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Research Article

Investigation of Corrosion Fatigue Crack Growth in Aluminium Alloy-Based Metal Matrix Composites: A Comparative Study

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ABSTRACT

The need for high-strength alloys that can withstand the harsh conditions of saline environments is a common challenge in engineering applications. These materials must maintain their structural integrity under corrosive conditions. Corrosion fatigue of aluminium-based composites is an important consideration in the design and use of these materials, as it can significantly reduce the strength and service life of the composite. Corrosion fatigue occurs when a material is repeatedly exposed to a corrosive environment and cyclic loading, leading to the formation of cracks and eventual failure. The susceptibility of aluminium-based composites to corrosion fatigue depends on several factors, including the type and amount of reinforcement used, the composition of the matrix and the specific corrosive environment. It is therefore important that these factors are carefully considered and appropriate testing carried out to ensure the longevity and reliability of the composite in its intended application. In this study, fatigue crack growth tests were carried out at four different stress ratios on 2124-T4 +25% SiCp/Al composites at room temperature and in a 3.5% salt solution environment. It was found that the influence of the salt solution at low stress ratios was significant on the fatigue crack growth rates. However, the effect of the saline environment on the fatigue response diminished at high stress ratios.

Keywords: *Corrosion fatigue, fatigue crack propagation, Al-alloy composites, salt solution, hydrogen embrittlement*

Alüminyum Alaşımlı Metal Matris Kompozitlerde Korozyon Yorulma Çatlak Büyümesinin İncelenmesi: Karşılaştırmalı Bir Çalışma

ÖZ

Tuzlu ortamların zorlu koşullarına dayanabilecek yüksek mukavemetli alaşımlara duyulan ihtiyaç, mühendislik uygulamalarında yaygın bir zorluktur. Bu malzemeler korozif koşullar altında yapısal bütünlüklerini korumalıdır. Alüminyum bazlı kompozitlerin korozyon yorgunluğu, kompozitin mukavemetini ve hizmet ömrünü önemli ölçüde azaltabileceğinden, bu malzemelerin tasarımında ve kullanımında önemli bir husustur. Korozyon yorgunluğu, bir malzeme tekrar tekrar korozif bir ortama ve döngüsel yüklemeye maruz kaldığında ortaya çıkar ve çatlak oluşumuna ve nihayetinde malzemenin hasar görmesine yol açar. Alüminyum bazlı kompozitlerin korozyon yorgunluğuna karşı duyarlılığı, kullanılan takviye tipi ve miktarı, matrisin bileşimi ve spesifik aşındırıcı ortam gibi çeşitli faktörlere bağlıdır. Bu nedenle, kompozitin amaçlanan uygulamada uzun ömürlü ve güvenilir olmasını sağlamak için bu faktörlerin dikkatlice değerlendirilmesi ve uygun testlerin yapılması önemlidir. Bu çalışmada,

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2124-T4 +%25 SiCp/Al kompozitler üzerinde oda sıcaklığında ve %3.5 tuz çözeltisi ortamında dört farklı gerilme oranında yorulma çatlağı büyüme testleri gerçekleştirilmiştir. Düşük gerilme oranlarında tuz çözeltisinin etkisinin yorulma çatlak büyüme oranları üzerinde önemli olduğu bulunmuştur. Bununla birlikte, tuzlu ortamın yorulma tepkisi üzerindeki etkisi yüksek gerilme oranlarında azalmıştır.

Anahtar Kelimeler: *Korozyon yorulması, yorulma çatlak ilerlemesi, Al-alaşım kompozitler, tuz çözeltisi, hidrojen gevrekleşmesi*

I. INTRODUCTION

The exceptional properties of high strength-to-weight ratio, good wear resistance, fatigue resistance and toughness make aluminium-based metal matrix composites a popular choice for advanced engineering applications [1]. In particular, 2124 aluminium alloy is a heat treatable alloy that belongs to the 2000 series of aluminium alloys. It consists mainly of aluminium, copper and magnesium. This alloy is known for its strength and durability, making it a popular choice for aerospace and aircraft applications, as well as highly stressed structural components. Aluminium alloy 2124 is also widely used in automotive and marine applications and in the manufacture of high strength aluminium products such as armour plate and pressure vessels. The high strength-to-weight ratio of the alloy makes it a good choice for applications where weight reduction is a priority. In the petroleum industry, corrosion fatigue is a particular concern for equipment used in the production, transportation and storage of crude oil and natural gas. This equipment is often exposed to harsh environments such as salt water or high temperatures, which can accelerate the corrosion fatigue process. In addition, the fluids used in the petroleum industry are often highly corrosive, which can exacerbate the problem. Mitigating corrosion fatigue is important to ensure the safety and reliability of equipment used in the petroleum industry and to prevent unplanned downtime and costly equipment failures. The addition of particles to aluminium alloys has shown significant improvements in both tensile and fatigue properties. This is particularly evident when the alloys are produced using a powder metallurgical process optimised to achieve uniform particle distribution, refined matrix microstructure and minimal matrix strengthening reaction [2].
Corrosion fatigue is a phenomenon that occurs when a material experiences a combination of corrosion and cyclic loading, such as bending or twisting. This can lead to premature failure of the material, even at loads that would not cause failure through the tensile stress alone. The corrosion fatigue process begins with the formation of small cracks on the surface of the material, which grow over time due to the combined effects of corrosion and cyclic loading. Earlier studies have suggested that fatigue cracks tend to initiate earlier and propagate at a faster rate in corrosive environments compared to those in air. This phenomenon can result in premature failure of metallic materials [3]. To address this issue, engineers and scientists in the various industry use a variety of techniques to evaluate the susceptibility of equipment to corrosion fatigue, and to design equipment that is more resistant to this phenomenon. These techniques include laboratory testing, computer simulations, and field testing of equipment in simulated or actual service environments. Additionally, corrosion inhibitors, corrosion protection coatings and coatings with corrosion resistant alloys are used to reduce the material degradation by corrosion [4]. In our previous works, the effects of stress ratio, particle sizes, notch behaviour and volume fraction of particulate SiC (SiCp)/Al composites on fatigue lives have been studied in detail [5], [6]. The fatigue lives and ductility of the materials corresponded to the strain or stress ratios. Also microstructural observations showed that the density and length of slip bands increased with the increasing strain or stress ratio at the given strain or stress amplitude, and so did the volume fraction and size of coarse constituents or particles, which were responsible for the reduction of fatigue life and ductility of the material [7], [8]. Although there is a significant amount of literature on the fatigue properties of 2000 series aluminum alloys, the impact of stress ratio on the growth rates of corrosion fatigue cracks (FCGR) has not been extensively explored. Therefore, this study aims to investigate the FCGR of 2124-T4 +25% SiCp /Al composites under four different stress ratios in both room temperature and a 3.5% salt solution environment. The primary objective of this research is to provide a more

comprehensive understanding of the corrosion fatigue behavior of 2124-T4 +25% SiCp /Al composite and to demonstrate how stress ratios affect it.

The fatigue life and ductility of the materials corresponded to the strain or stress ratios. Microstructural observations also showed that the density and length of slip bands increased with increasing strain or stress ratio at a given strain or stress amplitude, as did the volume fraction and size of coarse constituents or particles, which were responsible for the reduction in fatigue life and ductility of the material [7], [8]. Although there is a considerable amount of literature on the fatigue properties of 2000 series aluminium alloys, the effect of stress ratio on corrosion fatigue crack growth rates (FCGR) has not been extensively investigated. Therefore, this study aims to investigate the FCGR of 2124-T4 +25% SiCp /Al composites under four different stress ratios both at room temperature and in a 3.5% salt solution environment. The primary objective of this research is to provide a more comprehensive understanding of the corrosion fatigue behaviour of 2124-T4 +25% SiCp /Al composite and to demonstrate how stress ratios affect it.

II. MATERIAL AND METHOD

The materials were 2124 (Al-Cu-Mg-Mn) Al alloys with 25 vol% SiCp MMCs. All materials were manufactured by Aerospace Composite Materials (UK) and were designated as AMC225 (25 vol% 2-3 μm SiCp). Prior to machining, solution annealing was carried out at 505 oC for 1 hour, followed by cold water quenching and then natural ageing (T4) at room temperature. The alloy composition, particle size determination and distribution, and tensile response of these composites have been extensively investigated and discussed elsewhere [9]. For the evaluation of fatigue crack propagation, a 5x5 mm 'corner crack' (CC) specimen was adopted. A crack was initiated from a 0.25 mm deep edge slit. Pulsed direct current potential drop (DCPD) systems were used to monitor crack growth. At pre-determined stages of the test, a constant DC power supply delivered a 50A, two pulse to the specimen for 2 s while the fatigue cycles were held at 75% of the peak load.

During this period, the potential drop across the crack was measured. The potential drop data were converted to length and the FCGR was evaluated as a function of the applied stress intensity range ΔK [10]. The effects of cyclic frequency (55Hz), stress (R) ratios R=0.1, R=0.3, R=0.5 and R=0.9 and 1 Hz sinusoidal waveform were applied to all specimens. All tests were performed under constant amplitude load control test conditions using the Ampsler Vibraphore testing machine. All tests were carried out in air and 3.5% saline solution. A typical specimen and the DCPD wires are shown in Figure 1. The fracture surfaces of the specimens were observed in a Jeol 35c SEM to determine the dominant fracture modes and to characterize the fine scale topography of the fatigue fracture surfaces.

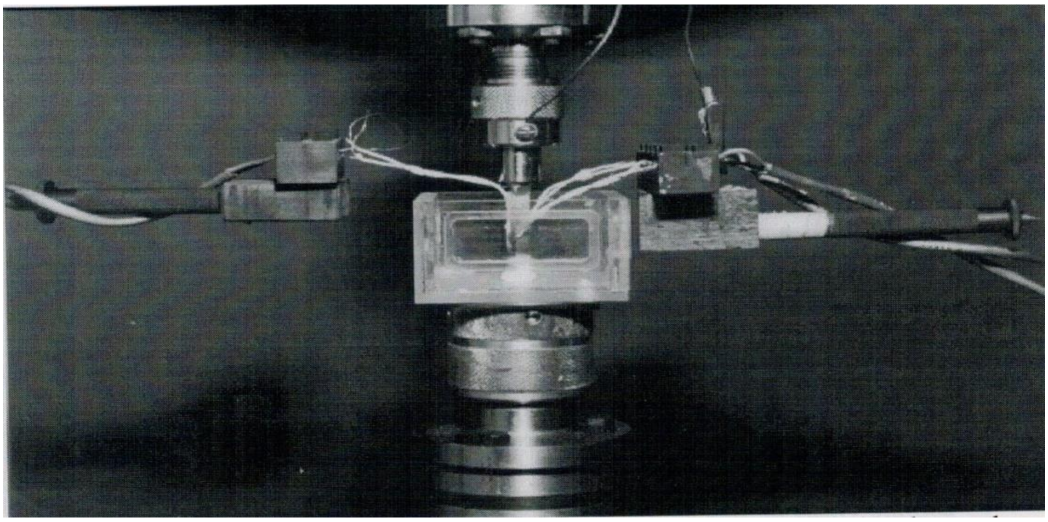

Figure 1. *Vibraphore tester with salt solution environmental chamber and AC PD wire connection*

III. RESULTS AND DISCUSSION

Comparisons of crack growth rates in air and salt solution environments at various R-ratios are shown in Figure 2-4 for the MMC material AMC225. It is clear that there is a strong environmental enhancement of the crack growth rates. In particular, the FCGR increased by a factor of 4 in the aggressive environment at R=0.1 (see Figure 2). However, the effect of the hostile environment on crack growth rates decreased as the R ratio increased (see Fig. 3 and Fig. 4). The effect of the saline solution on the FCGR is shown in Figure 5 for the AMC200 base alloy. For an equivalent ΔK, the FCGR increased rapidly in salt solution compared to air. However, unlike the MMC, there is no reduction in the FCGR of the base material as the R ratio increases. It can be said that as ΔK values and general growth rates increase, the effect of the environment on FCGR decreases due to the dominant role of static fracture modes and the relatively reduced time available for any interaction to occur.
Figure 6 summarizes the effects of environment on crack growth for AMC225 MMC material in terms of crack length versus cycles. It can clearly be seen that the life to failure is 5 times longer in air than in the 3.5% salt solution environment at R=0.1. However, the difference between the two environments decreased as the R ratio in salt solution increased. For example, at R=0.9, the life differences between air and saline environments were only 17%. The largest effect of the environment was observed at R=0.1 for AMC225. It is well known that corrosion fatigue is a time-dependent phenomenon. The acceleration of FCGR and the reduction of the threshold stress intensity range ΔKth in salt solution have been reported previously for Al alloys [10]-[12].

Three main mechanisms have been proposed to explain the detrimental effects of the environment on fatigue in Al-alloys [13]. i. electrochemical dissolution of film rupture, ii. crack surface film effect and iii. hydrogen embrittlement (HE). Based on the circumstantial evidence, HE is often cited as the primary damage mechanism for environmental fatigue crack propagation [14]. The presence of hydrogen in the metal lattice is thought to increase dislocation mobility at low stress levels. This results in a loss of ductility and tensile strength. Consequently, hydrogen induced embrittlement is associated with very high crack velocity in the hostile environment. At the frequencies provided by the Vibrophore test facility, most of the corrosion fatigue tests in this study lasted only 3 to 6 hours (see Figure 6). This is unlikely to be sufficient time for the alternative electrochemical dissolution and surface film cracking (O2 related) process to act as a controlling mechanism. However, H2 is extremely mobile and can act quickly by influencing dislocation motion. Therefore, HE is likely to be the dominant mechanism during the present study.

The effect of salt solution on FCGR is generally attributed to the HE mechanism in a wide range of materials including Al alloys [14], [15]. For Al-alloy MMC in an aggressive environment, corrosion fatigue models developed to describe crack growth should address the following factors: i: microstructural properties (grain size, volume fraction, particle size), ii: stress-strain behaviour [6]-[8], iii: fracture toughness, iv: the effect of O_2, H_2 and Cl^- on FCGR in an aggressive environment [2] and v: dislocation kinetics in composites.

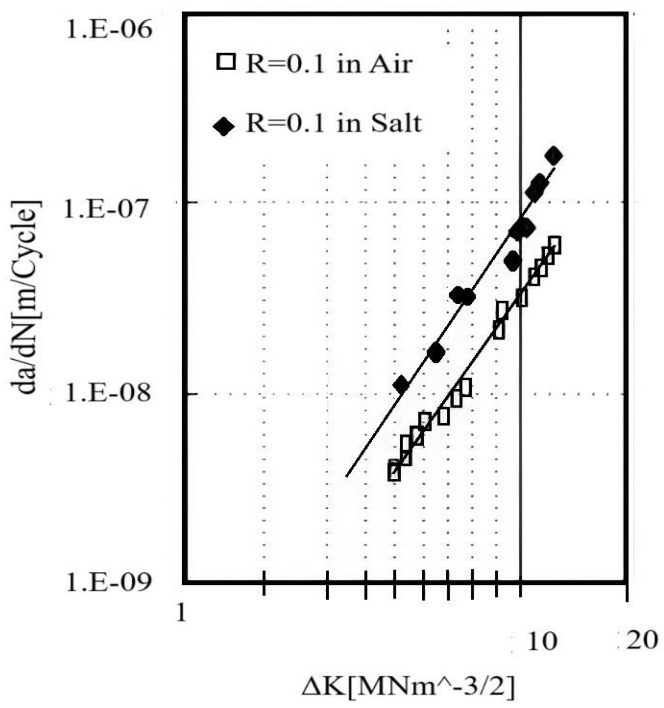

Figure 2. *The effect of 3.5% NaCl solution on the FCGR at R=0.1 for AMC225-T4*

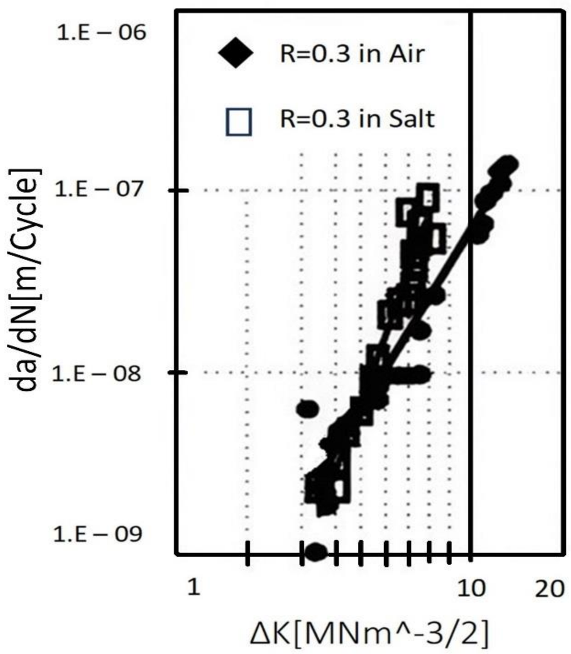

Figure 3. *The effect of 3.5% NaCl solution on the FCGR at R=0.3 for AMC225-T4*

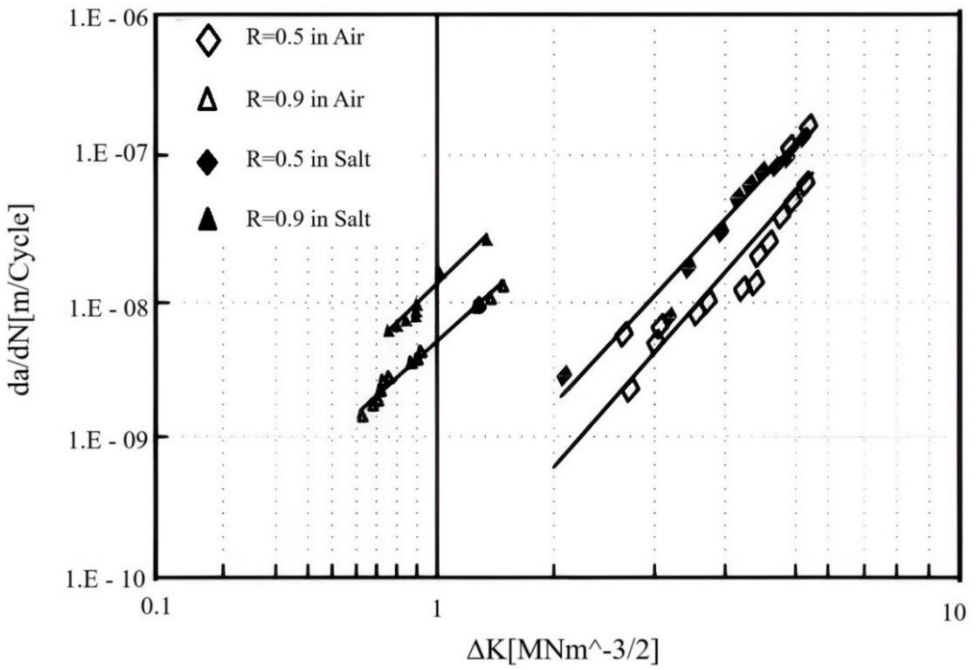

Figure 4. *The effect of 3.5% NaCl solution on the FCGR at R=0.5 and R=0.9 for AMC225-T4*

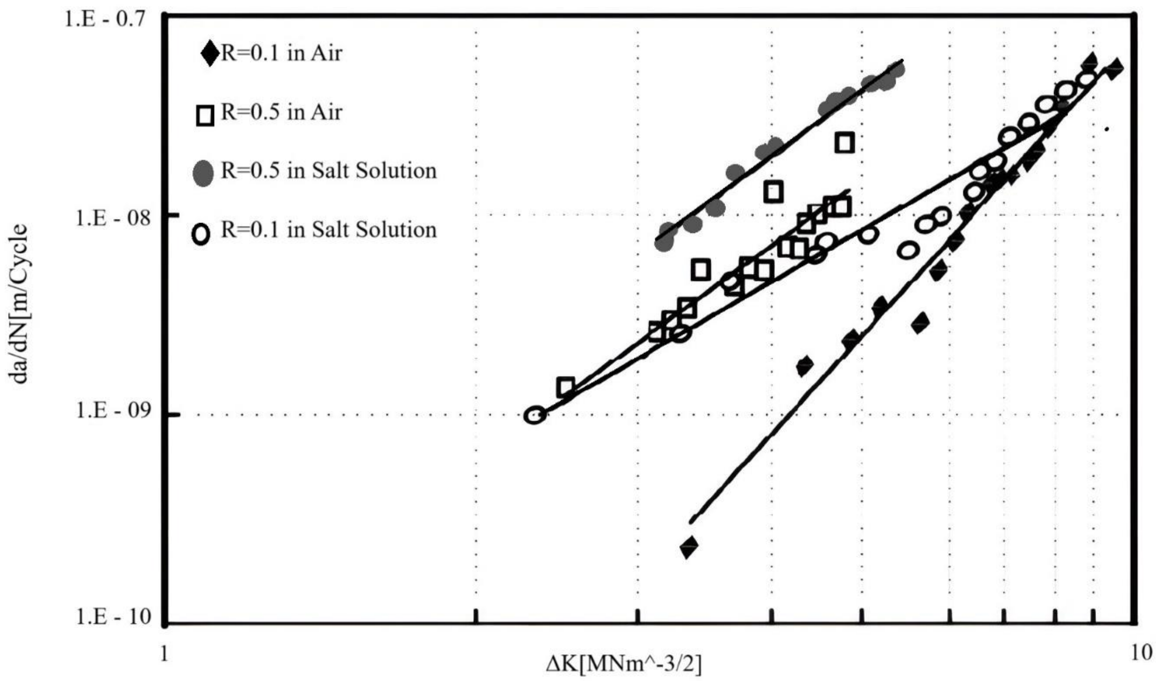

Figure 5. *The effect of 3.5% NaCl solution on the FCGR at R=0.1 and R=0.5 for AMC225-T4 for AMC200-T4 unreinforced base material at a maximum applied stress of 150 Mpa*

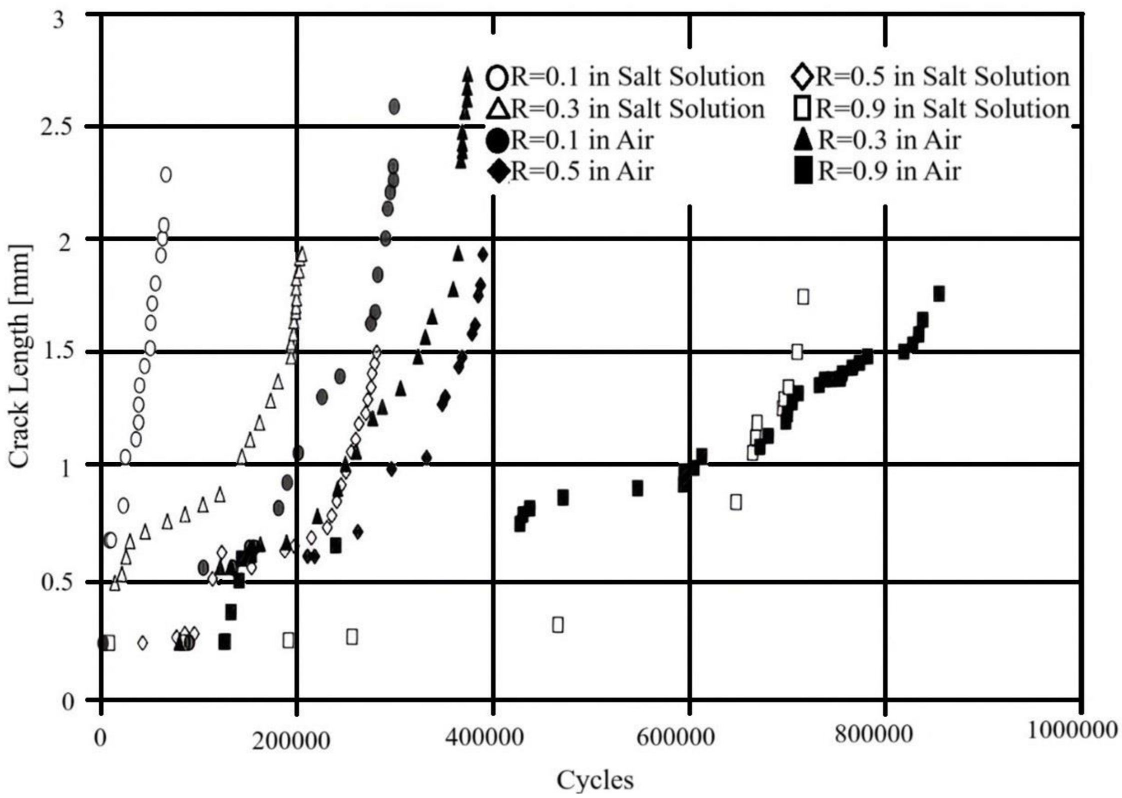

Figure 6. *The effect of environments on crack length of AMC225-T4 MMC material with various stress ratios*

The fracture behaviour of the specimens was investigated using the SEM. The specimens examined were tested at the same stress level (150 MPa). The fracture behaviour of all materials is compared in Figures 7 to 9 at magnifications of 17x and 3500x. In the composite material the crack was perpendicular to the applied tensile stress. All composite samples failed in a similar manner in air or salt solution and at the various stress ratios. It can be seen that the crack started from a 0.5 mm slit and grew in a quarter circular fashion to a length of 5 mm2 when fast fracture occurred in air (see Fig.8.a). A typical high magnification SEM image of the composite is shown in Fig.8.b. At the low ΔK values, the fracture surfaces were featureless and very flat. However, at stress intensities of 6MPa√m the appearance of the fracture surface changed (see Fig.8.b). The fracture surface was quite rough with many peaks and valleys. Extensive deformation was observed around the SiC particles. The SiCp were associated with large ductile pits and the Cu2 Mn3 Al20 precipitate particles with small pits. Typical SEM images of the composite in a salt solution environment are shown in Figure 9.a and b.

Comparison with room temperature fracture surfaces showed that there was no major difference in fracture mode and crack growth mechanism. However, typical differences in fracture surface appearance were observed; i: the semicircular slow crack growth region was 2 mm2 in salt solution, which is significantly smaller than in air (5 mm2), ii: corrosion products occurred on the fracture surface. EDX analysis of the dark areas showed that these were composed mainly of Cl and Na residues. iii: Crack growth fracture surfaces were rougher than in air (see Fig.8.b and Fig.9.b). iv: Many individual microcracks were observed in the stage II growth region in salt solution. v: Fracture particles were more prominent in salt solution than in air. The alloys investigated exhibited brittle fracture behaviour in both environments, as evidenced by the presence of cleavage facets and quasi-cleavage areas on the fracture surfaces. However, the more hostile environment resulted in a flatter fracture surface, enhanced particle interface cleavage and particle cracking, and promoted corrosion pits on the fracture surface (Figure 9.b). In general, in saline environments, freely initiated corrosion fatigue cracks often originated from pits caused by exposure to the hostile environment [16], [17].

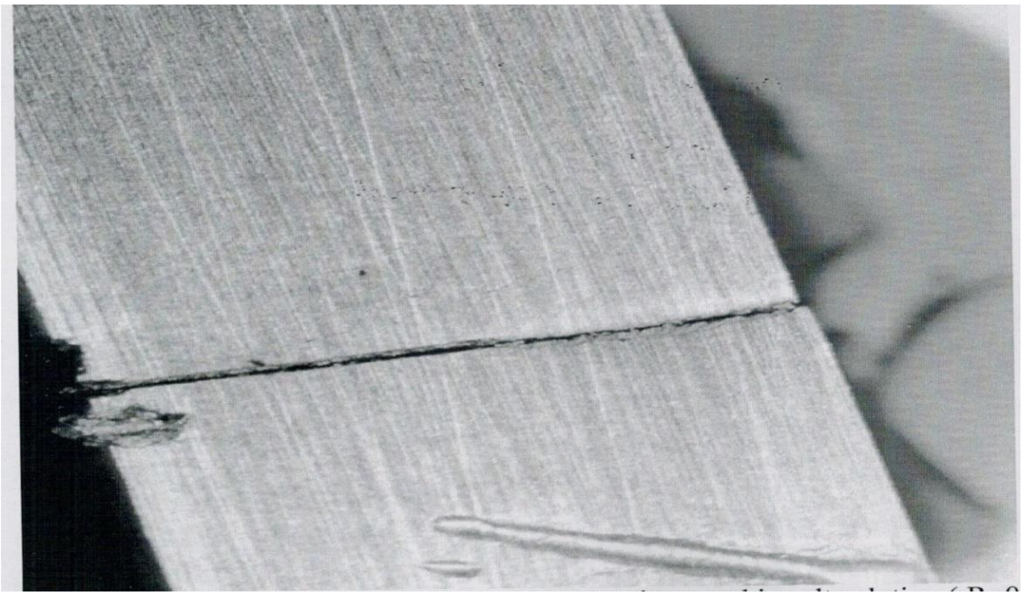

Figure 7. *Fatigue crack path of AMC 225 composite tested in salt solution (R=0.5, σmax = 175 MPa, Nf =265000cycles)*

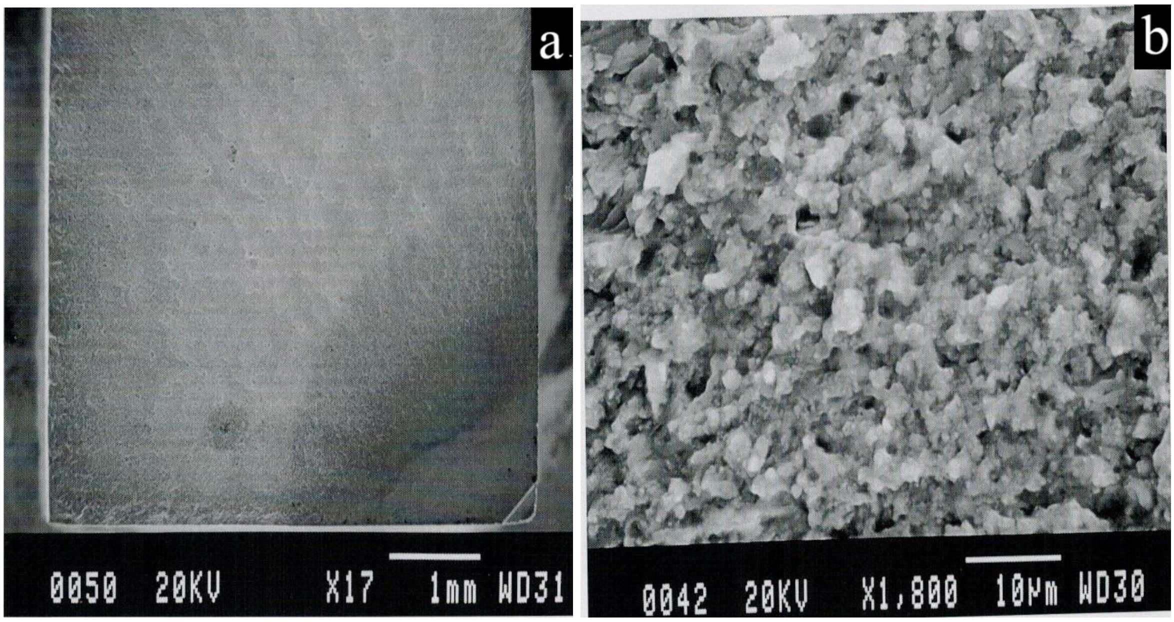

Figure 8. a) *Fracture surface of AMC225 in air* ***b)*** *Fracture surface of the same MMC in the overload region. The fatigue crack has propagated from left to right*

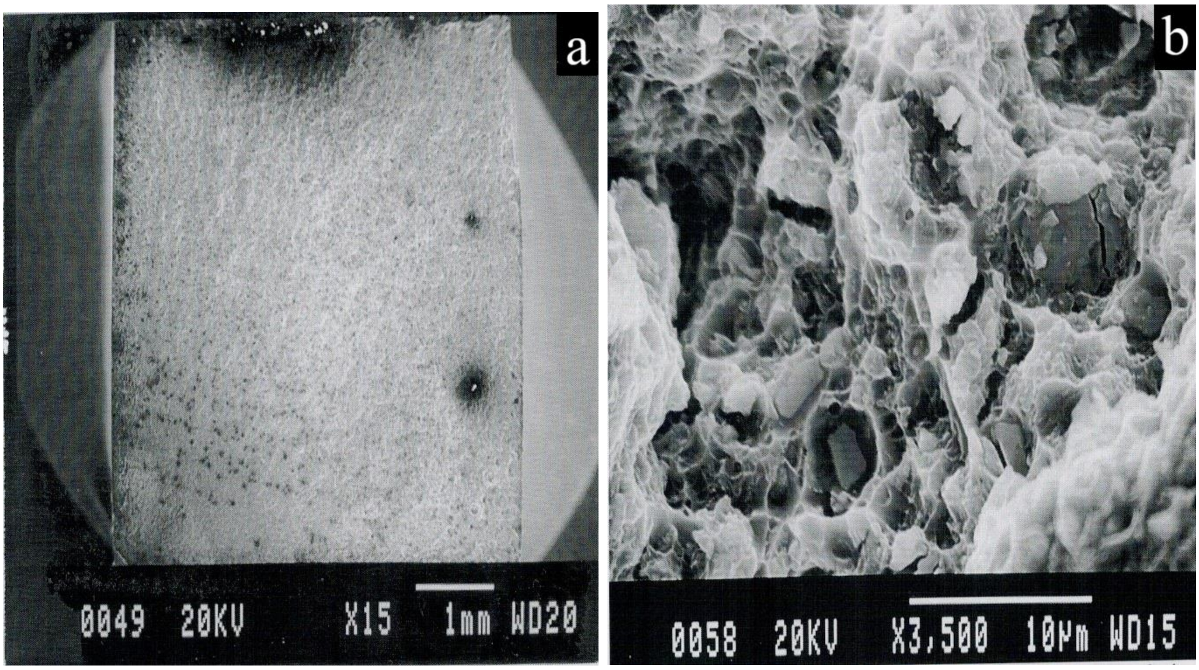

Figure 9. a) *Fracture surface of AMC 225 in salt solution* ***b)*** *Fracture surface of the same MMC in the overload region. The crack propagates from left to right*

IV. CONCLUSION

This study investigated the influence of an aggressive environment on the fatigue crack propagation rates of 2124/SiCp composites under naturally aged (T4) conditions. The main conclusions can be summarised as follows:

1. The influence of the salt solution was significant at low stress ratios on the fatigue crack growth behavior of AMC225 MMC and the unreinforced alloy AMC200. However, the effect of the saline environment on the fatigue crack growth rate (FCGR) decreased at higher stress ratios.
2. The AMC225 composite exhibited superior crack growth resistance at high stress ratios in both air and saline environments. In particular, the FCGR increased by a factor of 4 in the aggressive environment at R=0.1. Unlike the MMC, the FCGR of the AMC200 base material did not decrease with increasing R-ratios.
3. Hydrogen embrittlement is likely to be the dominant mechanism contributing to crack growth in the aggressive environment.
4. The fracture behavior of the AMC225 composite was brittle, showing features such as cleavage facets and quasi-cleavage areas on the fracture surfaces in both environments. The more hostile environment resulted in a flatter fracture surface, increased particle-interface cleavage and particle cracking, and promoted corrosion pits at the fracture sites.
5. Future research should explore the fatigue crack growth behavior of these composites under different environmental conditions, such as high temperatures or exposure to various corrosive agents.

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