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Investigation of the fatigue crack propagation behaviour in the Al alloy/Hybrid MMC Bi-layer material

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Abstract. In this study, the fatigue crack propagation behaviour in the Al alloy-hybrid MMC bi-material system has been investigated. Three-point bending fatigue test is carried out on the Shimadzu servopulser machine. The plastic replica technique is used to observe the crack growth during cyclic loading. The crack growth rate is analyzed at different stress intensity factor range, ΔK. The experimental results showed that the crack growth decelerates in the MMC layer side and maximum crack retardation occurs on the boundary of the bi-material system. Near the boundary of the bi-material, the crack tip becomes curved, which reduces the crack growth rate in the vicinity of the boundary of the bi-material even at higher ΔK. The particle-matrix interfacial debonding, as well as particle fracture, is observed in the hybrid MMC layer during fatigue loading.

1. Introduction

Discontinuously reinforced metal matrix composites (MMCs) have attracted significant research interest in the past few decades due to their excellent mechanical properties as compared to their corresponding monolithic alloys [1]. Therefore, MMCs are now increasingly used for critical structural applications in advanced sectors. MMCs composed of a light alloy matrix, such as aluminium alloy, reinforced with ceramic particulates, have a combination of high strength, high stiffness, and low density [2]. These composites can be processed by conventional processing techniques with low cost [3, 4]. These properties allow the aluminium based MMCs as the attractive materials for use in weight-sensitive and stiffness-critical engineering components. In spite of their advantages, the expansion of Al-MMCs still causes many questions that must be resolved for a better use of these materials in the advanced sector. Many engineering components involve cyclic loading in service, therefore, fatigue degradation inevitably takes place within the matrix materials [5]. Thus, the knowledge of fatigue behaviour and resultant fracture properties of such materials become crucial for the design of the structural components. With the engineering application of MMCs, the fatigue crack growth (FCG) behaviour becomes a critical factor in design, life-prediction and reliability analysis of the components made of these materials.

The FCG behaviour in particle MMCs is very much dependent on a variety of factors, including reinforcement particle volume fraction, particle size, matrix and interfacial microstructure, the presence of inclusions and testing environment [6, 7]. Amongst these variables, particle size is one of the microstructural parameters influencing the FCG behaviour [8]. Sugimura et al. [9] have reported that increasing the volume fraction of SiC particulates in cast Al alloy stimulates higher FCG rate. Moreover, Chawla et al. [10] have investigated the effects of SiC volume fraction and particle size on the fatigue behaviour of powder metallurgy 2080 Al alloy and found that increasing volume fraction and decreasing particle size result in an increase in fatigue resistance. Xu et al. [11] observed the retardation of FCG when crack propagates from a low volume fraction of SiC to a high volume fraction of SiC. Both crack deflection and branching decrease FCG rates. Other than the reinforcement characteristics and matrix microstructure, factors like crack closure, residual stress and elastic-plastic mismatch of matrix and reinforcement play a significant role in the FCG mechanism. Mason and Ritchie [12] observed that the crack growth resistance in the composite is superior than the monolithic alloy at low-stress intensity factor ΔK, owing to the formation of the twisted crack path, which enhanced roughness induced crack closure. In addition, Iqbal et al [13] found a higher threshold stress intensity factor range, ΔK_{th}, in the hybrid MMC as compared to whisker reinforced MMC. They explained the crack growth behaviour in terms of elastic-plastic mismatch of the reinforcement-matrix and the void nucleation in the matrix part. However, all these above phenomenon of crack profile and crack growth was explained when the crack developed in the homogeneous MMC material. The FCG in the bi-material system has been limited investigation. Few studies showed that in the case of a bi-material system, the thermal residual stress as well as the elastic mismatch of the different components of the bi-material influence the FCG rate. This mismatch of elasticity is responsible for load partitioning and elastic stress singularities that affect the value of the stress intensity factor, ΔK. Although these researches provided some guidelines of the crack growth phenomena in the bi-material system, still there is a lack of understanding of how the crack propagates in the interface region and which factors affecting the crack growth mechanism in this circumstance. Therefore, in this study, the fatigue crack propagation behaviour in an Al alloy-hybrid MMC bi-material has been investigated and the factors affecting the mechanism have been analysed.

2. Materials and experimental procedures

The bi-material used in this study is composed of Al alloy and hybrid MMC. The Al alloy-hybrid MMC bi-material and the microstructure of this material is shown in Figure 1. In the monolithic alloy part, Al alloy AC4CH is used. This alloy is also used as the base material in the hybrid MMC part. The chemical composition of the Al alloy AC4CH is shown in the Table 1. In the hybrid MMC part, the Al alloy is reinforced with 21 vol% of SiC particles and 9 vol% of Al_2O_3 fibers. In the subsequent part of this manuscript, we will call this Al alloy- hybrid MMC bi-material system as bi-material.

Figure 1. (a) Al alloy-hybrid MMC bi-material, (b) Microstructure of bi-materials.

Table 1. Chemical composition of AC4CH alloy, (wt%).

Si	Mg	Fe		Ti	Al
7.99	0.57	0.2 (max)		0.07	Bal.

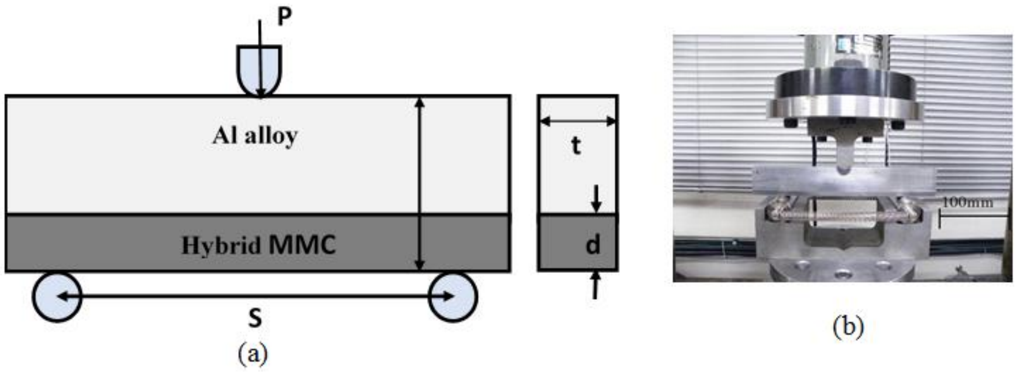

Figure 2. Specimen dimension and experimental set-up.

The material is fabricated by the squeeze casting process. Hybrid preform of SiC particles and Al_2O_3 fibers is prepared and used for the fabrication of hybrid MMC part. The preform is placed in the mould and the molten Al alloy is poured into it. The casting pressure, 100 MPa is maintained throughout the process to overcome the resistance against the flow during casting. This pressure also helps to sufficiently press the melt and fill all the open pores of the composite preforms. Finally, all the materials are heat treated by the T7 process. All the specimens are polished by using the high precision polishing machine. The polishing is carried out by using the abrasives containing 15 µm, 3 µm, 1 µm diamond particles and 0.3 µm alumina particles sequentially to remove all the machining marks and scratches from the specimen surface. To investigate the crack growth in the bi-material, 0.5 mm notch is cut in the MMC layer side. Conventional three-point bending fatigue test is carried out on the Shimadzu servopulser machine in accordance with the guideline in ASTM E647. The dimension of the specimen of the bi-material and the schematic illustration of the 3-point bending test is shown in the Figure 2. Experiments are conducted at the constant load ratio $R = 0.1$, while the frequencies vary from 1 to 20 Hz. The crack is introduced from the MMC layer side. The stress intensity factor, ΔK is increased by 5% each time the crack growth stops. The ΔK is varied depending on the longitudinal elastic modulus of the material. The Plastic replica technique is used to observe the crack growth on the surface of the specimen during cyclic loading. This technique is also used to observe the presence of the micro-cracks near the crack tip that may develop during the fatigue testing. Consequently, the FCG behaviour in the MMC layer and in the vicinity of the boundary of the bi-material is analyzed.

3. Results and discussion

The fatigue crack growth rates in the bi-material at different ΔK and at a constant load ratio, $R= 0.1$ are shown in the Figure 3 and 4. Figure 3 shows the crack growth rate in the MMC layer while Figure 4 shows the crack growth rate in the Al alloy part. The gradient of the crack growth rate is found similar in both the cases. It is observed in Figure 3 that the crack propagation slows down in the MMC layer side at higher ΔK. According to the previous study, this phenomenon of crack retardation in the MMC is due to the effect of residual stress that occurs on the specimen surface during fatigue loading [14]. However, in this research deceleration of the crack growth is also found in the Al alloy layer (Figure 4), where the residual stress is within the tensile range. Moreover, deceleration of the crack growth rate is found maximum near the boundary as shown in both the figures. According to Kang et al [15], the elastic mismatch due to the different Young's modulus of the bi-material components affects the value of the stress intensity factor (ΔK) that eventually influences the crack growth rate. Usually, an elastic-plastic interaction mismatch occurs in the composite that intensifies the crack growth rate. However, the presence of the large volume of ceramic particles creates a roughness induced crack closure that reduces the crack driving force [13]. In addition, it has been seen that when the crack approaches the boundary of the bi-material system from the higher modulus material, the ΔK value increases as compared to the monolithic material that subsequently reduces the FCG in the interface. In this research, the crack grows from the MMC layer side and penetrates to the boundary.

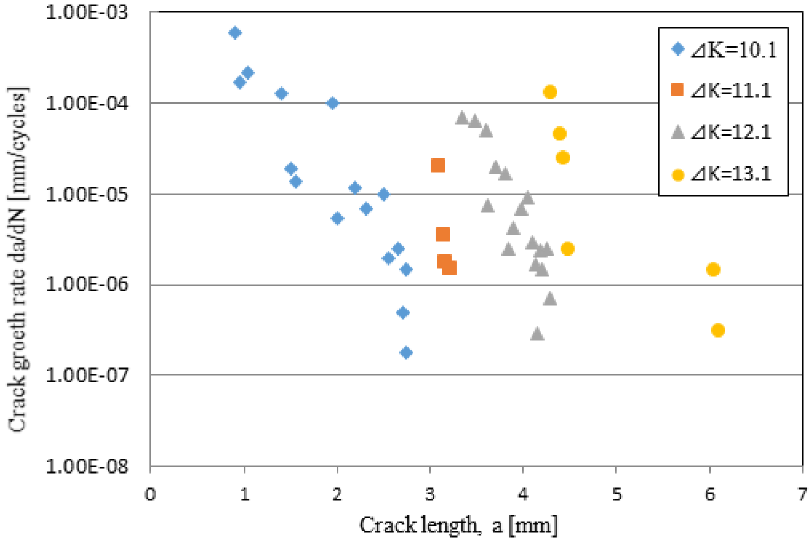

Figure 3. Crack growth rate in the hybrid MMC layer of the bi-material.

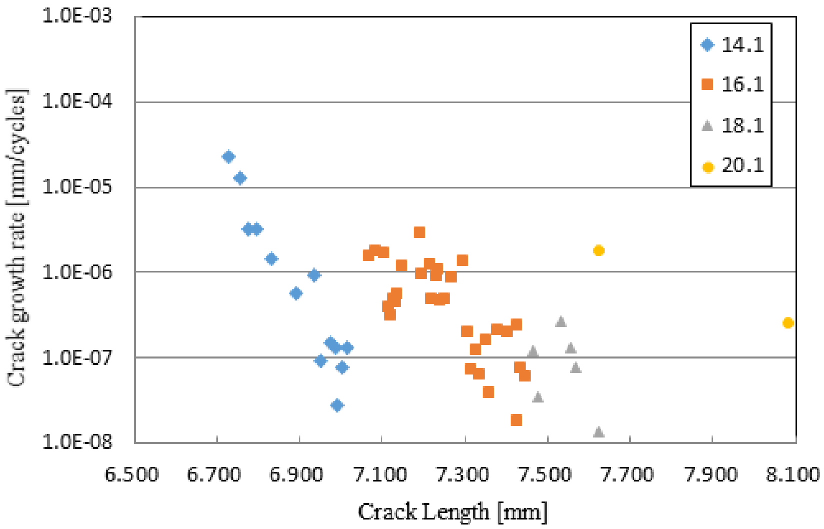

Figure 4. Crack growth rate in the Al alloy layer side of the bi-material

As both the components of the bi-material have a different elastic modulus, modulus mismatch, as well as elastic-plastic interaction mismatch, occurs at the interface. However, due to the roughness induced closure mechanism, the crack driving force is reduced, resulting in decelerating crack growth at the interface. The crack propagation behaviour on the surface of the MMC layer side near the boundary of the bi-material is shown in the Figure 5. The crack propagation direction is from the top to the bottom of the figures. Figure 5(a) shows that the crack is developed at the interface of the ceramic particle and Al matrix. This crack moves to the base material in subsequent fatigue cycle as shown in Figure 5(b). Another crack progression is shown just before the ceramic particles in Figure 5(c). This crack propagates and broke the SiC particles as shown in the circle in Figure 5d. Finally, the crack moves through the base material and stops. This observation indicates that the crack due to fatigue initiates in the particle-matrix interface and propagates through the interface as well as the base material. The interface debonding and the particle fracture occurs as the fatigue cycle increases. The crack stops at the particle or at the base material if the corresponding ΔK is low.
The fracture surface near the boundary of the bi-material specimen is analyzed to investigate the nature of the crack tip, and the surface is shown in the Figure 6. The fracture surface is found dark

near the boundary as shown by the bracket in the figure 6(a) but bright at the center of the specimen. This is due to the difference in crack propagation speed at the boundary and in the center of the specimen. It is found that the fracture occurs in different ways in different places of the specimen. Tearing is observed at the center of the specimen while fatigue failure is observed in the surface. The schematic illustration shown in Figure 6(b) indicates the different nature of the fracture in the bi-material. During the experiment, the crack length is measured on the surface of the specimen as well as beneath the surface. The crack length measured on the surface is found larger than the crack length found in the specimen. This indicates that the crack tip moves far on the surface compared to that of the crack tip inside the material. Therefore, a curved crack tip (corner crack) is developed in the specimen. Due to the nature of the curved crack tip, the deceleration of the crack growth occurs in the vicinity of the boundary of the Al alloy-hybrid MMC bi-material system.

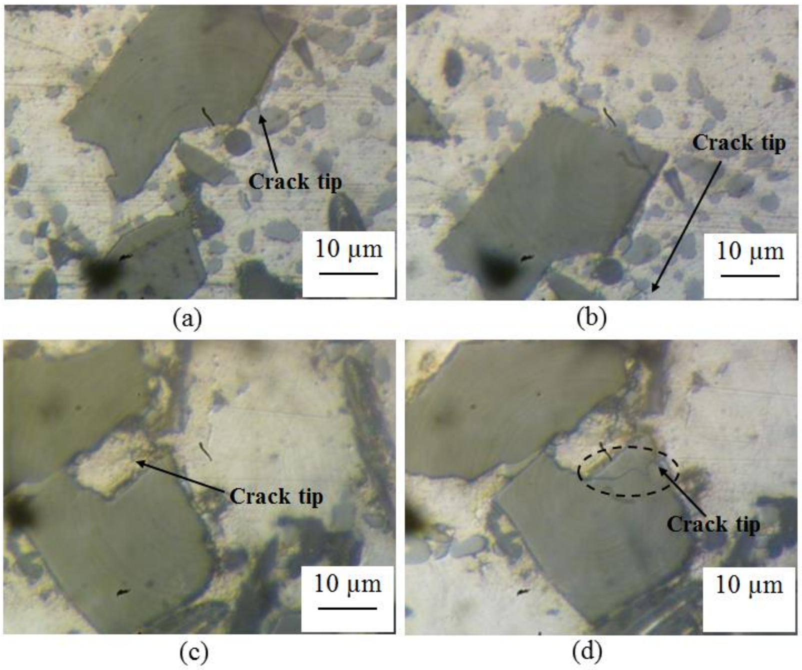

Figure 5. Fatigue crack propagation in the MMC layer side near the boundary of the bi-material.

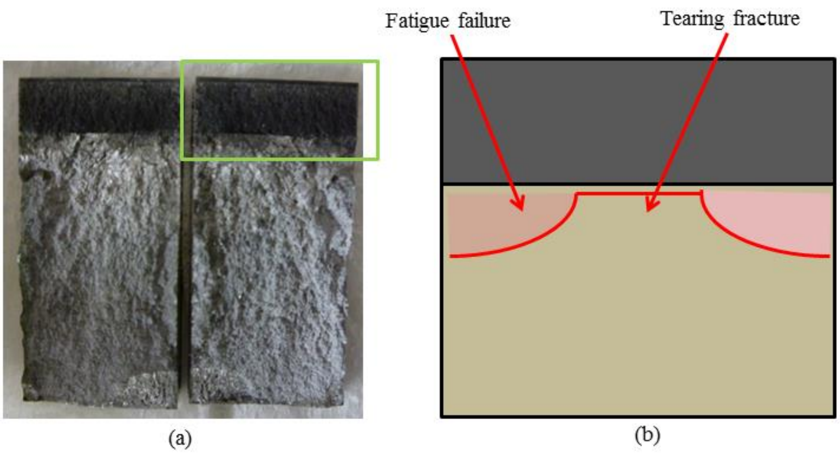

Figure 6. (a) Fracture surface of the bi-material, (b) Schematic illustration shows different types of fracture in bi-materia.l

4. Conclusions

In this research, the fatigue crack propagation behaviour in the Al alloy-hybrid MMC bi-material system has been investigated. The results highlights that the crack propagation slows down in the MMC layer side and maximum crack retardation occurs on the boundary of the bi-material system. The crack in the MMC layer initiates in the particle-matrix interface and propagates through the base material. The particle-matrix interfacial debonding, as well as particle fracture, is observed during fatigue loading. Near the boundary of the bi-material, the crack tip is found curved due to the difference of crack growth rate on the surface and inside the specimen. Therefore, a corner crack is generated. Due to this corner crack, the deceleration of the crack growth occurs in the vicinity of the boundary of the bi-material even at higher ΔK.

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