 3.5% NaCl solution

Table 5 lists the potentiodynamic polarization curves results for BM-T6 and WM-T6 for different WM widths in 3.5% NaCl. The corrosion rate values of the BM-T6 and WM-T6 were investigated corresponding with the values of the corrosion current and polarization resistance. The WM-T6 for WM width 2 mm showed the lowest corrosion rate and the highest polarization resistance compared with other WM widths and BM-T6. The corrosion potential E<sub>corr</sub> for different WM widths shifted to more positive values from BM-T6 (-685 mV). Corrosion behavior of HAZ-T6 for different WM widths is provided in Fig. 7(b) and Table 6. The HAZ-T6 for WM width 2.5 mm has the lowest corrosion rate as it compared with other WM widths.

Both BM-T6 and WM-T6 contained significant pitting corrosion over the corroded surfaces as shown in Figs. 8 and 9. The corroded surface microstructures of BM-T6, HAZ-T6 and WM-T6 for different WM widths are given in Fig. 9. The EDAX results of the corroded BM-T6 showed 11.97%O, 0.72%Na, 1.64%Mg, 0.05%Cl, 1.91%Cu and 83.71%Al as clear from Fig. 8(b) where the EDAX results for WM-T6 for different WM widths are given in Fig. 10 and Table 7. The mapping of HAZ-T6 at a different WM widths are illustrated in Fig. 11. In heat-treatable Al alloys, the corrosion behavior is

generally controlled by the type, size and volumetric fraction of the precipitates, and precipitates form, dissolve or grow in various temperature ranges [43].



**Figure 9.** The SEM image of corroded HAZ-T6 in 3.5% NaCl solution with different WM widths (a) 1 mm, (b) 1.5 mm, (c) 2 mm, (d) 2.5 mm and (e) 3 mm and corroded WM- T6 in 3.5% NaCl solution with different WM widths (f) 1 mm, (g) 1.5 mm, (h) 2 mm, (i) 2.5 mm and (j) 3 mm



**Figure 10.** The EDAX analysis of corroded WM-T6 in 3.5% NaCl solution with different WM widths (a) 1 mm, (b) 1.5 mm, (c) 2 mm, (d) 2.5 mm and (e) 3 mm



**Figure 11.** Mapping of the corroded HAZ-T6 in 3.5% NaCl solution with different WM widths (a) 1 mm, (b) 1.5 mm, (c) 2 mm, (d) 2.5 mm and (e) 3 mm

# 3.3 General Discussion

The BM-T6 corrosion rate is higher than the BM-O corrosion rate. Generally, the BM's corrosion rate for the two sample groups is higher than the WM. The AA2024 alloy has a low corrosion resistant which limited their wide applications [47]. Even after using two different heat treatment modes, it still showed low corrosion resistance. Fig.12 provides a comparison for different WM widths between the

WM-O and WM-T6. For different WM-T6 widths except 1.5 mm width, the WM-T6 corrosion rates are higher than Wm-O, and nearly equal for 2 mm width. For different WM widths except 3 mm width, the corrosion rates of HAZ-O are higher than HAZ-T6 however as provided in Fig. 12(b).



(b)

**Figure 12.** Comparison for different WM widths between the corrosion rates in 3.5% NaCl solution of the (a) WM-O and WM-T6, and (b) HAZ-O and HAZ-T6

WM-T6 reveals various forms of corrosion, such as uniform corrosion, localized pitting and forming a local galvanic cell. The intermetallics (IMs) and surrounding areas that form micro-galvanic cells, resulting in [48, 49] trenching as seen in Figs 6 and 11. Alloying Al is caused by increasing intensity by forming the particles from IMs. Al's good corrosion resistance is due to the effective passivity of a protective oxide film made up of Al<sub>2</sub>O<sub>3</sub>, Al(OH)<sub>3</sub>, and AlO(OH)<sub>2</sub>. The involvement of

18

IMs in alloys, therefore, reduces their resistance to corrosion. Cu-enrichment at Al-Cu-Mg precipitates occur after selective dissolution of Mg and Al which leaves residual Cu-rich particles. If copper dissolves, it can then redeposit to the alloy matrix around the IMs as a thin layer of Cu [21]. The key fortifying particle precipitations include MgZn<sub>2</sub> in WM-T6 [36]. Due to their extremely low electrochemical potential [50], these precipitations can create anodic pathway for the localized attack along grain boundaries, leading to intergranular corrosion [36, 49]. It is noted that corrosion occurs around the precipitates of MgZn<sub>2</sub> for WM-T6, leaving these precipitates uncorroded until the attack has penetrated deep enough theses precipitates are washed away leaving voids in their positions [51]. EDAX results show the element mapping of HAZ-O and HAZ-T6 in different WM widths, revealing the precipitated phases were rich in Cu and Fe elements [26].

#### 4. CONCLUSIONS

The corrosion behavior of the BM (AA2024) and WM (AA7075) with different widths 1.0, 1.5, 2.0, 2.5 and 3.0 mm WM were investigated. The samples were pre-heat treated before welding with two heat treatment conditions, the first one was annealing, heat treatment (TO), where the second case was solution heat treatment followed by artificial aging (T6). The corrosion rate of AA2024 is relatively higher for T6 heat treatment than for annealed condition and this was confirmed with SEM and EDAX results. The corrosion rates of AA2024 are higher than corrosion rates of AA7075 for all heat treatment conditions and EDAX results confirmed this behavior. Similar trends were obtained for AA7075 as T6 pre-heat treated samples have higher corrosion rate than annealing pre-heat treated samples. Uniform corrosion, localized pitting and local galvanic cells formation were observed. However, The HAZs with T0 pre-heat treatment with different WM widths have generally higher corrosion rates than HAZs with T6 pre-heat treatment. WM-T6 has a uniform corrosion and a localized pitting induced by reinforcing particles of precipitates or intermetallics.

#### ACKNOWLEDGEMENT

The authors acknowledge Prof. Dr. Iman El Mahallawi (Cairo University, Faculty of Engineering, Department of Mining, Petroleum and Metallurgical Engineering) and Associate Prof. Yassar Reda (Higher Institute of Engineering and Technology Tanta) for English revision. Also, the authors gratefully acknowledge the supports of running some of the experimental work in the Mining, Petroleum and Metallurgical Engineering Department, Faculty of Engineering, Cairo University.

#### References

- 1. M. Abu-Okail, I. Sabry, A. Abu-Oqail, W.M. Shewakh, J. Fail. Anal. Prev., (2020)
- 2. Z. Kailun, J. Denis, W. Liliang, J. Lin, Int. J. Lightweight Mater. Manuf., 1 (2018) 55-80.
- 3. P.L. Niu, W.Y. Li, N. Li, Y.X. Xu, D.L. Chen, Mater. Charact., 147 (2019) 93–100.
- 4. R. Mishra, Y. Ma, Mater. Sci. Eng.: R: Reports, 50(1–2) (2005) 1–78.
- 5. M. Abu–Okail, M.H. Ata, A. Abu-oqail, G.M.F. Essa, T.S. Mahmoud, I. Hassab–Allah, J. Mater. Sci. Technol., 34(16) (2018) 2030–2041.
- 6. S. Rajesh, V. J. Badheka, Mater. Manuf. Process., 33 (2017) 323-332.

- 7. R. Nandan, T. DebRoy, H. Bhadeshia, Prog. Mater. Sci., 53(6) (2008) 980-1023
- 8. J.F. Guo, H.C. Chen, C.N. Sun, G. Bi, Z. Sun, J. Wei, Mater. Des., 56 (2014) 185-192
- 9. Y.S. Sato, M. Urata, H. Kokawa, Metall. Mater. Trans. A, 33 (2002) 625-635
- 10. J. Yan, A.P. Reynolds, Sci. Technol. Weld. Joi., 14(4) (2009) 282-287
- 11. Y. Chen, H. Liu, J. Feng, Mater. Sci. Eng. A, 420 (2006) 21-25
- 12. V. Dixit, R.S. Mishra, R.J. Lederich, R.K. Talwar, Sci. Technol. Weld. Joi., 12(4) (2007) 334-340
- 13. H. Aydin, A. Bayram, A. Ug`uz, K.S. Akay, Mater. Des., 30 (2009) 2211-2221
- 14. C.A. Widener, D.A. Burford, B. Kumar, J.E. Talia, B. Tweedy, *Mater. Sci. Forum*, 539–543 (2007) 3781–3788
- 15. S. Chen, K. Chen, G. Peng, L. Jia, P. Dong, Mater. Des., 35 (2012) 93-98
- 16. Y.P. Xiao, Q.L. Pan, W.Q. Li, X.Y. Liu, Y.B. He, Mater. Des., 32 (2010) 2149-56
- 17. S. Maitra, G. English, Metall. Trans. A, 12 (1981) 535-41
- 18. F. Viana, A. Pinto, H. Santos, A. Lopes, J. Mater. Process. Technol., 92 (1999) 54-9
- 19. M. Jariyaboon, A.J. Davenport, R. Ambat, B.J. Connolly, S.W. Williams, D.A. Price, *Corros. Eng. Sci. Technol.*, 41(2) (2006) 135–142
- 20. Q. Meng, G. Frankel, J. Electrochem. Soc., 151 (2004) B271-83
- 21. P. Rodic, I. Milosev, J. Electrochem. Soc., 163(3) (2016) C85-C93
- 22. X. Zhang, Zhou X., Hashimoto T. and Liu B., Mater. Charact., 130 (2017) 230-236
- 23. J.B. Lumsden, M.W. Mahoney, G. Pollock, C.G. Rhodes, Corrosion, 55 (1999) 1127-1135
- 24. M. Cabrini, S. Bocchi, G. D'Urso, C. Giardini, S. Lorenzi, C. Testa, T. Pastore, Materials, 13 (2020) 2600
- 25. D.B.T. Mascagnia, M.E.P. de Souza, Mater. Res., 17(6) (2014) 1449-1465
- 26. S. Sun, Y. Fang, L. Zhang, C. Li, S. Hu, J. Mater. Res. Technol., 9 (2020) 3219-3229
- 27. N.D. Alexopoulos, W. Dietzel, Procedia Struct. Integrity, 2 (2016) 573-580
- N. Siskou, C.H. Charalampidou, N.D. Alexopoulos, S.K. Kourkoulis, *Procedia Struct. Integrity*, 10 (2018) 79–84
- 29. Y. Liu, J.M.C. Mol, G.C.A.M. Janssen, J. Bio- and Tribo-Corrosion, (2016) 2-9
- W. S. Miller, L. Zhuang, J. Bottema, A.J. Wittebrood, P.D. Smet, A. Haszler, A. Vieregge, *Mater. Sci. Eng.* A, 280 (2000) 37–49
- 31. R.L. Deuis, C. Subramanian, J. M. Yellupb, Compos. Sci. Technol., 57 (1997) 415-435
- 32. E.A. Starke, J.T. Staley, Prog. Aerosp. Sci., 32 (1996) 131-172
- 33. E.A. Starke, J.T. Staley, Prog. Aerosp. Sci., 32 (1996) 131-172
- 34. S.W. Lee, J.W. Yeh, Y.S. Liao, Adv. Eng. Mater., 6 (2004) 936-943
- 35. D. Liu, H.V. Atkinson, P. Kapranos, W. Jirattiticharoean, H. Jones, *Mater. Sci. Eng. A*, 361 (2003) 213–224
- 36. F. Andreatta, H. Terryn, J.W. de Wit, *Electrochim. Acta*, 49 (2004) 2851–2862
- 37. M. Gao, C.R. Feng, R.P. Wei, Metall. Mater. Trans. A, 29 (1998) 1145-1151.
- K. El-Menshawy, A.A. El-Sayed, M.E. El-Bedawy, H.A. Ahmed, S.M. El-Raghy, Corros. Sci., 54 (2012) 167–173
- 39. A. Singh, Y. Lin, W. Liu, J. Pan, C. Ren, D. Zeng, S. Yu, Int. J. Electrochem. Sci., 9 (2014) 5164 5176
- 40. D. Zhang, J. Xia, Q. Yang, T. Wei, L. Gong, S. She, Int. J. Electrochem. Sci., 15 (2020) 1072 1081
- 41. M. Abu–Okail, W. Shewakh, A. Brisha, Y. Abdelraouf, A. Abu-Oqail, *Ceram. Int., 46*(11-A) (2020) 18037-18045
- 42. M. Abu-Okail, T.S. Mahmoud, A. Abu-Oqail, J. Fail. Anal. Prev., 20(1) (2019) 184-196
- Md.I. Ahmed, A. Islam, N. Ali, 4th Int. Conf. Mechan. Eng. Renewable Energy (ICMERE2017-PI-357), (2017) 1-4
- 44. SR. Al-Sayed, A. Abdelfatah, Metallogr. Microstruct. Anal., 9 (2020) 553-560.
- 45. H.A. Fetouh, T.M. Abdel-Fattah, M.S. El-Tantawy, Int. J. Electrochem. Sci., 9 (2014) 1565-1582

- 46. D. P Field, T.W. Nelson, Y. Hovanski, D.F. Bahr, Friction Stir Welding and Processing, TMS: Indianapolis, Indiana (2001) 246.
- 47. P. Wang, W.X. Wei, J. Pu, X.L. Zhou, W. J. Cao, Y.T. Xiao, Z.Y. Gong, J. Hu, *Int. J. Electrochem. Sci.*, 14 (2019) 4338 4349
- 48. F. Andreatta, M.M. Lohrengel, H. Terryn, J.H.W. de Wit, *Electrochim. Acta*, 48 (2003) 3239–3247.
- 49. N. Birbilis, M.K. Cavanaugh, R.G. Buchheit, Corros. Sci., 48 (2006) 4202-4215.
- 50. N. Birbilis, R.G. Buchheit, J. Electrochem. Soc., 152 (2005) B140-B151.
- V.A. Arizmendi-Salgado, S.A. Serna, A. Torres-Islas, R. Soto-Espitia, P. Althuzer, S. Mejia-Sintillo, J. Campos-Alvarez, J.G. Gonzalez-Rodriguez, *Int. J. Electrochem. Sci.*, 14 (2019) 8243 – 8255

© 2021 The Authors. Published by ESG (<u>www.electrochemsci.org</u>). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).