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Corrosion Properties for Roll-Bonded Two-Layer AA4045/AA3003 for Heat Exchanger Application

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Abstract. During their service life, heat-exchangers are subjected to a variety of environments, including heating and cooling cycles, salt water environment on the surface, and mechanical loading. As a result, corrosion performance is critical, as perforation of the material could result in system failure. Corrosion behaviour of brazed roll-bonded aluminium sheet is significant since this is the most common mode of failure for automotive heat exchangers, especially with the trend toward lighter automotive parts. Furthermore, thermal treatments such as solution heat treatment, homogenization, and brazing alter the microstructure and, as a result, vary the corrosion behaviour. The effect of homogenization temperature and duration on the microstructure of AA-3xxx aluminium alloys has been studied, but more research is needed. The goal of this investigation was to see how different holding times during homogenization heat treatments affect corrosion behaviour. Accelerated laboratory corrosion tests are essential for ranking trial materials and ultimately qualifying an alloy for production. The corrosion behaviour of two-layer modified aluminium sheets (AA4045/3003 Modified) was examined in this research before and after brazing. The corrosion propagation was attributed to potential differences between the brazing sheet, creating a galvanically driven perforation of the core material by the diffusion zone after sea water acid accelerated testing (SWAAT) and electrochemical testing of the AA4045/3003 modified brazing sheet. Furthermore, a link between SWAAT and potentiodynamic polarization measurements has been established, suggesting that these electrochemical approaches could be used to replace or reinforce the SWAAT and so reduce the cost.

1 Introduction

Aluminium is used in the heating, ventilation, and air conditioning systems as well as the engine cooling systems in automobiles. Aluminium alloys achieve high part product performance (i.e. performance characteristics of a product including, but not limited to, safety, efficacy, potency and application) and production efficiencies due to some interesting properties like high thermal conductivity, low density, and relatively good corrosion

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resistance. As a result, they are the primary material used to manufacture heat exchangers, commonly known as radiators, in the automotive industry [1].

The heat exchanger and/or condenser is typically mounted close to the car's front grill, where it is exposed to the elements and consequently corrodes from the outside [2, 3].

The automobile industry continues to put pressure on the heat exchanger manufacturing sector to develop heat exchangers that are of less than average dimension, light, efficient, and affordable as possible [4, 5, 6, 7]. Materials become more vulnerable to pitting corrosion when material thickness decreases [8]. The most vulnerable locations to corrosion are those where different materials are brazed together and phase heterogeneity is an inevitable occurrence [9].

The qualities of the finished product, such as mechanical properties and corrosion resistance, are impacted by microstructural variation in AA3xxx that results in the development of manganese (Mn) bearing dispersoids during preheat treatment before rolling.

Therefore, it was decided that the laboratory rolling simulation approach should be used to calculate the maximum safe residence time in order to better understand how homogenization, preheat, and annealing temperatures affect the mechanical properties of the finished product.

In this study, metallic composite sheets were created using a two-layer roll-bonding procedure, where severe plastic deformation was introduced during the process, as described in the literature [10]. The composite sheets were thereafter homogenised at 505 °C for prolonged periods of time up to 45 hours in order to better understand the effect of long homogenization times on the corrosion properties of the roll-bonded aluminium alloys AA3003 and AA4045 before brazing i.e. in un-brazed condition. The core layer, often an AA3xxx alloy, remained thicker throughout processing and provided strength to the composite sheet. Product formed from this two layer rolling process is tube and AA3xxx is a core layer (i.e. inside of the tube). Aluminum alloys used in heat exchangers are generally Al-3xxx as the substrate with Al-4xxx as external cladding when used as tubes.

2 Experimental Procedure

2.1 Materials

The South African Aluminium Company provided the experimental plate samples made from modified alloy 3003 and standard alloy 4045 in the cast and homogenised state. These commercial quality aluminium plates were cut into 120 mm (L), 60 mm (W), and 30 mm thick pieces parallel to the rolling direction of the plate. Chemical composition specifications are listed in Table 1.

Table 1. Chemical composition of the aluminium alloy plate materials.

	Elements (wt. %)								
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
AA3003	0.06	0.20	0.42	1.50	0.21	0.01	0.001	0.07	Bal
AA4045	10.0	0.15	0.004	0.019	0.006	0.002	0.004	0.01	Bal

2.2 Surface Preparation

Contaminants were remove from the surfaces of the two metals to be bonded in order to establish a suitable bond between the layers in heated roll bonding [11]. The optimum procedure for surface preparation, according to a number of publications, is degreasing, followed by scratch brushing with a revolving steel brush [12]. In this investigation, the recommended ratio of 1:10 was used to roll-bond commercial modified aluminium alloy AA 3003 plates with AA 4045 at warm temperatures. Mod-AA3003 material and AA-4045 were stacked together to create the Rolled Bond Product depicted in Figure 1 [13].

A 33 mm thick pack of AA3003/AA4045 bound by aluminium wire was homogenized at 505 °C for five different holding times of 20, 30, 35, 38, 40, and 45 hours with the AA4045 as a clad alloy and the AA3003 as a core alloy. According to Figure 1a and b, the pack was warm roll-bonded down to 3 mm thickness before being annealed and cold rolled further to a final thickness of 0.3 mm. Accelerated salt spray testing (SWAAT) testing were performed on the final roll-bonded sheets and potentiodynamic polarization testing were performed on the AA4045 sheets in two different heat treated, homogenised states (electrochemical corrosion). The materials employed for heat exchangers are depicted in Figure 1c, and this study focused on corrosion behaviour before brazing [13 14].

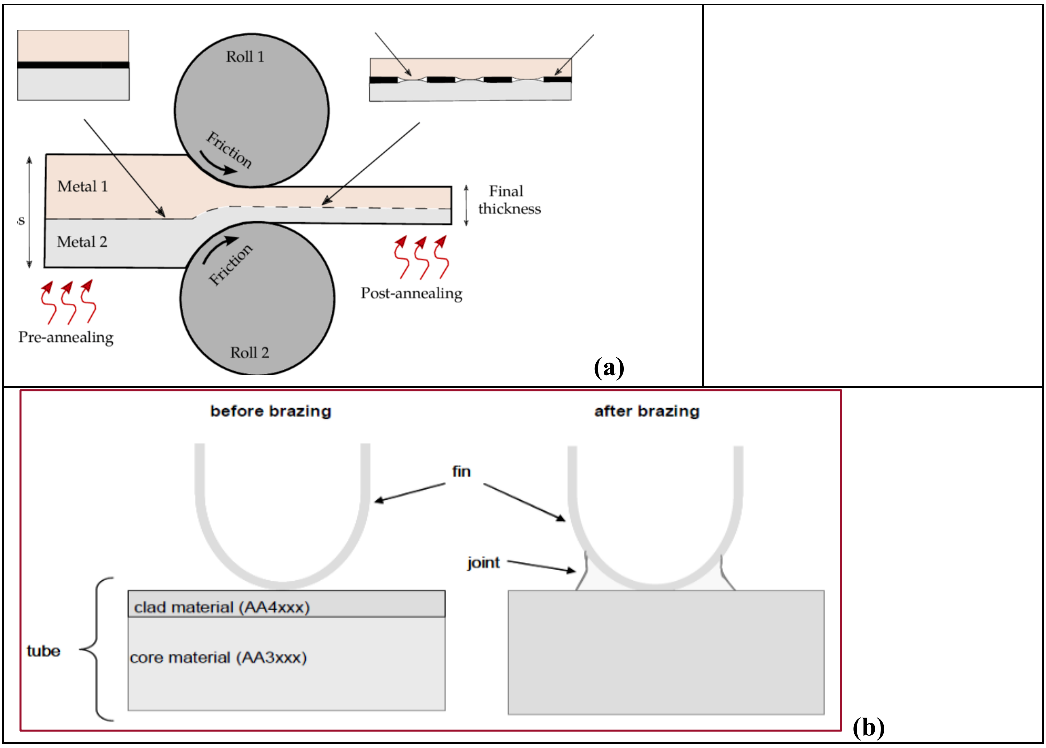


Fig. 1. Schematic representation showing (a) the warm roll bonding process and (b) brazing process for heat exchangers [13, 14]

2.3 Accelerated Salt Spray Testing (SWAAT)

For exposure times of 480, 720, 1080, and 1440 hours, 72 sections of the roll-bonded sheet with dimensions of 110 mm in length, 60 mm in breadth, and 0.3 mm in thickness were placed in the salt spray cabinet (20, 30, 45 and 60 days). The standard used for the tests-SWAAT process was ASTM G85 Annex A3: Acidified Synthetic Sea Water (Fog) Testing [15]. Samples of 110 mm x 60 mm were placed in a salt spray cabinet and tested as necessary. Acetic acid was used to acidify the saltwater solution to a pH range of 6.5 to 7.2, and the cabinet was heated to 35 °C. SWAAT testing is a cyclic procedure that involves spraying the samples for 30 minutes, followed by 90 minutes of soaking wet at a relative humidity of at least 98 percent. After the corrosion test, the sheets were thoroughly cleaned and dried before measuring the weight in as-corroded condition. The corrosion products were chemically removed by immersing in 1000 ml solutions consisting of 50% Nitric acid (HNO_3) at room temperature for 120 minutes. Additionally examined and the corrosion scale thickness was measured using an Olympus DSX510 high-resolution upright motorized microscope.

The samples were then cut, mounted in phenolic resin to expose their cross-sectional area and then prepared for metallographic observation (ground and polished to 1μm surface finish).

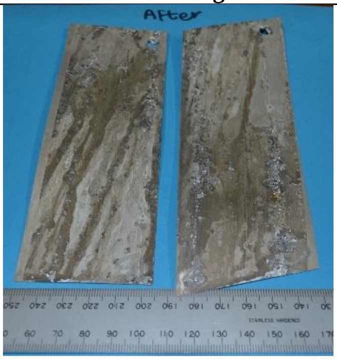
2.4 Electrochemical Corrosion

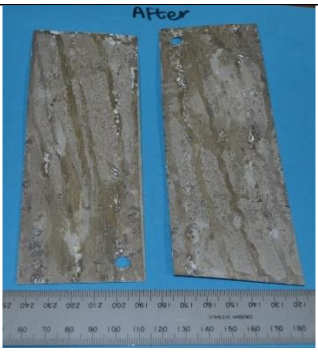
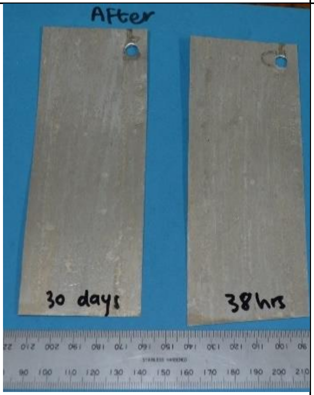
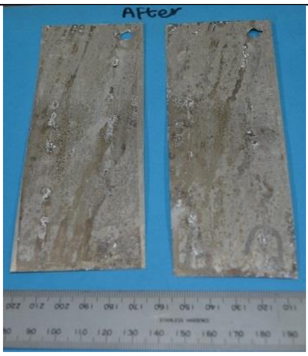
By performing a potentiodynamic polarization test in 3.5 percent NaCl at 70 °C, corrosion resistance was determined AA4045 sheets in two different heat treated, homogenised states. Using a PC-driven "ACM Gill AC" potentiostat, tests were carried out in accordance with the ASTM-G5-2013 Standard [16]. The open circuit potential (OCP) was maintained for 2 hours in order to reach equilibrium. Potentiodynamic polarization experiments were carried out on AA4045 sheets after the OCP was stable. Each scan was performed at a rate of 10 mV/min and ranged from -250 mV to +2000 mV in relation to the corrosion potential.

3 Results and Discussion

3.1 Accelerated Salt Spray Testing (SWAAT)

SWAAT is frequently used in industry to evaluate how well heat exchanger alloys resist corrosion. After the salt spray test, observations of the surface of roll-bonded sheets reveal significant variations in the generated scale's shape (Figure 2). The scale forms "islands" and does not entirely cover the surface of the sheets in the AA3003 (core) and AA4045 (clad layer) (Figure 2). On the other hand, it does not develop as much of a layer on AA4045 sheets and forms a thick layer on sheets made from the AA3003 series alloy.

Homogenization and SWAAT Period	A4045 (clad layer) After Cleaning	AA3003 (core layer) After Cleaning
Homogenized for 20hrs followed by SWAAT for 30 days		

the clHomogenized for 30hrs before SWAAT for 30 days		
Homogenized for 35hrs before SWAAT for 30 days		
Homogenized for 38hrs before SWAAT for 30 days		
Homoginized for 40hrs before SWAAT for 30 days		

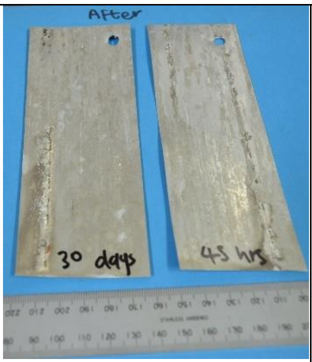
Homoginized for 45hrs before SWAAT for 30 days		

Fig. 2. Images taken showing surface of the AA4045 and AA3003 alloy sheets after corrosion test and cleaning of scale showing heavily corroded AA3003 core material.

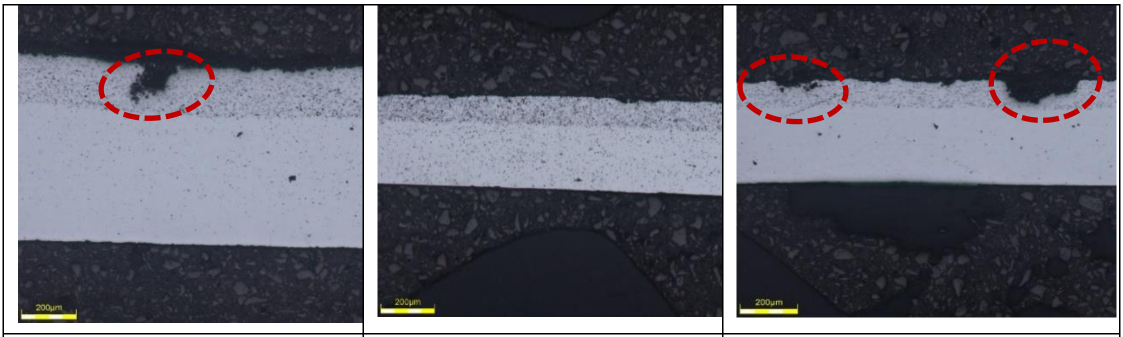
Following the corrosion test, a thorough analysis of the sheet surface reveals the presence of pitting corrosion. Cross sections of the sheets were investigated to determine the potential effect of a corrosive environment on the deterioration of components in the subsurface layer. The findings demonstrated that the surface or clad layer was degraded in each instance, although the extent of the alterations that permeated the material depended on the alloy exposure (Figure 3). The most corrosion-sensitive alloy was AA4045, which had localized pitting that reached even close to the material's core, while the modified AA3003 alloy had the strongest resistance to the effects of a corrosive environment (see Figures 3a and c). The AA3003 alloy "core layer" shows no corrosion until the worst case that was tested - 45 hrs homogenization, followed by 30 days SWAAT, Figure 3 (f).

Local intercrystalline corrosion may be seen in Figure 3 and it is especially noticeable in the AA4045 alloy. This type of corrosion is quite harmful because it can cause cracks especially when the temperatures and stresses are fluctuating and the car air conditioning or heat exchanger components are exposed to the atmosphere. The mechanical properties deteriorate as a result of the developing corrosive changes.

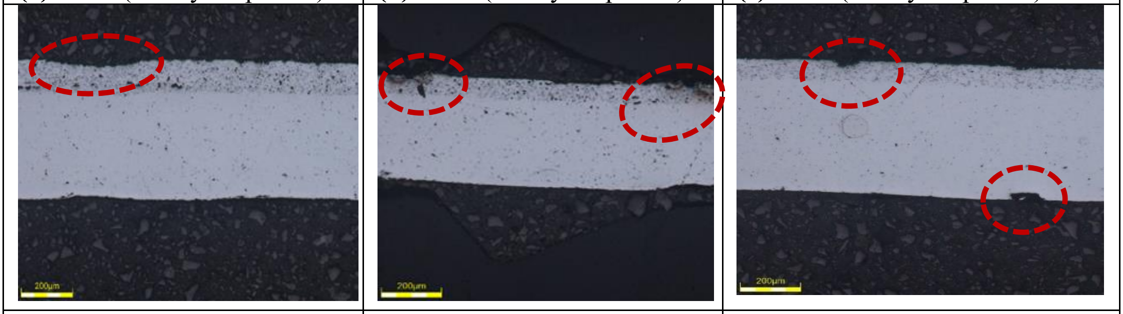
After the exposure time, pits were found forming on the cladding layer of AA4045. To quantify the depth of the produced pits, more work needs to be done. However, it is evident that the pits appear to be more prominent for longer homogenization times and longer exposure times. The sheets that had been homogenized for 20 hours exhibited pits on the core material after 30 days of exposure.

After 20 days of the SWAAT test, more pits formed with a 30 day exposure period increase. Additionally, the pits are now twice as deep and twice as wide, but the percentages of the corroded surface area almost remained the same. This shows that pits increased more in diameter than depth.

Another finding was that more pits formed on both the cladded layer and the core material as the homogenisation time increases (from 20 to 45 hours).



(a) 20hrs (20 days exposure)	**(b)** 35hrs (20 days exposure)	**(c)** 45hrs (20 days exposure)



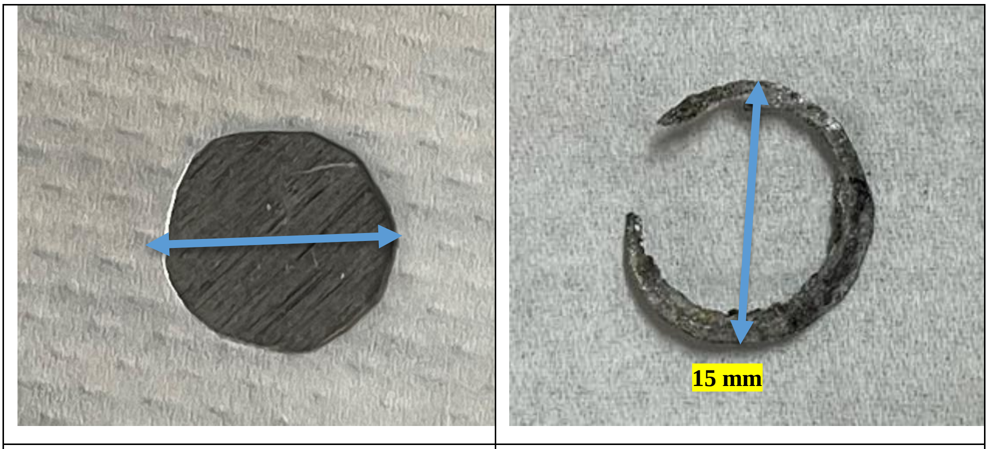
(d) 20hrs (30 days exposure)	**(e)** 35hrs (30 days exposure)	**(f)** 45hrs (30 days exposure)

Fig. 3. Optical microscopy images taken showing pits on samples exposed for 20 and 30 days

3.2 Electrochemical Corrosion

The corrosion potential of brazing sheets is frequently measured as a function of time at various depths, in accordance with the brazing industry's criteria [17], or the corrosion potential is depth profiled [18]. It has also been reported that SWAAT solution has been used for such a test of corrosion potential [17]. In this study, the electrochemical corrosion of unbrazed sheets was measured.

After being homogenized at 505 °C for 30 and 45 hours, the samples were analyzed. According to Figure 4b, all samples suffered severe corrosion, which might have been caused by the testing conditions being overly rigorous. For both samples, the calculated corrosion rates were found to be more than 0.1 mm/y and were similar and extremely high for generally accepted corrosion rate. Table 2 showed the electrochemical corrosion results.



(a) Samples before testing (b) Samples after testing

Fig. 4. (a) 15 mm diameter circular disc sample of AA4045 40Hrs before corrosion testing, (b) sample after corrosion showing corrosion from the centre outwards (crevice corrosion)

Table 2. Potentiodynamic polarization test results.

Alloy	**Ecorr (mV)SCE**	**Icorr (mA/cm^2)**	**Corrosion Rates (mm/y)**
AA4045 H40 hrs	-767	$1.3x10^{-3}$	0.13
AA4045 H30 hrs	-659	$9.9x10^{-3}$	0.11

The potentiodynamic scans of the two samples of AA045 are shown in Figure 6, which reveal that corrosion had taken place. Due to the intensity of the corrosion, the curves were identical, which suggests that the results are unreliable and that the exposed copper electrode may have interfered. However, the corrosion current densities (icorr) of the cladded layers were notably different and the corrosion rate was roughly constant, according to the polarization curves obtained in deaerated seawater, Figure 5.

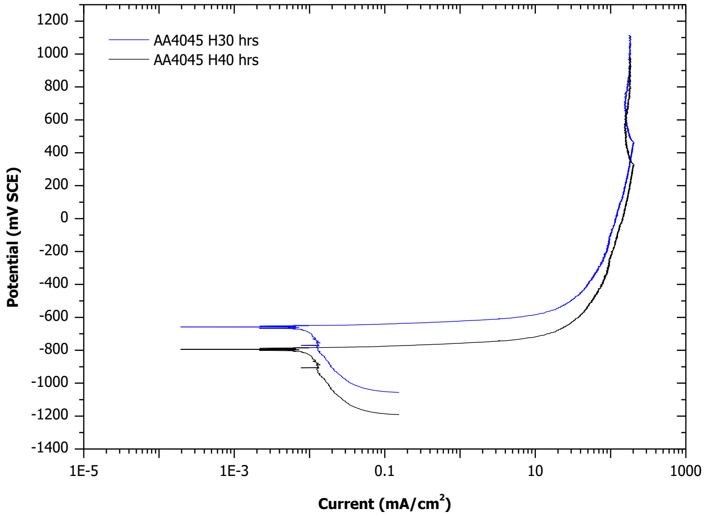


Fig. 5. Potentiodynamic scan of both samples homogenized for 30 and 40 hours for AA4045.

4 Conclusions

The corrosion behaviour of the roll-bonded aluminium alloys AA3003 and AA4045 in unbrazed state was investigated and the following conclusions were drawn:

- Pitting was the typical onset of corrosion in the cladding material AA4045. However, because these sheets were not brazed, there was no band of dense precipitates (BDP), hence the damage was not severe.
- High corrosion rates of greater than 0.1 mm/y were demonstrated by electrochemical experiments on the AA4045 sheet in two different homogenised conditions. The AA4045 clad layer experienced extensive corrosion.
- On an AA3003 core with Al-Si cladding of AA4045, the corrosion attacks persisted on the latter into the core.

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