

Analysis of Fracture Mechanism for Al-Mg/SiC_p Composite Materials

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Abstract. The present study aims to examine the fracture mechanism of silicon carbide particle (SiC_p) reinforced aluminium matrix composite (AMC) material with 1 wt% addition of magnesium is fabricated using the stir casting process. The aluminium composite (Al-Mg/SiC_p) is investigated for fatigue life and impact strength considering reinforcement weight fraction and influence of temperature on fracture toughness. The fabricated composite was tested using fatigue testing machine and charpy impact tester. Fractographic observations were evaluated with the scanning electron microscopy (SEM) on the fracture surface. It was found that increasing the SiC_p weight fraction increased the fatigue life of the composite. Moreover, the 20 wt% SiC_p Al-Mg composite attained the highest number of cycle and fatigue life compared to other variations. The mechanism responsible for the phenomena includes load transfer from the Al matrix alloy phase to the high strength and stiffness of the incorporated SiC_p. The temperature variation influenced the impact strength of the composite and improved fracture toughness is achieved at 150 °C. It can be concluded from this study that reinforcement weight fraction and temperature affects the fracture behavior of the composites.

1. Introduction

Aluminium reinforced silicon carbide particle composite possess improved operational potential for critical structural components due to its attractive properties when compared to monolithic materials. These properties include improved strength and stiffness, high elastic modulus, hardness, wear resistance and low coefficient of thermal expansion. Moreover, the possible lightweight benefit of particle reinforced composite also makes it an alternative choice for researchers [1, 2]. Furthermore, the application of particle reinforced composite as component material for emerging structures involving cyclic loading and toughness strength requires sufficient amount of energy absorption and cyclic load resistance [3]. In order to achieve this, the influence of the particle reinforcement weight fraction and processing technique play a major role in determining the appropriate properties. Various studies [4, 5] have shown that, the stir casting technique is a simple and cost effective route to fabricate the particle reinforced composite. The influence of stir casting processing condition determines the intrinsic fatigue response of the composite. Therefore, by carefully choosing the reinforcement weight fraction of the particles with suitable casting conditions, it is possible to optimize the fatigue and impact properties of the aluminium matrix composite [6]. Moreover, the presence of reinforcement particle influences the toughness and fatigue life cycle of the composites



under operational condition. Uygur [7] found that addition of hard ceramic particle in aluminium composite material reduces the low cycle fatigue behaviour under strain controlled cyclic loading conditions as compared to unreinforced aluminium alloy. This reduction is attributed the brittle nature of ceramic particles phase, high dislocation density at the interfaces, hydrostatic stress development and plastic flow constraint within the aluminium alloy. Moreover, the effect of temperature is also a vital factor in determining the energy absorbed and fracture properties of composites. However, studies have been conducted on the impact toughness behaviour of reinforced aluminium composite at room temperature [8]. In order to further understand the fracture mechanism of aluminium composite, this study aims to investigate the fatigue and impact strength of Al-Mg/SiC_p composite considering reinforcement fraction and influence of temperature on fracture toughness.

2. Methodology

2.1. Materials and method

Aluminium alloy 6061 is used as the matrix phase and silicon carbide particle (SiC_p) as the reinforcing phase material. The matrix phase contains magnesium and silicon as major alloying elements and are commonly used as components for automotive and aerospace applications due to their superior mechanical strength. The chemical composition is shown in Table 1.

Table 1. Chemical Composition of Al6061 by weight percent (wt %)

Composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al 6061	0.62	0.23	0.22	0.03	0.84	0.22	0.10	0.10	Bal

The SiC_p phase comprises of the mixture of three different particle sizes; 15 µm, 40 µm and 80 µm in the ratio 1:1:2 respectively. In order to obtain homogenous mixture of the SiC_p, the Fritsch Pulverisette P5 planetary ball milling set-up is utilized with a powder to ball mixing ratio of 5:1 at a speed of 150 rpm for 15 min. [9]. The Al-Mg/SiC_p composite is produced using the stir casting technique and the process is explained as contained in [10]. The reinforcement weight fraction varies from 5, 10, 15, 20 and 25 wt% to the matrix alloy.

2.2. Fatigue testing

The fatigue test sample as shown in Figure 1 is produced to dimension from the cast billet using the ROMI M420 CNC lathe machine with cutting speed of 1500 rpm and feed rate of 0.2 mm/rev. Fatigue test was carried out using INSTRON 8874 Universal Testing Machine according to ASTM E466-15. Test sample of five different compositions 5, 10, 15, 20 and 25 wt% were tested. The constant amplitude sinusoidal loading at a stress ratio of 0.1 and a frequency of 50 Hz was applied. The test was conducted at a maximum stress levels of 200 MPa. Result was obtained by measuring the number of cycles each composite sample can withstand before fracture occurred using the S-N curve.

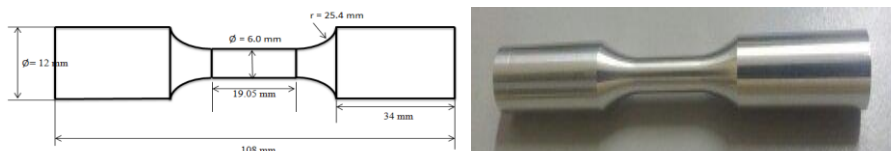


Figure 1. Standard fatigue test sample

2.3. Impact testing

The V-notched impact specimen was cut using EDM wire cut machine in order to obtain the desired rectangular shape of length of 55 mm with thickness and width of 10 mm and a V-notch angle of 45°. Figure 2 shows the actual V-notched impact specimen. The impact test is carried out using the INSTRON Charpy impact tester according to ASTM E23-12c. In this study, the specimens were tested at different temperature (-15, 25, 150, 200 °C). After all test has been conducted, the characterization

of the fracture surface analysis is examined using JEOL, JSM 5600 field emission scanning electron microscope (FESEM).

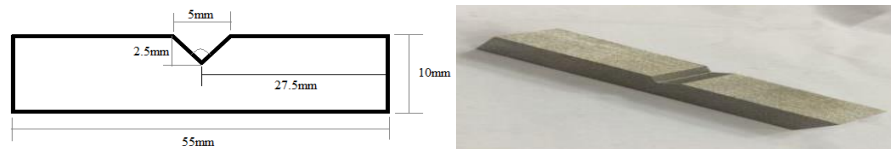


Figure 2. Standard V-notched impact test specimen

3. Failure Properties of Al-Mg/SiC_p Composite

3.1. Fatigue life

The fatigue life of each composite material considering the reinforcement weight fraction was investigated by the number of cycles it can withstand before fracture failure. A maximum stress of 200 MPa was applied to the composite samples and results obtained is presented by S-N curve in Figure 3. The result shows that fatigue life of SiC_p reinforced Al-Mg composite increases as the reinforcement weight fraction increases resulting higher load bearing capacity of the composite materials. Moreover, increasing the amount of reinforcement fraction initiates increase in elastic modulus, yield strength and ultimate strength with a corresponding decrease in ductility.

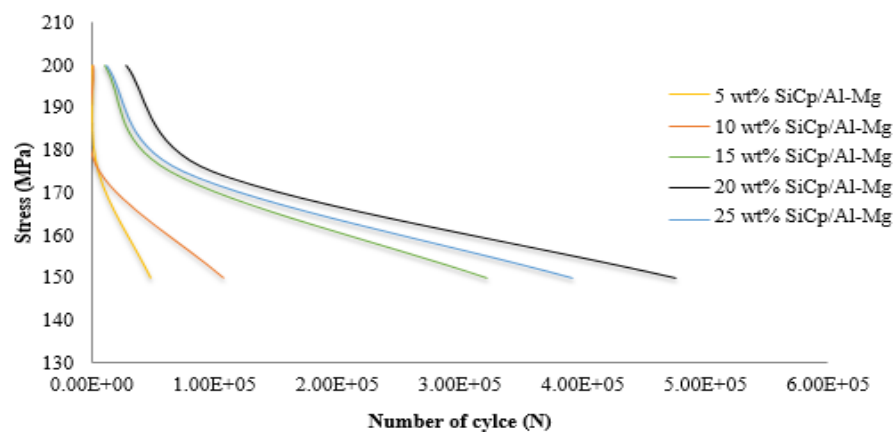


Figure 3. S-N curve profile of fatigue life strength with different reinforcement weight fraction

From Figure 3, Al composite with 5 wt% SiC_p has the shortest fatigue life strength at maximum stress of 200 MPa followed by 10 wt% SiC_p and 15 wt% of SiC_p composite respectively. SiC_p reinforcement with < 10 wt% SiC_p shows that it is insufficient to withstand the cyclic stress applied to the composite which means reinforcement is insufficient in the composite formulation to transfer the load to the matrix. Higher weight fraction of SiC_p reinforcement increases the elastic modulus of the composite materials, thus, the number of cycle is expected to increase. It is observed from the S-N curve profile that 20 wt% SiC_p Al-Mg composite has the highest fatigue life. Though, 25 wt% SiC_p shows a slightly shorter fatigue life than 20 wt% SiC_p reinforced aluminium composite at maximum stress level of 200MPa. This is as a result of decrease in cyclic ductility which is due to the presence of substantial amount of SiC_p reinforcement which induces brittleness in the fatigue properties [11].

3.2. Impact toughness

The toughness is analyzed considering the influence of temperature on 20 wt% SiC_p Al-Mg composite. Figure 4 shows the impact toughness of the composite considering temperature variations. However, the unreinforced aluminium alloy attained impact toughness energy of 14 J. The ductile nature of Al

alloy makes it to undergo plastic deformation which is responsible for the high energy impact especially at room temperature. The impact toughness Al-Mg alloy decreased with the presence of reinforced SiC_p . Considering the temperature effect, the toughness is increased as the temperature rises. However, this is not the case for temperature above 150°C as indicated in the Figure 4. At higher temperature beyond 150°C , the microstructure of the Al alloy experiences overaging which increases diffusion rate and accelerate the dissolution and growth rates, therefore enhances the particle coarsening. The maximum solute solubility in the matrix alloy also increases and precipitates dissolve to release solute in solid solution. These mechanisms increases the interparticle spacing which in turn soften the Al alloy. Due to this condition, energy absorbed before plastic deformation is lower as the failure occurs in the matrix alloy phase or near the matrix-reinforcement interface at temperature between 200 to 250°C . Thus, for temperature higher than 150°C , the impact toughness starts to drop.

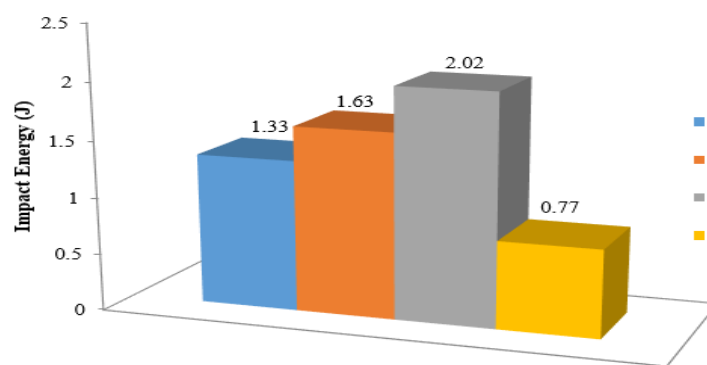


Figure 4. Impact toughness of 20 wt% SiC_p Al-Mg composite considering temperature variation

4. Fracture surface analysis of Al-Mg/ SiC_p Composite

4.1. Fatigue fracture

The fatigue resistance of the Al-Mg/ SiC_p composite increases with increasing the weight fraction of SiC_p reinforcement which inturn increases the fatigue life of the composite material. Basically, fracture occur in composite material by crack initiation which subsequently proceeds at the debonded interface between Al-Mg alloy and SiC_p . The study shows that presence of SiC_p either assisted or resisted the crack propagation of the composite. Due to the presence of brittle ceramic SiC_p with different weight fraction (5, 10, 15, 20, 25 wt%), the composite materials exhibit tendencies of brittle behavior. Al-Mg composite reinforced with 5 wt% and 10 wt% SiC_p shows some ductile behavior before fracture as observed in Figure 5(a). The ductile properties is characterized by the dimple structures observed on the fractured surface. These dimple structures are produced by the decohesion of SiC_p from Al alloy matrix. Figure 5(b) also exhibited the ductile tendencies resulting in necking and plastic deformation of the matrix alloy before failure.

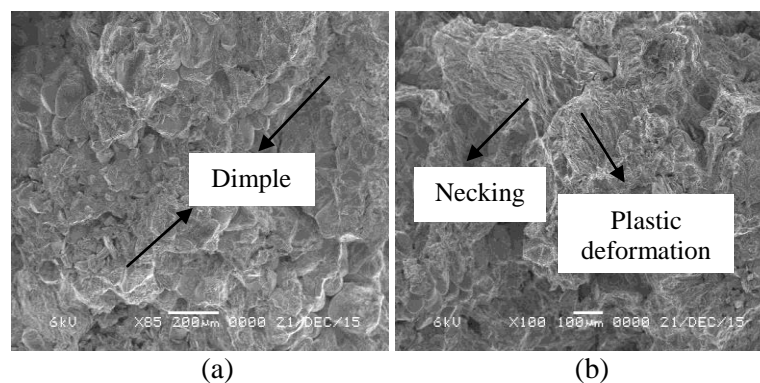


Figure 5. Fractography analysis of (a) 5 wt% SiC_p and (b) 10 wt% SiC_p Al-Mg composite

Figure 6(a) shows the fractured surface of Al-15 wt% SiC_p composite. The surface analysis shows the combination of dimple ductile behaviour of the matrix alloy phase and the brittle failure of the reinforcement. Some of the SiC_p were observed to crack due to high stress intensity. Moreover, the larger particles are prone to crack while the fine particles decohere from matrix alloy phase to form void nucleation.

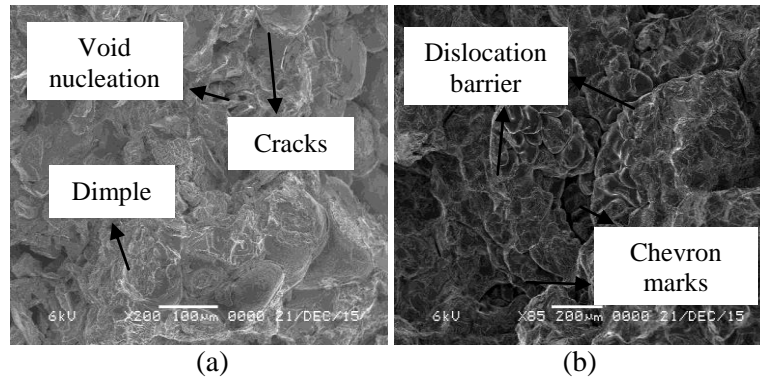


Figure 6. Fracture surface analysis of (a) 15 wt% SiC_p and (b) 20 wt% SiC_p Al-Mg composite

Al-Mg composite reinforced with 20 wt% of SiC has longest fatigue life because the crack growth is hindered by the effect of SiC_p as shown in Figure 6(b). The presence of SiC_p provides a tough barrier to the dislocation motion. The SiC_p act as the load bearer and also resist the crack propagation which is evidence with the higher number of cycles before failure. With the dispersion of 20 wt% SiC_p in Al-Mg alloy, the load is transferred more effectively. From Figure 6(b), the microstructure shows that there is no void nucleation around the SiC_p as it acts as stress reliever and also the presence of the chevron marks on the fractured surface proves that Al-20wt%SiC experienced brittle fracture.

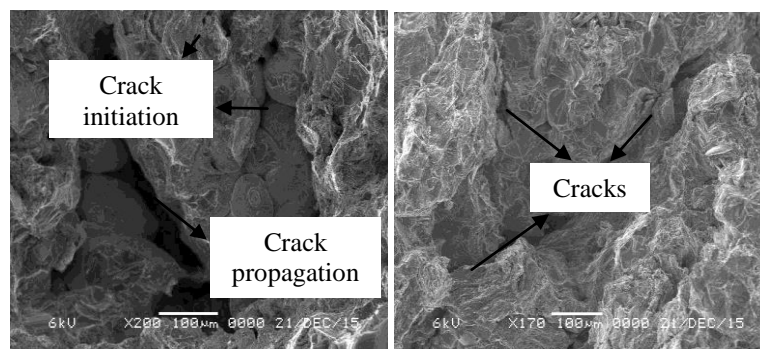


Figure 7. Crack initiation and propagation for 25 wt% SiC_p/Al-Mg composite

The 25 wt% reinforced SiC_p Al composite shows shorter fatigue life strength compared to 20 wt% SiC_p composite due to excessive crack initiation spotted around the particles as a result of the weight fraction of reinforcement. These regions serves high stress concentration, which in turn develops to crack initiation sites as shown in Figure 7. As the cracks approaches the interphase area, SiC_p tend to absorb the crack energy, which eventually fracture with rapid failure. In this condition, SiC_p no longer act as stress relievers but behaves in a brittle manner as the crack propagates through the particles.

4.2 Impact fracture

The impact toughness fracture surface of Al-Mg alloy tends to exhibit higher ductility properties compared to the SiC_p reinforced Al-Mg composite. Figure 8(a) shows the cup and cone shape of fracture surface which indicates necking before major failure occurred. The rough surface indicates that the matrix alloy shows a gross plastic deformation during fracture. It proved that the material needed high energy for the fracture to occur. The effect of temperature is observed on failure analysis

using surface fracture micrograph. At room temperature, the Al-Mg alloy experienced a transgranular fracture as the crack propagations occurs across the grain boundaries as shown in Figure 8(b). When the Al-Mg alloy is reinforced with SiC_p , a transformation from ductile to brittle phase takes place depending on the wt % of reinforcement. The fracture process propagates with little or no plastic deformation before the composite material fails. The presence of hard ceramic SiC_p act as stress concentration areas which leads to formation of unstable crack resulting in low energy absorption and impact energy in resisting the load.

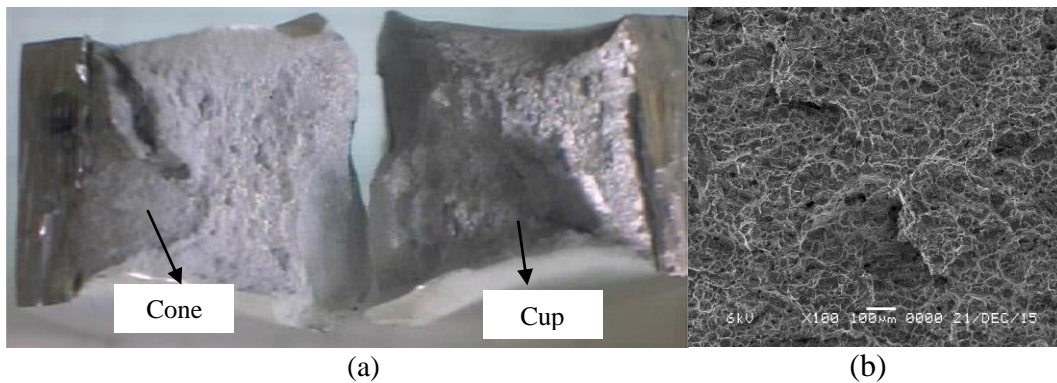


Figure 8. Failure surface of Al-Mg alloy (a) Cup and cone; and (b) transgranular fracture at room temperature

At temperature of $-15\text{ }^{\circ}\text{C}$, the 20 wt% SiC_p/Al composite exhibits flat cleavages with small areas of fracture surfaces, hence, low energy is required for the fracture to occur. Further analysis shows that the composite material exhibited brittle fracture consisting transgranular cleavage facets as shown in Figure 9(a). At room temperature the composite experiences fast propagation of transgranular crack across the grains. These are represented with river lines as shown in Figure 9(b) between the cleavages which converged in the direction of local crack propagation. As the propagation of the crack occurs rapidly, chevron marks are spotted at the crack area instead of dimple microstructure.

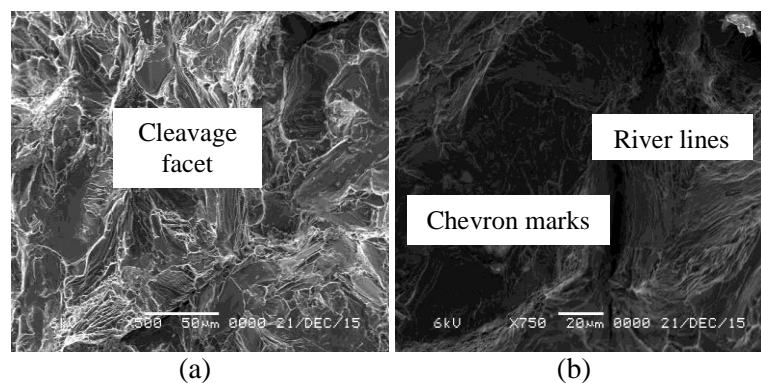


Figure 9. Impact fracture surface of 20 wt% SiC_p/Al -Mg at (a) $-15\text{ }^{\circ}\text{C}$ and (b) room temperature

At $150\text{ }^{\circ}\text{C}$, the 20 wt% SiC_p/Al composite was found to exhibit some external necking prior to fracture. In addition, high elastic loads are built up in the reinforcement, thus induces matrix yield and plastic deformation before interfacial debonding as shown in Figure 10(a). However, as the temperature increases, the bonding between matrix and reinforcement become weaker, where the particles served as void nucleation sites. At temperature of $200\text{ }^{\circ}\text{C}$, the composite exhibited ductile characteristics with the presence of dimples observed on the fractured surface. Though, the crack propagates catastrophically with high speed through the grains and dominantly at the interface between matrix and particulate reinforcement, resulting in lower energy absorption compared to the

composite material at temperature of 150 °C. Void nucleation can be seen around the SiC_p, providing crack propagation across the matrix-reinforcement interface which serves as preferential sites for cavity initiation as shown in Figure 10(b).

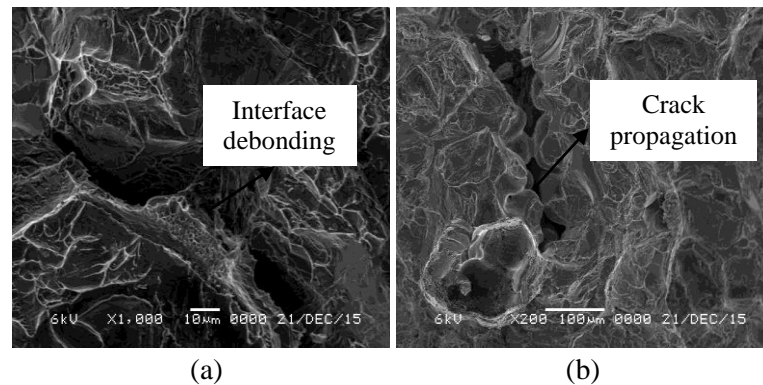


Figure 10. Impact toughness feature of 20 wt% SiC_p/Al-Mg at (a) 150 °C and (b) 200 °C

5. Conclusion

The following results can be concluded from the study;

1. The stir casting process was successfully utilized in fabricating Al-Mg/SiC_p composite with different weight fraction of the reinforcement phase.
2. The reinforcement weight fraction of 20 wt% SiC_p recorded the optimum and longest fatigue life strength due to the highest number of cycle attained compared to other reinforcement variations which in turn influences the elastic modulus. On the other hand, the 25 wt% SiC_p shows a slightly shorter fatigue life than 20 wt% SiC_p composite at maximum stress level of 200MPa. This can be ascribed to decrease in cyclic ductility which is due to the presence of substantial amount of SiC_p reinforcement which induces brittleness in the fatigue properties.
3. With 20 wt% reinforcement the crack growth is hindered by the effect of SiC_p which provides a tough barrier to the dislocation motion and also act as load bearer in order to resist the crack propagation.
4. The impact toughness of the composites decreased compared to the unreinforced Al-Mg alloy. However, the influence of temperature play a role in the toughness value of the composite.

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