Mechanics and Mechanical Engineering
Vol. 21, No. 4 (2017) 833–841

Study of the Microstructure and Stress Corrosion Cracking (SCC) Resistance of Marine Grade Aluminium Matrix Composite

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Received (26 June 2017)
Revised (19 July 2017)
Accepted (2 August 2017)

The aim of this research was to develop marine grade aluminium (Al-3%Mg) matrix composite resistant to stress corrosion cracking (SCC). Silicon carbide particulate (SiCp) was used as reinforcement at 5% interval from 0- 25%. Sodium chloride (3.5% NaCl) was used as marine environment. The materials were developed through stir casting process. Slow stain rate testing (SSRT) machine was used for the study of the SCC in 3.5% NaCl. The XRF analysis conducted on the materials proved that the elements were within the scope. Microstructural analysis of the materials showed a clear evidence of dendritic formation of the alloy matrix coupled with the SiC_p reinforcement. SCC test showed that control sample A failed at a lower energy of 12.3KN with an extension of 0.7472 mm while Sample F recorded the highest value of energy up to 20 KN with an extension of 1.829 mm. The developed composite materials were found to be more reliable for use in marine environment than the existing marine grade alloy presently in use in most of the facilities in marine environment. It was learned that with little improvement on the existing marine grade Al alloy a lot of life and resources will be saved.

Keywords: stress corrosion cracking, composite material, microstructure, aluminium alloy, marine environment.

1. Introduction

The primary aim of studying the corrosion of materials is safety and economy. Failure of structures and operating equipments due to corrosion can result in human injury or even loss of life. The indirect costs resulting from actual or possible corrosion are more difficult to evaluate especially in developing nations. Cost of corrosion is estimated to be around \$300 billion in the US and around \$15 billion per annum in India. These figures were confirmed by various technical organizations, including the National Association of Corrosion Engineers (NACE) [1, 2]. Included in this estimate was corrosion attributed to various outdoor structures such as buildings, bridges, towers, automobiles, ships, and innumerable other applications exposed to the atmospheric environment. A lot of work has been done to reduce the failure but failures due to stress corrosion cracking (SCC) continue to occur in many industrial applications and marine structures. In most cases the personnel working in the plant are unaware of the measures that must be implemented to avoid SCC in service [3]. These concerns and studies have been responsible for the development of new alloys and many nonmetallic materials of construction [4].

When selecting a material of construction for a particular application, that material must have certain physical, mechanical, and corrosion-resistant properties. Cost is very important component in the selection process of engineering materials. Although many alloys may be available to meet the criteria of the specific application, the cost of these alloys may be prohibitive. As a result of this, many coating and lining materials have been developed that can be applied to less expensive materials of construction to supply the necessary corrosion protection. Carbon steels are mostly used in most engineering structures due to their cost advantage but their corrosion resistance is very weak [5]. Researchers have seriously focused their attention towards the development of reliable material for structural and industrial application to prevent loss of lives and property especially due to SCC.

Nowadays the slow strain rate test (SSRT) has become widely used and accepted for SCC evaluations to screen materials and to identify alloys that should not experience SCC in service. SSRT involves the slow straining of a specimen of the material of interest in a solution in which will be in service. Thus SSRT could be used to screen or evaluate materials in a fast way within a few days to determine SCC susceptibility. It is well known that the SSRT provides not only a useful information on SCC susceptibility of the materials in any corrosive environments, but also a relatively short experimental time to evaluate SCC susceptibility, where a maximum fracture time is that obtained at the lowest strain rate in an inert environment. For that reason, SSRT has been widely used for SCC assessment [6].

It was observed by [7] that a commonly used aluminium (Al) alloy in ship superstructures, AA5083-H116 is susceptible to sensitization from thermal exposure leading to beta-phase (Mg_2Al_3) precipitation. [8] also examined the effect of sensitization on the SCC behavior of marine grade Al alloys (Al-Mg) and [9] conducted a research to compare the stress corrodibility of the 5083 Al alloy with that of the new 5059 (Alustar) alloy, metal inert gas (MIG) and friction stir welding (FSW) welded.

Most researchers are focusing on improving the properties of the marine grade aluminium alloy (Al-Mg) to avoid failure in marine environment. This research in particular aimed at improving the mechanical properties and SCC resistance of Al-Mg in sea water by developing a marine grade composite material.

The research was a very critical one because as you are reinforcing the alloy for better mechanical properties, the SCC resistance must also be considered to avoid failure. The research will be very useful and beneficial for the shipping industry, naval facilities, offshore oil and gas facilities, etc.

2. Materials and methods

2.1. *Production of Al-3% Mg/SiC composites*

Stir casting process was used in the production of the alloy and composite materials. Al was melted at a temperature of about 660^0C in a crucible and mixed with up to 3% Mg by continuous stirring. The well stirred alloy was poured into a metallic mould for the production of the control sample A (Al-3% Mg alloy). The other part of the alloy was further heated up to about 800^0C and was allowed to remain above melting point to reduce surface tension while adding the preheated SiC_p particulates for proper wetting of the reinforcement. The composite material was thoroughly mixed with stirrer and then allowed to cool in a mould. The prepared SiC_p was used to produce sample B (5wt%SiC/Al-Mg alloy), sample C (10% SiC/Al-Mg alloy), sample D (15% SiC/Al-Mg alloy), sample E (20% SiC/Al-Mg alloy) and sample F (25% SiC/Al-Mg alloy) composites respectively.

2.1.1. *Characterization of the composite material*

The materials developed were fully investigated by studying its microstructure and the elemental analysis. Photographic Visual Metallurgical Microscope with rating 230V – 50/60 Hz) was used for the microstructural study while X-ray fluorescence (XRF) was used for the elemental analysis of the developed materials.

2.1.2. *Stress corrosion cracking (SCC) evaluation*

The SCC behaviors of the developed samples were investigated using LETRY SCC testing equipment. SSRT machine was used to study the susceptibility of the produced alloy and composite materials to SCC in 3.5% NaCl solution. The test samples were subjected to stress at low strain rate of 0.002 mm/min until it failed. The test coupons before and after experiment were as shown in Figs. 1a and 1b respectively.

3. Results and discussion

3.1. *Results*

Tab. 1 shows the elements present in each of the developed samples as obtained by (XRF) analysis. The quantity of Mg and Al present in all the samples were averagely within the scope of the research.

Figs. 2-7 displayed the microstructure of the materials developed for the research. The reaction of the Mg and the SiC_p was seen to increase across the plates as the dendrites increases.

Figure 1 a) Before SCC test, b) After SCC test

Table 1 XRF Analysis of the developed materials

Sample	Mg (wt %)	Al (wt %)	Other elements (wt %)
A(Al-3% Mg alloy)	2.55	95.30	2.15
B(5% SiC_p/Al-Mg alloy)	2.37	94.85	2.78
C(10% SiC_p/Al-Mg alloy)	2.34	94.86	2.80
D(15% SiC_p/Al-Mg alloy)	2.11	90.86	7.03
E(20% SiC_p/Al-Mg alloy)	2.31	95.07	2.62
F(25% SiC_p/Al-Mg alloy)	2.33	94.76	2.91

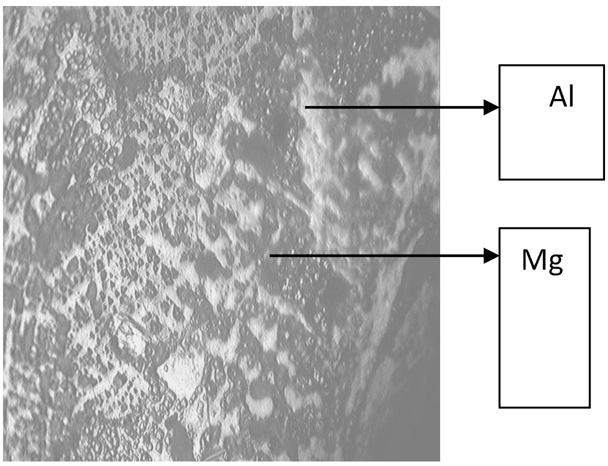

Figure 2 Microstructure of Sample A (Al-3%Mg alloy) ×200

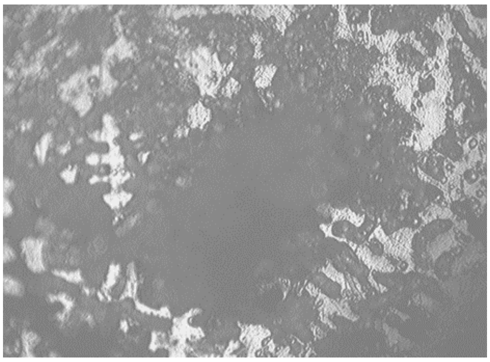

Figure 3 Microstructure of Sample B (5wt%SiC_p/Al-Mg alloy) ×200

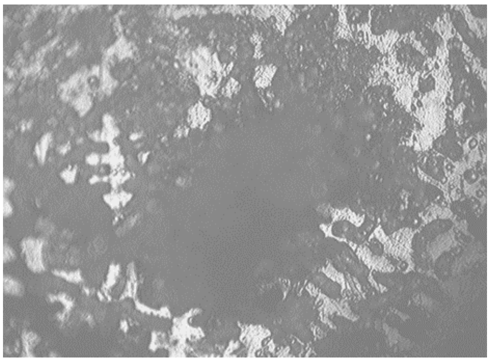

Figure 4 Microstructure of Sample C (10% SiC_p/Al-Mg alloy) ×200

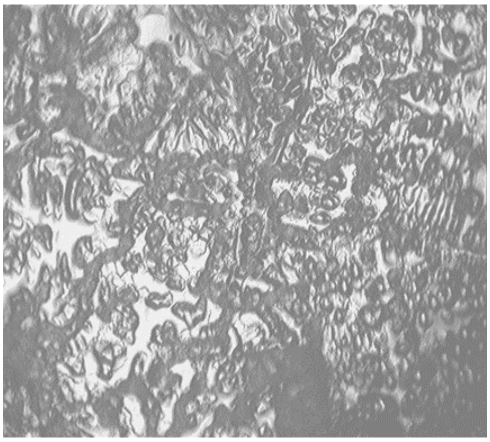

Figure 5 Microstructure of Sample D (15% SiC_p/Al-Mg alloy) ×200

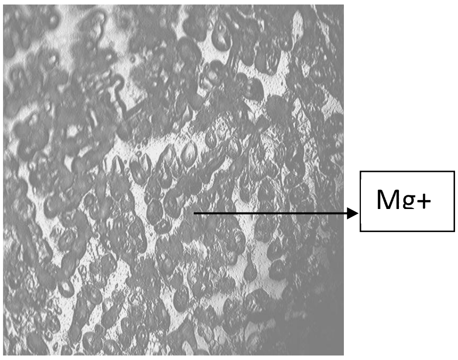

Figure 6 Microstructure of Sample E (20% SiC_p/Al-Mg alloy) ×200

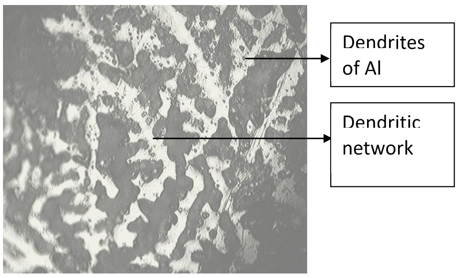

Figure 7 Microstructure of Sample F (25% SiC_p/Al-Mg alloy) ×200

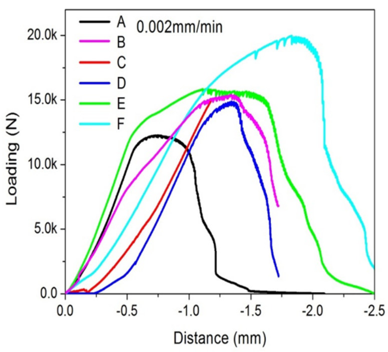

Figure 8 SCC results of the developed alloy and composite materials at constant strain

The SCC result of the materials developed was presented in Fig. 8. Test conditions used for the experiment are: speed-0.002 mm/min, 3.5% NaCl solution. A (Al-3% Mg alloy) is the alloy which is the control sample while samples B to F represent the developed composite materials based on the percentage of SiC_padded from 5-25%. Increase in the amount of SiCp resulted in higher values of strength and ductility.

3.2. *Discussions*

The XRF analysis of the materials presented in Table 1 has shown that the major elements are within the range proposed for the research having the quantity of Mg around 2-3%. Relatively high content of silicon was also observed due to the addition of SiC_pinto samples B (5wt% SiC_p/Al-Mg alloy), C (10% SiC_p/Al-Mg alloy), D (15% SiC_p/Al-Mg alloy), E (20% SiC_p/Al-Mg alloy), and F (25% SiC_p/Al-Mg alloy) compared to the control sample. The other traces of element present did not significantly affect the properties of the materials.

The microstructures of the developed composite material were presented in Figs. 2-7. The microstructure of sample A (Al-3% Mg alloy) gave a fair distribution of Mg (black) in α-Al (white) matrix as shown in Fig. 2. Introduction of SiC_pinto the matrix in sample B (5wt% SiC_p/Al-Mg alloy) produced Al (white) and Mg (black) with agglomerate SiC_p though not evenly distributed as seen in Fig. 3. The pattern of the microstructure for sample C (10% SiC_p/Al-Mg alloy), sample D (15% SiC_p/Al-Mg alloy), sample E (20% SiC_p/Al-Mg alloy) and sample F (25% SiC_p/Al-Mg alloy) presented in Figs. 4-7 were similar to that of sample B (5wt% SiC_p/Al-Mg alloy). Evidence of dendritic formation of the alloy matrix coupled with the SiC_p reinforcement is clearly visible in all the materials developed. More network of dendritic Al-3% Mg interface with the SiC_p and formation of pronounced particulate reinforcement agglomerate observed with increase in percentage of the $SiC_{p.}$It was also observed in Fig. 6, that the SiC_p itself was forming networks with the matrix that were disintegrated. The geometric arrangement of grains and phases in the material was fairly okay and no visible formation of weak phases or pores discovered which was in line with the findings of [10].

The result of the SCC test conducted on the materials in 3.5% NaCl at ambient temperature was as shown in Fig. 8. Sample A (Al-3% Mg alloy) was observed to fail at a lower energy of 12.3KN and at extension value of 0.7472 mm. The composite materials absorbed more energy compared to sample A (Al-3% Mg alloy) but sample C (10% SiC_p/Al-3% Mg alloy) failed without much extension. Sample F (25% SiC_p/Al-3% Mg alloy) recorded the highest value of tensile loading of 20 KN with an extension of 1.829 mm. The result showed that increase in percentage of the SiC_p improved the toughness of the materials by absorbing more energy before fracture. This could be due to unpredictable metallurgical condition of the materials in terms of their microstructure and the combined effect of the 3.5% NaCl solution and the applied stress. The macroscopic observation of the fractured surface shows a partially brittle feature and negligible reduction in diameter of the failed samples. Due to complex nature of such experiment it is also advisable to quote the composition and history of the material as fully as possible for SCC results to be valid as advised by many researchers including [11, 12].

4. Conclusions

This work was able to explore the importance of using Al metal matrix composite for corrosive environments compared to the marine grade alloy presently in use. With all the valuable research work conducted so far in the field, it was clear evidence that Al alloys especially the Al-Mg (5000 series) played a pivotal role in the development of composite materials reinforced with $SiC_p$for use inmarine environment. It turned out that alloy composition influenced the processing route to be employed as well as the mechanical, physical and corrosion behavior of the composites. SiC_p has attracted much attention because it has a good match of chemical, mechanical and thermal properties for application in harsh environment. To obtain high-performance SiC_p ceramics, fine powder distribution as well as high purity is required. The developed composite materials and alloy were characterized and arrived at such results:

1. Al-Mg alloy and its composites reinforced with SiC_p(5-25%) were developed through stir casting process because it is readily available and cost effective.

2. The materials were physically and chemically tested and confirmed to be within the scope. The XRF and microstructural analysis showed that the quantity of Mg is within 2-3% and the structure was well developed.

3. Evidence of dendritic formation of the alloy matrix coupled with the SiC_p reinforcement is clearly visible in all the materials developed.

4. The result of the SCC test conducted on the materials in 3.5% NaCl at ambient temperature shows that Sample A (Al-3%Mg alloy) failed at a lower energy and extension values compared to the developed composite materials.

5. It was finally concluded that increase in percentage of SiC_p improves its resistance to SCC under the test condition and procedures followed in the research.

References

[1] **Schweitzer, P. A.**: Fundamentals of corrosion-mechanisms, causes, and preventative methods, *CRC Press, Taylor & Francis Group*, New York, **2010**.

[2] **Popoola, A., Olorunniwo, O. E, and Ige, O. O.**: Corrosion resistance through the application of anti-corrosion coating, in: ed. M. Aliofkhazraei, Developments in Corrosion Protection, *InTech*, **2014,** 241-270. DOI: 10.5772/57420.

[3] **Lobley, G. R.**: Stress corrosion cracking: case studies in refinery equipment, *The 6th Saudi Engineering Conference*, KFUPM, Dhahran, 5, 17-26, **2002**.

[4] **Muazu, A., Yaro, S. A. and Abdulwahab M.**: Sacrificial anode stability and polarization potential variation in a ternary Al-xZn-xMg alloy in a seawater-marine environment. *Journal of Marine Science and Application*, 2, 20, 8-213, DOI: 10.1007/s11804-016-1356-8, **2016**.

[5] **Julka, S., Ansari, M. I. and Thakur, D. G.**: Effect of pH on mechanical, physical and tribological properties of electroless Ni-P-Al_2O_3 composite deposits for marine applications. *Journal of Marine Science and Application*, 4, 484-492, DOI: 10.1007/s11804-016-1385-3, **2016**.

[6] **Conteras, A., Salazar, M., Albiter, A., Galvan, R. and Vega, O.**: Assessment of stress corrosion cracking on pipeline steels weldments used in the petroleum industry by slow strain rate tests, in: ed. W. Sudnik, Arc Welding,*In-Tech*, 127-150, DOI: 10.5772/26569, **2011**.

[7] **Brandenburg, K. A., Hornbach, D. J. and Mason, P.W.**: Use of engineered compressive residual stresses to mitigate stress corrosion cracking and corrosion fatigue in sensitized 5XXX series aluminum alloys, *Proceedings of Department of Defense Virtual Corrosion Conference Pretreatments*, Cincinnati, **2013**.

[8] **Cormack, E. C.**: *The effect of Sensitization on the stress corrosion cracking of aluminum alloy 5456.* Master's Thesis, Naval Post Graduate School Monterey, CA 93943-5000, **2012**.

[9] **Czechowski, M.**: Slow-strain-rate stress corrosion testing of welded joints of Al-Mg alloys. *Journal of Achievements in Materials and Manufacturing Engineering,* 20, 1–2, **2007**.

[10] **Poovazhagan, L., Kalaichelvan, K., Rajadurai, A. and Senthilvelan, V.**: Characterization of hybrid silicon carbide and boron carbide nanoparticles-reinforced aluminum alloy composites, *International Conference on Design and Manufacturing, IConDM 2013, Procedia Engineering,* 64, 681–689. DOI:10.1016/j.proeng.2013.09.143, **2013**.

[11] **Campbell, H. S.**: Metallurgical factors, in: ed. W. H. Ailor, Handbook on Corrosion Testing and Evaluation, *John Wiley and sons, Inc.*, New York, 5–30, **1971**.

[12] **Kumar, R. S., Kondaiah, G., Venkatachalam, P. and Ravisankar, B.**: Stress corrosion cracking of Al7075 alloy processed by equal channel angular pressing, *International Journal of Engineering, Science and Technology,* 2, 12, 53–61, **2010**.