# *AN INVESTIGATION ON THE INFLUENCE OF SIC VOLUME PERCENT AND HEAT-TREATMENT ON THE CORROSION BEHAVIOUR OF AL-6063/ $SIC_p$ COMPOSITES IN HCL – $H_2SO_4$ ENVIRONMENT*

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***Abstract***

*The influence of SiC volume percent and temper conditions (namely, as-cast, solutionized, and artificial age hardening at 180$^0$C and 195$^0$C) on the corrosion behaviour of Al – 6063 alloy composites and its monolithic alloy in acidic environment (pH 1.37) has been investigated. The composites were produced using a two step stir casting approach having volume percents of 12 and 15. It was observed that preferential corrosion attack of the composites occurred along grain boundaries and by pitting within the grains at particulate/matrix interfaces. The composites exhibited a greater susceptibility to corrosion in comparison to the monolithic alloy for all temper conditions. Furthermore, solutionizing and water quenching treatment was observed to significantly improve corrosion resistance of the unreinforced Al 6063 alloy while ageing at both 180$^0$C and 195$^0$C significantly increased its corrosion susceptibility. However for the 12 and 15 volume percent SiC reinforced Al-6063 composites, it was observed that both solutionizing and water quenching, and the age hardening treatments improved corrosion resistance in comparison to the as-cast temper condition. Unlike its unreinforced alloy, the effect of the type of heat-treatment was almost invariant on the corrosion resistance of the composites.*

***Keywords***: *A. Metal matrix composite; C. casting; Corrosion; optical microscopy*

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## 1.0 Introduction

Aluminum alloy matrix composites are remarked for the wide range of properties it offers at relatively low processing cost in comparison with other metal matrix composites and conventional materials [1 – 2]. High specific strength, stiffness, reduced density, improved high temperature properties, controlled thermal expansion coefficient, improved wear and abrasion resistance, and improved damping capacity; are some of the attractive properties of the Al matrix composites which has made it a versatile material for many potential applications [3 – 5]. In the automobile, aerospace, mining and marine sectors, mineral and chemical processing industries; Al matrix composites have been successfully utilized for component design and structural use with improved service performance obtained [6 – 7].

The processing route for the development of Aluminium matrix composites has though been identified as a factor that influences the service performance of the composites [3, 8 – 9]. Microstructural homogeneity, wettability and percent porosity are some of the parameters which are reported to affect mechanical properties of the composites [10 – 11].

The liquid metallurgy route (casting method) remains the cheapest route to develop metal matrix composites and lots of effort has been put into optimizing the composite quality through this method [12 – 13]. The ease of fabrication and low cost of this method makes it a great attraction to materials engineers from developing African countries.

This work intends to investigate the corrosion behaviour of Al-6063/SiC composites produced from an indigenous stir casting process (which essentially is a liquid metallurgy route). The Al-6063 alloy grade is processed in large quantities by the Aluminium processing industries in the country; its potentials for the development of high performance Al alloy composites has not received much attention. The elevated temperature mechanical properties of the Al-6063/SiC composite have been investigated with encouraging results obtained [14] while information on the corrosion properties can hardly be sourced in literature. Generally, the corrosion performance of Al-based SiC composites has been a major concern to researchers as efforts made to understand the corrosion behaviour of these composites, yielded results which to a large extent are not matching since the corrosion resistance of these composites varies with processing techniques, type of reinforcements and particulate size of the reinforcements [15 – 16]. In the current work, the potentials of the composite for use in typical mine water; and chemical processing industrial environments where they frequently are in contact with acids during cleaning, chemical and electrochemical processes is investigated.

## 2.0 Materials and Method

### 2.1 Composite Production

Al6063-$SiC_p$ composites containing 12 and 15 volume percents (vol.%) SiC reinforced particulates (30μm size) were prepared for the research investigation. The problem of wettability common to Al –SiC composites was tackled by mixing the SiC with dehydrated Borax in ratio 2:1. The samples were made using two step stir casting method which involved melting the Al-6063 ingots and then cooling to a semi-solid state before introducing the SiC particulates – Borax mixture and stirring manually for 10 – 15 minutes. This was followed by heating of the mixture to 30$^0$C above the liquidus and then performing a second stirring using a mechanical stirrer at a revolution of 300rpm for 10 minutes before casting into rectangular block moulds. Al6063 alloy without reinforcement was also prepared for control experimentation. The composition of the base Al-6063 alloy (determined using a spectrometric analyzer) was 0.46Si, 0.23Fe, 0.02Cu, 0.03Mn,

0.51Mg, 0.02Zn,0.03Cr, 0.03Ti and the balance Al (in wt.%).

## 2.1 Heat treatment

Four different temper conditions were desired for the study, the as-cast condition, and three others developed by heat-treatment, namely, solutionized and water quenched; artificially age hardened at 180$^0$C; and artificially age hardened at 195$^0$C. The Solutionized and quenched temper was achieved by solutionizing the samples at 550$^0$C for 3hours and then quenching in water. The samples heat-treated to this condition were designated S550/3h. The two artificial ageing tempers were achieved by initially solutionizing at 550$^0$C for 3hours followed by water quenching. Age hardening treatments were performed at 180$^0$C and 195$^0$C for 2hours before water quenching. The samples produced under the ageing conditions were designated A180/2h and A195/2h respectively.

## 2.2 Electrochemical Testing

The corrosion tests were carried out in 0.2M$H_2SO_4$ + 0.2MHCl solution (pH 1.37) which was prepared using standard procedures. The specimens for the test were cut to size 20 × 20 × 5 mm, after which the sample surfaces were mechanically polished with emery papers starting from 120grit down to 640grit size. The samples were de-greased with acetone and then rinsed in distilled water before immersion in still solutions of 0.2MH2SO4 + 0.2MHCl exposed to atmospheric air. The solution-to-specimen surface area ratio was about 150 ml cm$^{-2}$. The results of the corrosion tests were evaluated by mass loss, corrosion rate, and electrode potential measurements; and the electrochemical experiments were monitored on two day intervals for a period of 45days. Mass loss (mg/cm$^2$) for each sample was evaluated by dividing the weight loss (measured using a four decimal digit electronic weighing balance) by its total surface area which is in accordance with ASTM G31 standard recommended practice [17]. Corrosion rate for each sample was evaluated from the weight loss measurements following standard procedures. The electrode potential measurements were also performed employing a digital multimeter and using Zn electrode as reference electrode.

### 2.3 Microstructural Characterization

The microstructures of the test samples prior to and after the corrosion experiment were characterized using a Datteng Software–Driven Metallurgical Microscope. Before the immersion test, the specimens for the optical microscopy were polished using a series of emery papers of grit sizes ranging from 500μm – 1500μm; while fine polishing was performed using polycrystalline diamond suspension of particle sizes ranging from 10μm – 0.5μm with ethanol solvent. The specimens were etched with 0.5% HF solution by swabbing for 3 – 6 minutes (followed by rinsing in water and drying) before observation in the optical microscope. Microstructural characterization after the immersion test involved cleaning with ethanol and then observation in the optical microscope. Optical micrographs were produced at a magnification of 500X.

## 3.0 Results and Discussion

### 3.1 Microstructure

Figure 1 shows representative optical micrographs of the 12vol% SiC reinforced Al (6063) composite before and after immersion in the $0.2MH_2SO_4$ + 0.2MHCl solution. It is observed that the structure before immersion (Figure 1a) shows a fairly uniform distribution of the SiC particulates in the Al (6063) alloy matrix with little localized particle clustering. However the structures after immersion in the acid (Figure 1b) show delineated grain boundaries and pitting within the grains indicating that there is preferential corrosion attack on the composites primarily along the grain boundaries and by pitting within the grains at particulates/matrix interfaces. This trend is observed to be similar to that for the 15vol% SiC reinforcements (Figure 1c) indicating that the corrosion mechanism is similar for both composites.

### 3.2 Influence of SiC volume percent on Corrosion Behaviour

Figure 2 presents the variation of mass loss and corrosion rate with exposure time for the composites. It is observed from Figure 2(a) that the mass loss (corrosion) increases with increase in volume percent of SiC in the composite. The mass loss observed for the composites can be attributed to the formation of micro-galvanic cells in the composites. The SiC which has a more noble electrochemical potential acts as the cathode while the Al6063 matrix at the Al/reinforcement interfaces the anode. The difference in potential between the two components of the composites leads to intense corrosion of the surrounding matrix around the SiC particulates [18]. The addition of SiC as a reinforcing phase could have led to discontinuities in the protective film, thereby increasing the number of sites where corrosion can be initiated and causing higher corrosion on the composite [15]. Figure 2(b) shows clearly that the corrosion rate was intense for the composites at the early stages of immersion in the solution in comparison with the unreinforced Al (6063) alloy. The 15vol% SiC reinforced Al (6063) composite had the most intense corrosion rate at the early stage of immersion with corrosion rates as high as 2mpy obtained as the peak. The corrosion rate is observed to drop significantly after the $20^{th}$ day of immersion for all specimens. Figure 2 (c) – (e) show the mass loss variation for the other temper conditions (solutionized, and age – hardened). It is also observed that the mass loss increases with increase in the volume percent of SiC (with the exception of the $180^0$C age – hardened condition in which the mass loss of the 12vol% SiC reinforcement was greater than that of the 15vol% SiC reinforcement). The corrosion rate profiles for the solutionized, $180^0$C and $195^0$C age – hardened tempers follow similar trend with that of the as-cast temper presented in figure 2(b) – for which reason the corrosion rate profiles are not presented.

### 3.3 Effect of Temper condition on corrosion behaviour

Figure 3 shows the variation of mass loss, corrosion rate and electrode potential with exposure time for the unreinforced Al6063 alloy. It is observed from figure 3a that the solutionizing and quenching treatment (S550/3h) resulted in significant reduction in corrosion of the monolithic alloy in comparison to the as-cast and age hardened samples (A180/2h and A195/2h). This can be attributed to the improved homogenization of the microstructure and the dissolution of the second phase incoherent particles/precipitates formed during cooling of the alloy. This results in the reduction of the galvanic effects in the alloy that usually occurs at the Al/precipitate and Al/intermetallic interfaces [15, 19]. Thus the pronounced corrosion of the as-cast and age hardened Al 6063 alloy is due to the greater population of Al/intermetallic and Al/precipitate interfaces in the alloy. Zhu and Hihara [20] observed that localized corrosion in metal matrix composites occur more readily at chemical heterogeneities such as precipitate/matrix and intermetallic/matrix interfaces. The corrosion rate data presented in Table1 and figure 3(b) supports the above observation. The electrode potential values presented in figure 3(c) show that the S550/3h samples have the highest electrode potentials a reflection of the greater resistance to corrosion due to the increased resistance posed by the flow of current by the oxide films formed on the surface of the samples. Also, the electrode potential for the S550/3h sample is observed to be relatively uniform in pattern in comparison to the other samples indicating that the oxide film formed is more stable and protective in comparison to the as-cast and age hardened samples.

From figure 4(a) it is observed that for the 12 volume percent SiC reinforcement, mass loss was most prominent for the as-cast sample in comparison to the solutionized and quenched sample (S550/3h) and the age hardened samples (A180/2h and A195/2h). This indicates that the specific heat-treatments improve the corrosion resistance of the composite, and can be attributed to the improved dispersion of the second phase particles/precipitates and the SiC particulates in the composites. This though is in contrast with the observations made for the unreinforced Al-6063 alloy (Figure 2). Figure 4(b) shows that the corrosion rate of the as-cast sample was initially lower than that of the heat-treated tempers at the early stages of exposure in the medium but the overall corrosion rate was observed to be greater as can be confirmed from the data in Table 1. The 15 volume percent SiC reinforcement is also observed to exhibit the same behaviour with the as-cast having the most pronounced mass loss (Figure 5a). The variation of mass loss and corrosion rate (Table 1) for this composite is observed to be almost invariant, indicating that the heat-treatment temper has little effect on the corrosion properties of the composite for this volume percent of SiC reinforcement.

## Conclusion

The influence of SiC volume percent and temper conditions on the corrosion behaviour of Al-6063 composites in HCl $-H_2SO_4$ environment has been investigated. The following conclusions are drawn from the results obtained:

Preferential corrosion attack of the composites occurred along the grain boundaries and by pitting within the grains at particulate/matrix interfaces.

Irrespective of temper condition, corrosion rate increases with increase in the volume percent of SiC.

Solutionizing and quenching treatment significantly improved the corrosion resistance of the unreinforced Al 6063 alloy while ageing at both $180^0$C and $195^0$C significantly increased corrosion susceptibility. However for the composite, it was observed that both solutionizing and water quenching, and the age

hardening treatments improved corrosion resistance in comparison to the as-cast temper condition.

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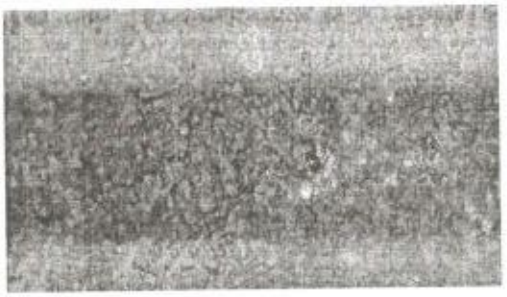
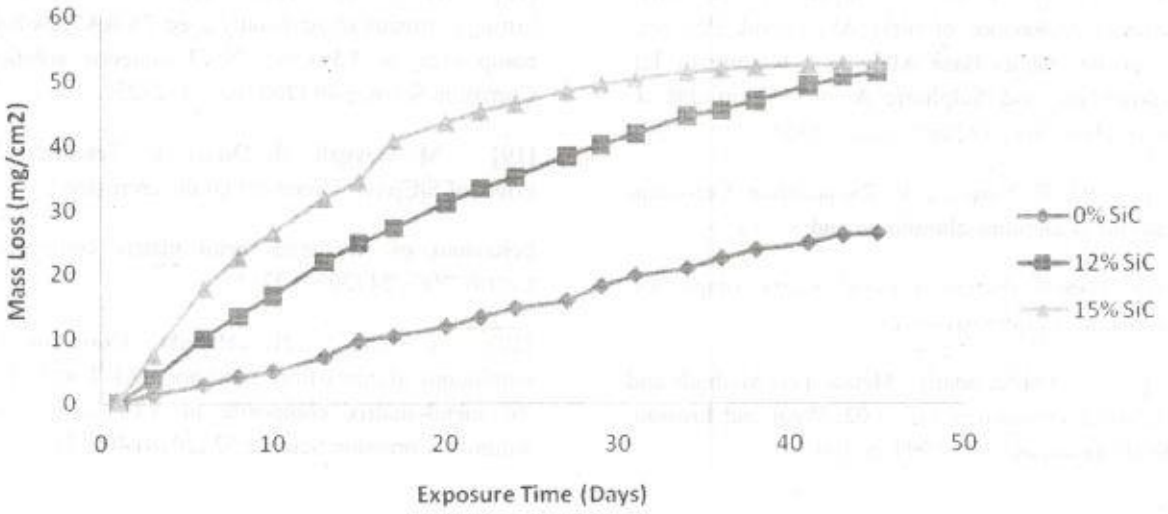


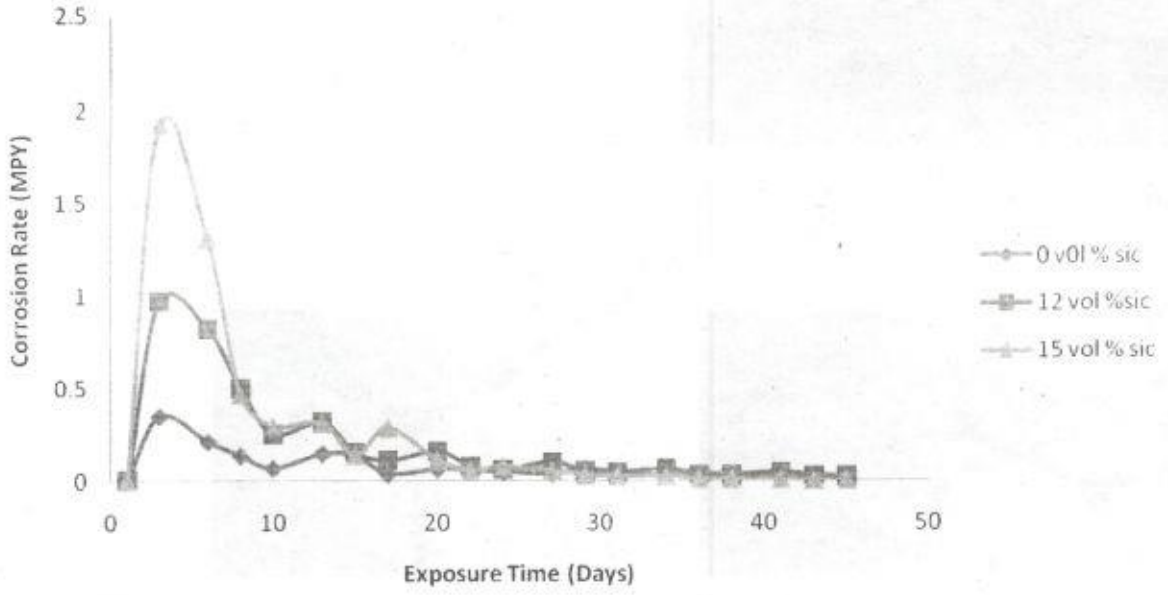
(a)

(b) (c)

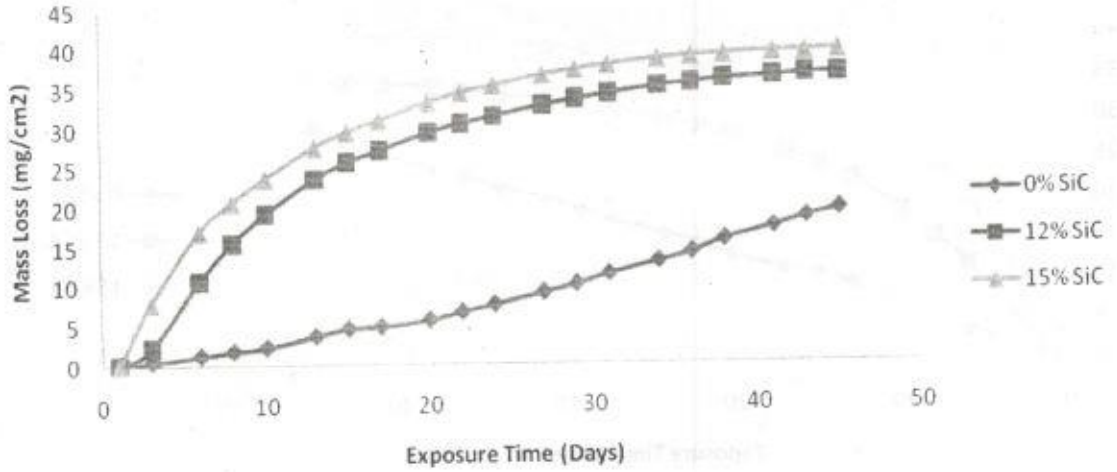
Figure 1. Representative micrograph of: (a) Al (6063) – 12vol% SiC composite before immersion revealing SiC particles uniformly distributed in the matrix; (b) and (c) showing respectively, the micrograph after 45 days immersion for the 12vol% and 15vol% SiC reinforcement revealing grain boundary attack and pitting within the grains of the composite.


Mass Loss (mg/cm2)
60
50
40
30
20
10
0
0
10
20
30
40
50
Exposure Time (Days)
0% SiC
12% SiC
15% SiC

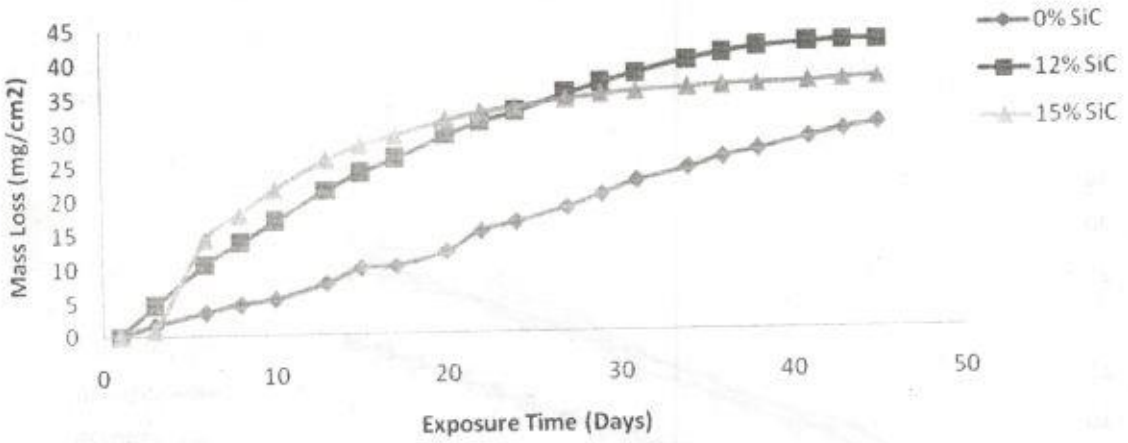
2(a)


Corrosion Rate (MPY)
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
Exposure Time (Days)
0 vol % sic
12 vol %sic
15 vol % sic

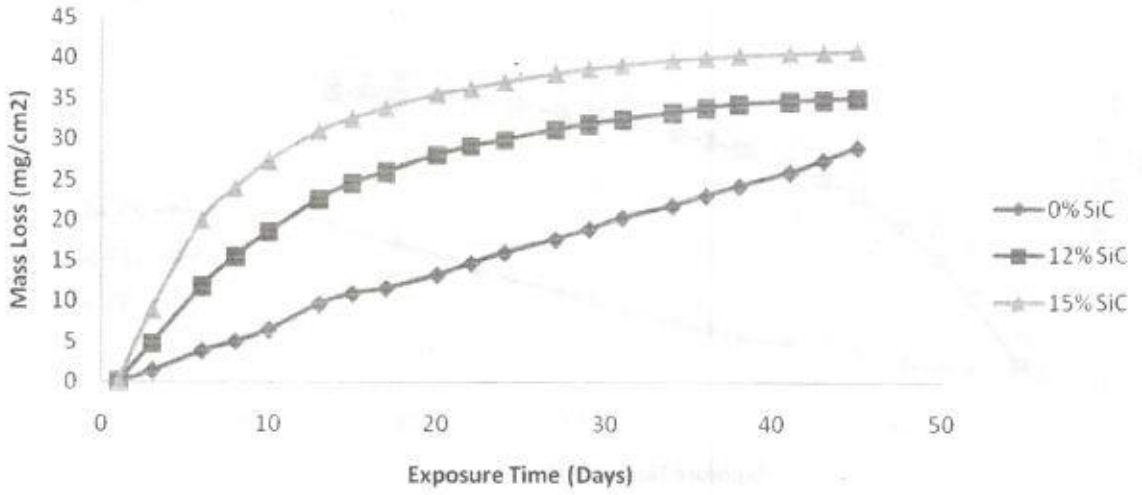
2(b)


Mass Loss (mg/cm2)
Exposure Time (Days)
0% SiC
12% SiC
15% SiC

2(c)

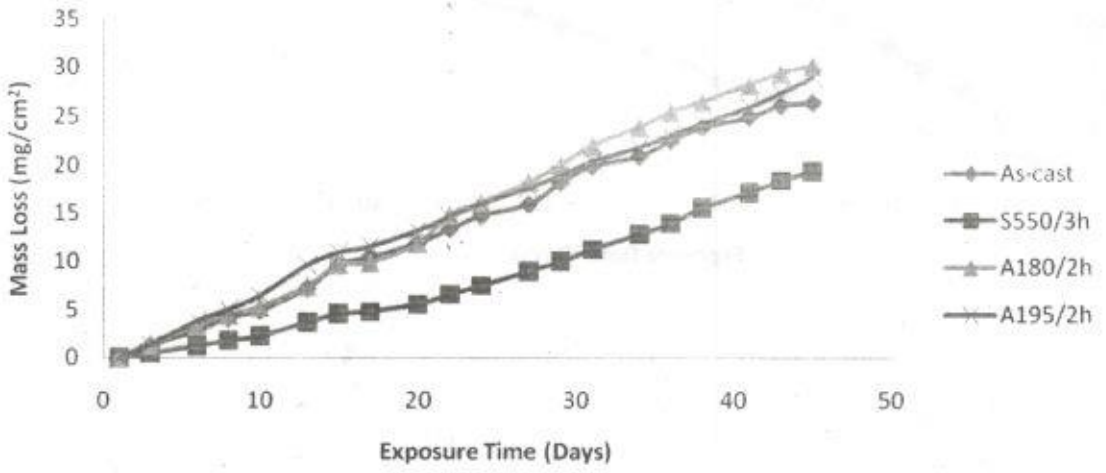

Mass Loss (mg/cm2)
Exposure Time (Days)
0% SiC
12% SiC
15% SiC

2(d)

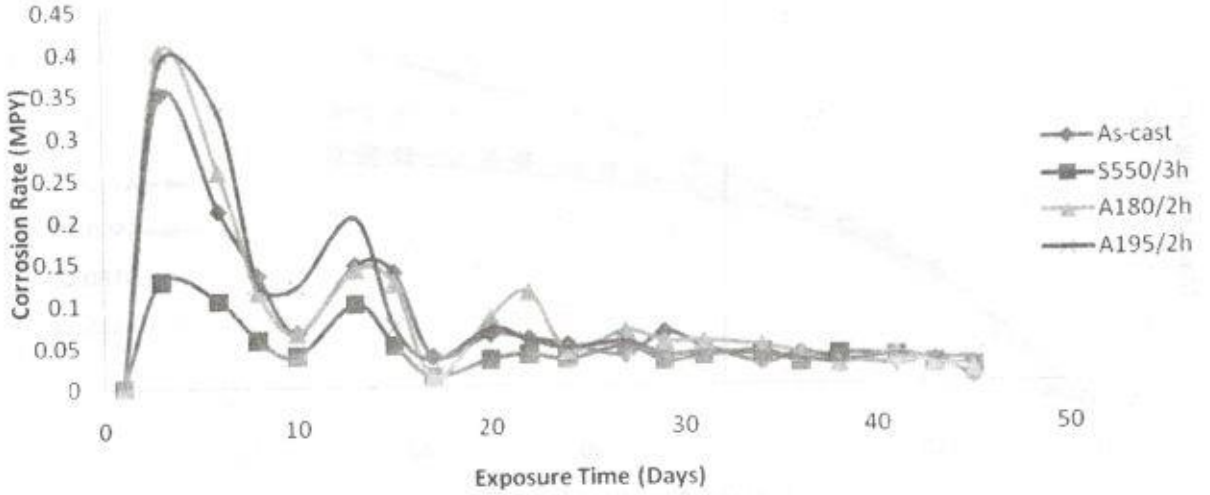



2(e)

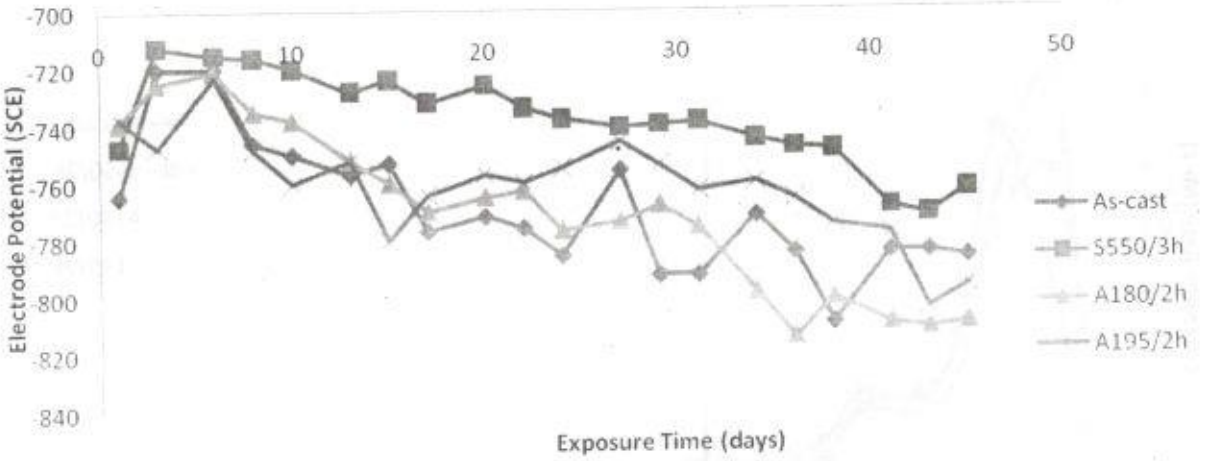
Figure 2. Immersion test results for unreinforced alloy and composites during the 45 days exposure in 0.2M HCl – $0.2MH_2SO_4$ solution: (a) Variation of mass loss for the as-cast temper, (b) variation of corrosion rate for the as-cast temper (c) variation of mass loss for the solutionized and water quenched temper, (d) variation of mass loss for the $180^0$C age hardened temper, and (e) variation of mass loss for the $195^0$C age hardened temper.




(a)

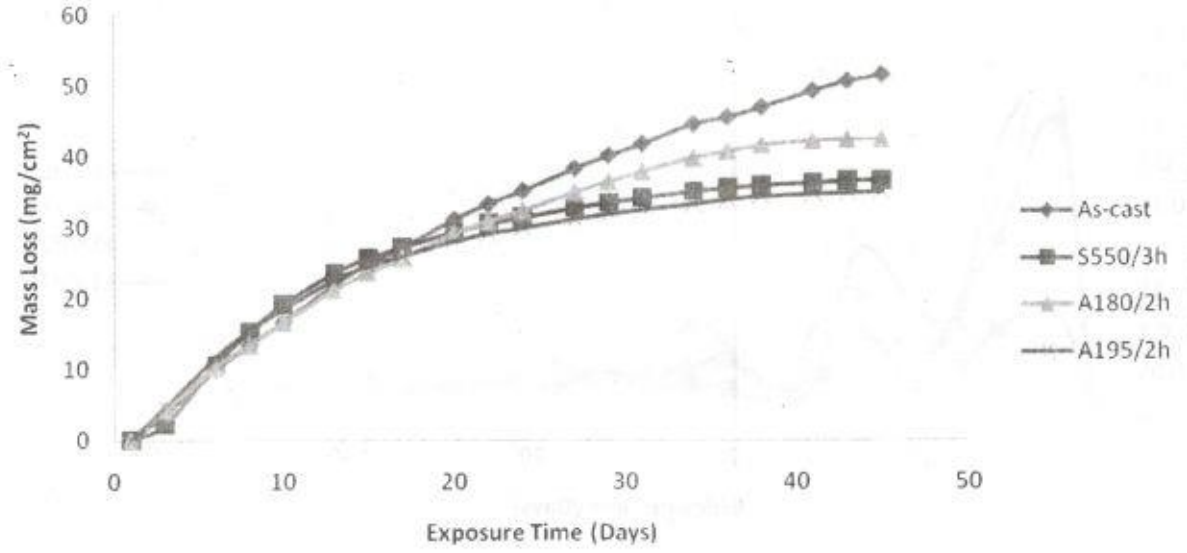



(b)




(c)

Figure 3. Influence of Temper condition on the corrosion behaviour of the unreinforced Al-6063 alloy (a) variation of mass loss for different temper conditions, (b) variation of corrosion rate for the different temper conditions, and (c) variation of electrode potential for the different temper conditions.



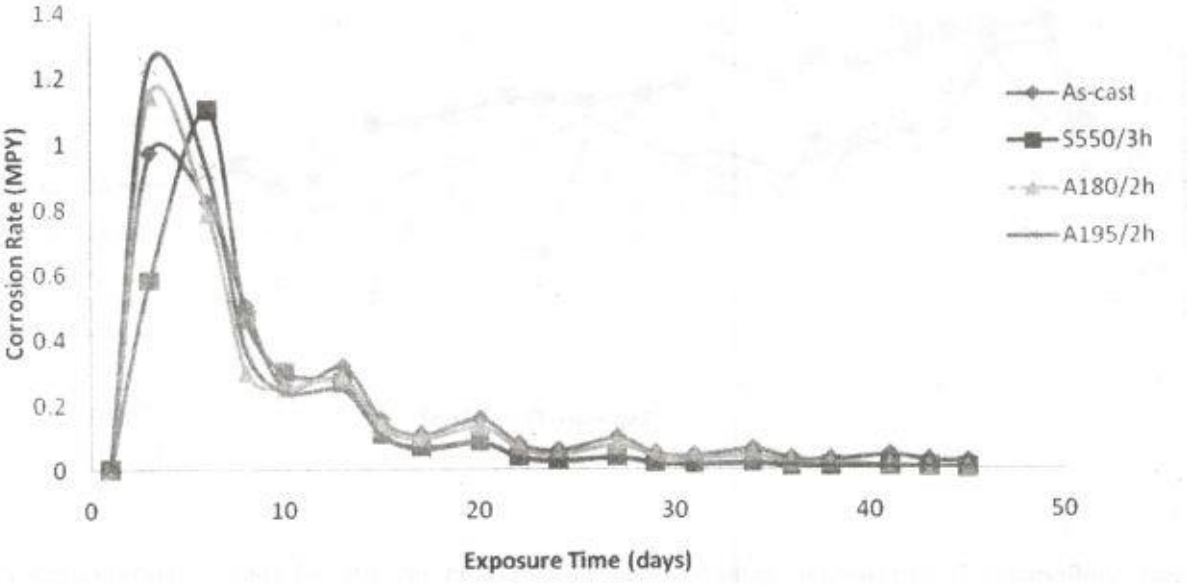




Figure 4. Influence of temper condition on the corrosion behaviour of the Al-6063/12vol.% $SiC_p$ composite (a) variation of mass loss for different temper conditions, and (b) variation of corrosion rate for the different temper conditions.

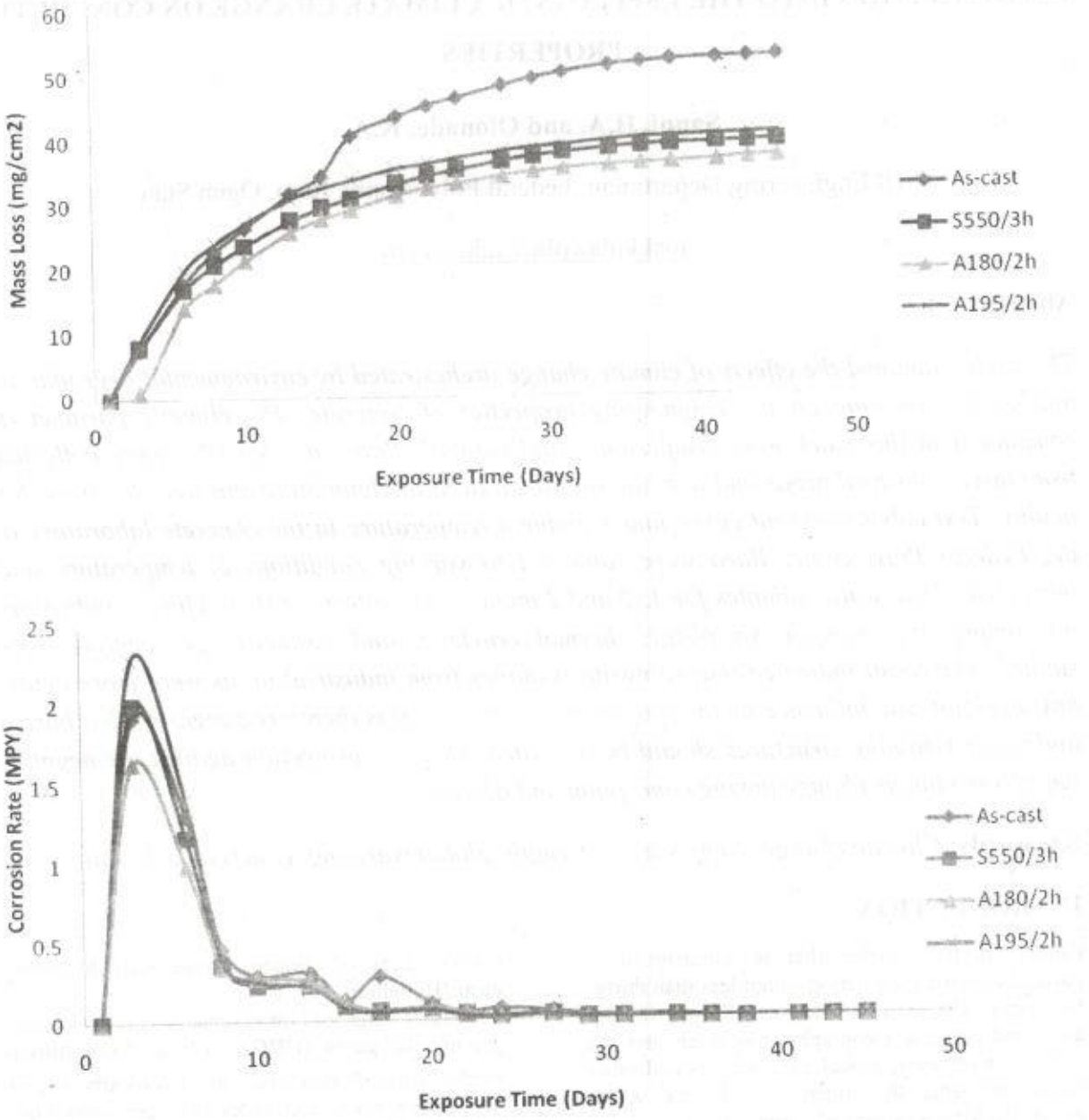



Figure 5. Variation of mass loss for the different temper conditions of the Al-6063/15vol.% $SiC_p$ composite