Effect of SiC particles on fatigue crack growth behavior of spray-formed SiC particulate-reinforced Al-Si alloy composites

Li Wei*, Chen Jian, Qiu Wei, Ren Yanjie

School of Energy and Power Engineering, Changsha University of Science and Technology, 410004, China

* Corresponding author: lwzzgjajie@126.com

Abstract

Fatigue crack growth (FCG) and closure mechanisms in spray-formed Al-7Si alloy matrix composites reinforced with two different sizes of SiC particles has been studied. The experimental dates demonstrate that the composite containing 4.5μm SiC particles exhibits lower FCG rate and higher threshold stress intensity factor range ΔK_{th} (3.878 $MPa \bullet \sqrt{m}$) than the 20μm SiC particles composite(3.630 $MPa \bullet \sqrt{m}$) and the unreinforced alloy (3.605 $MPa \bullet \sqrt{m}$). The SEM crack path observations show that the extent of micoracking inside in the 4.5μm SiC particles induces higher level of fatigue crack closure, which effectively reduces the crack growth driving force to slow down fatigue crack growth. Crack deflection caused by the SiC particles attributes the lower FCG rate in the 20μm SiC composite to the high levels of roughness-induced crack closure at the low ΔK, then the propensity for the fracture of large SiC particles increased with increasing ΔK resulted in a higher FCG rate in the fast fracture state.

Keywords Fatigue crack growth, spray-formed, SiC particulate-reinforced Al-Si alloy composites, closure mechanism, size

1. Introduction

The outstanding mechanical, physical, and casting properties of Al-Si–Mg alloys, on the other hand, make them attractive for use in cheaper and lighter engineering components[1]. These composites are produced by several processing methods, such as stir casting, squeeze casting [2], powder metallurgy [3] and spray forming, etc. Amongst these methods, spray forming technique has drawn considerable research interest due to its scope of forming near-net shape product with a reduced number of process steps compared to the powder metallurgy. Apart from this, the process offers advantage of rapid solidification, such as refined equiaxed structure with negligible segregation, extension of the solid solubility limit [4], and wider compositional flexibility. With the engineering application of metal matrix composites (MMCs), the fatigue crack growth behavior will become critical in design, life-prediction and reliability analysis of the components made of these materials.

The fatigue crack growth behavior 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 [5-7]. Of these variables, particle size is one of microstructural parameters influencing the fatigue crack growth behavior [8, 9]. Sugimura et al. [10] have reported that increasing the volume fraction of SiC particulates in cast Al-Si alloy promotes higher FCG rate. The effects of SiC volume fraction and particle size on the fatigue behavior of powder metallurgy 2080 Al alloy have been investigated by Chawla et al. [11]. They find that increasing volume fraction (from 10% to 30%) and decreasing particle size (from 23μm down to 5 μm) result in an increase in fatigue resistance. Xu et al. [12] have pointed out that the retardation of FCG was found when crack propagated from low volume fraction of SiC to high volume fraction of SiC. The crack deflection and branching decreased FCG rates.

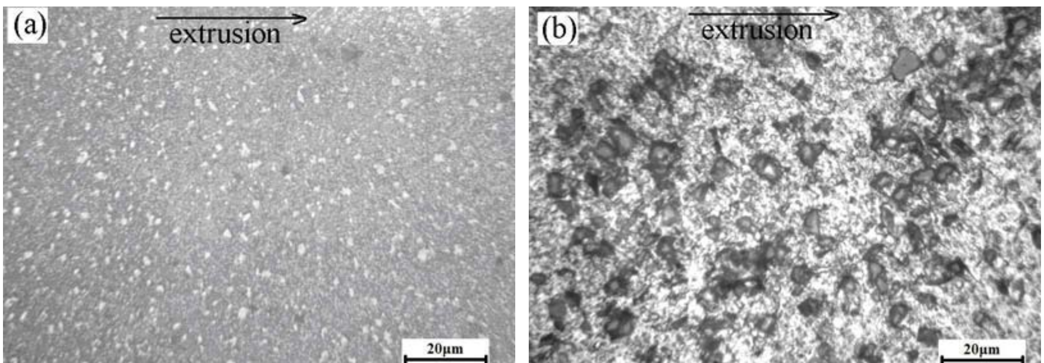
Although a number of studies on fatigue resistance and fatigue crack growth (FCG) in SiC_p/Al composites and Al-Si-Mg alloys have been done , the effect of particle size on fatigue crack growth behavior of this kind of composites produced by spray deposition has been limited. Thus it is necessary to carry out a fundamental research work in this respect. The purpose of the present study is to understand the effect of particle size on fatigue crack growth behavior and closure mechanism of spray-deposited SiC_p/Al composites.

2. Experimental

2.1 Material and microstructure

Al-7Si-Mg alloy fabricated by spray deposition was used in the unreinforced condition and with 15 vol.% SiCp reinforcement. The chemical composition (mass. %) is Si 7, Mg 0.3, Mn 0.01, Cu 0.01, balance Al. Extrusion at 450℃ was used to produce plates with dimensions of $10\times 120mm^2$.

Fig. 1 shows the microstructures of the sections parallel (L-plane) to the extrusion direction in the unreinforced alloy and the composites. It can be seen that SiC particles tend to be partially aligned along the extrusion direction. Some clustering tendency observed in the 4.5μm SiC_p/Al-7Si composite decreases as the size of the particulates increases.



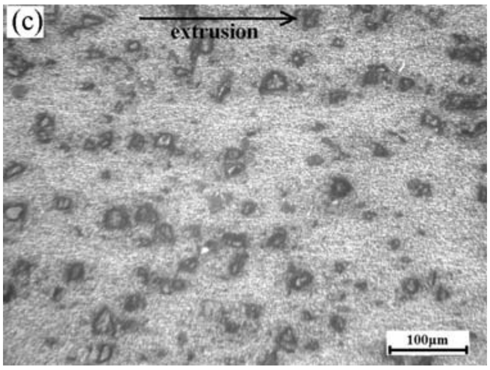


Figure 1. Optical micrographs of longitudinal planes of the (a) 4.5μm SiC_p/Al-7Si composite (b) 20μm Al-7Si/ SiC_p composite

2.2 Specimen preparation

All specimens were solution treated at 535℃for 2.5h, quenched in eater and then aged at 160℃ to achieve peak-aged condition. The aging time was 7h for the Al-7Si alloy and 4.5μm SiC_p/Al-7Si composite, 11h for 20μm SiC_p/Al-7Si composite. Compact tension (CT) specimens, of width W=48mm, height H=57.6mm, thickness B=10mm, were machined from the extruded plates of the materials with the loading axis parallel to the extrusion direction and with the plane of the notch perpendicular to the loading axis.

2.3 Mechanical properties

The room temperature tensile properties of the two kinds of the composites and the Al-7Si alloy are listed in Table 1. Incorporation of the reinforcing particles promotes the elastic modulus 15.84~18.94%. The composite containing large reinforcing particles is higher in yield strength, defined as the stress corresponding to a plastic strain of 0.2%, but lower in elastic modulus than that containing small particles. The composites display a slight decrease of the ultimate tensile strength and elongation with respect to the matrix alloy.

Table 1. Mechanical properties of the Al-7Si alloy and composite at room temperature

SiC content (vol. %)	SiC Size （μm）	Elastic modulus, E (GPa)	0.2% proof strength, $\sigma_{0.2}$ (MPa)	Ultimate tensile strength, σ_b (MPa)	Elongation, A (%)
0	0	72.3	242.5	336.2	11.2
15	4.5	86.0	240.5	328.8	9.0
15	20.0	83.7	270.9	321.3	8.6

2.4 Procedure

The tests according to ASTM E647 were conducted in laboratory air at room temperature (298K) and relative humidity 40-50% at constant stress ratio of 0.1, using a sinusoidal waveform signal at 25Hz.Region Ⅰdata were obtained following the guidelines for near-threshold testing. A computer controlled load shedding technique (normalized K gradient set at -0.10mm^{-1}) was used to gradually decrease crack growth rates to the near-threshold level. The fatigue threshold stress-intensity range (ΔK_{th}) was defined at a maximum growth rate of 10^{-10} m/cycle. For determine the Paris' constants *c* and *m* in Paris' equation (da/dN=mΔK^c). Constant amplitude technique (ΔK-decreasing) had been used. Data recorded during the tests were analyzed to obtain da/dN-ΔK curves.

3. Results

3.1 Fatigue crack growth

Fig. 2 shows the variation of the fatigue crack growth rates, da/dN, as a function of the stress intensity factor range, ΔK, for the unreinforced alloy and the two composites. It is obvious that the curve for the 4.5μm SiC reinforcement composite is below the other two curves for the 20μm and the Al-7Si alloy. Therefore, the 4.5μm SiC/Al-7Si composite has the best fatigue crack growth resistance. The threshold stress intensity factor range ΔK_{th} of $3.878\,\mathrm{MP}a \bullet \sqrt{m}$ for the 4.5μm SiC reinforcement composite is larger than the 20μm($3.630\,\mathrm{MP}a \bullet \sqrt{m}$) and the Al-7Si alloy ($3.605\,\mathrm{MP}a \bullet \sqrt{m}$). The 20μm SiC particulates reinforced composite shows lower FCG rate than the unreinforced alloy at $\Delta K < 14.88\,\mathrm{MP}a \bullet \sqrt{m}$, but exhibits lower fatigue crack growth rate at $\Delta K > 14.88\,\mathrm{MP}a \bullet \sqrt{m}$. This is to say, the values of the FCG rate for the 20μm are lower than the matrix alloy in the near-threshold regime and Paris regime, however, it become higher than those of Al-7Si alloy at the fast fracture state.

Comparison of the FCG curve of the 4.5μm SiC with 20μm gives a clear indication that the increase in particle size results in an obvious higher FCG rate in the near-threshold regime and the fast fracture state. However, in the Paris regime, i.e. between 10^{-6} and 10^{-4} mm/cycle, the composite reinforced with 20μm SiC particulates exhibits a slighter smaller slope than the 4.5μm SiC. The results depicted in Fig.2 for the particulate-reinforced spray-formed aluminum-matrix composite are similar to that reported of composite [10], where reinforcements cause marker improvements in resistance to fatigue fracture, especially in the near-threshold regime. In general, in the Paris region, there is almost no effect of SiC particle size on fatigue crack growth, while in the near-threshold regime and fast fracture state, the SiC particle size has great influence. This is possibly attributed to the different failure mechanism of crack growth caused by the actions of SiC size, shape and distribution.

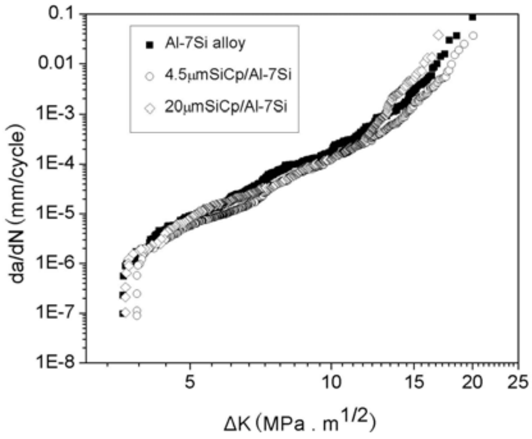


Figure 2. Fatigue crack growth rate as a function of ΔK in the Al-7Si-Mg alloy reinforced with 4.5μm and 20μm SiC particles

The extent of crack closure that developed in the three materials during tension fatigue crack growth is plotted in Fig. 3. This figure shows the variation of the experimentally measured closure stress intensity factor K_{cl}, normalized with maximum stress intensity factor K_{max}, as a function of the stress intensity range, ΔK. It can be seen that the small particulates-reinforced composite exhibits a significantly higher level of crack closure than the two materials over the entire range of fatigue crack growth. The 20 μm SiC reinforcement exhibits higher closure level than the matrix alloy in the $\Delta K < 7.4\,\mathrm{MP}a \bullet \sqrt{m}$ region, but shows lower closure level than the matrix alloy in the $\Delta K > 7.4\,\mathrm{MP}a \bullet \sqrt{m}$ region.

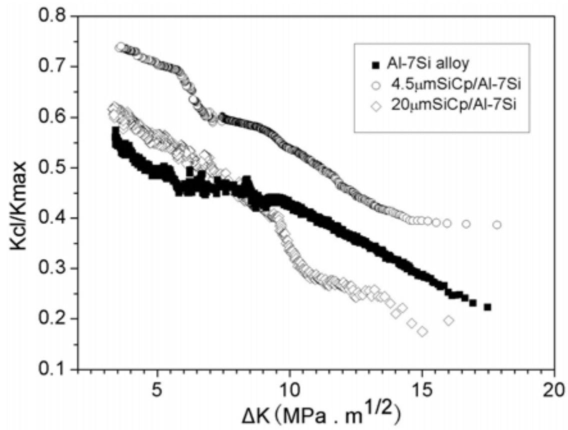


Figure 3. Variation of stress intensity factor at crack closure, K_{cl}/K_{max}, as a function of ΔK in the unreinforced alloy and the reinforced alloys

3.2 Crack path analysis

The relationship between fatigue crack propagation and SiC particle morphology is followed by carefully observing the propagation of the crack tip on well-polished surfaces of CT specimens processing different microstructures and tested at different values of ΔK. Figures 4 through 6 are SEM micrographs of fatigue surface cracks formed in CT specimens of the three materials, tested at various ΔK values, respectively. The direction of crack propagation for all surface cracks is from left to right in the micrographs.

For the unreinforced alloy, crack propagating around Si particles is observed in the near-threshold regime (Fig.4 (a)). It can be seen that the fatigue crack mainly propagate through the α-Al matrix. Crack deflection caused by Si phase, gives rise to a higher degree of roughness of crack surface, and then results in the occurrence of crack closure effect. Little of the Si breakage is observed in Fig 4(a). It means that Si particle is not easy to break and the crack path had predisposition to avoid Si particles in the near threshold. This is probably attributed to the spherical Si particle with small size (1~3 μm), whereas it is difficult to break at the low level ΔK because of the large fracture energy to break, according to the Griffith theory. Nevertheless, the occurrence of Si particle/matrix bebonding is increasing to the factor of the crack propagating due to the increase of the K value around the crack zone, which can be indicated by the arrows in Fig.4 (b). The crack profile is smoother in the matrix alloy than in the composite.

In the composite with 4.5μm and 20μm SiC particles, crack deflection caused by Si phase is observed just as in the case of the unreinforced alloy. Light microscopy also demonstrated that the fatigue crack in the composite follows a tortuous crack path and that crack branching occurs (Fig. 5 and Fig. 6). Significant differences were observed in the crack propagating characteristics of the two composites in the three regions.

As seen in the 4.5μm SiC composite (Fig 5(a) and (b)), crack deflection caused by the SiC particles and extensive microcracking inside SiC particles are observed through the whole fatigue crack growth region. And these microcracks remained open after they were unloaded behind the crack tip. Similar microcracks were also noted in fatigue crack growth of TiC/Ti-6Al-4V[13]. Reinforcing particles apparently serve as effective barriers to fatigue crack growth in 4.5μm SiC/Al-7Si composite.

For the composite with 20μm SiC particle, it can be seen that the fatigue crack avoid SiC particles, consequently the direction of propagation of fatigue crack is changed at the low ΔK(see as Fig. 6(a)). They attributed the lower crack growth in the composite to the high levels of roughness-induced crack closure. With the increase of ΔK level, it was apparent that the crack with an inclination angle to the SiC particles < 45° or >135°had a tendency to progress around SiC particles, while crack with angles between 45° and 135° was expected to advance through SiC particles (see as Fig. 6(b)). Fatigue crack makes function on SiC particles in two ways: SiC particle/matrix debonding and particle breakage. Then, the propensity for the fracture of SiC particles increased with increasing ΔK in the 20μm SiC. A higher FCG rate in the fast fracture state is considered to be a reflection of the strong tendency toward particle fracture in the 20μm SiC material.

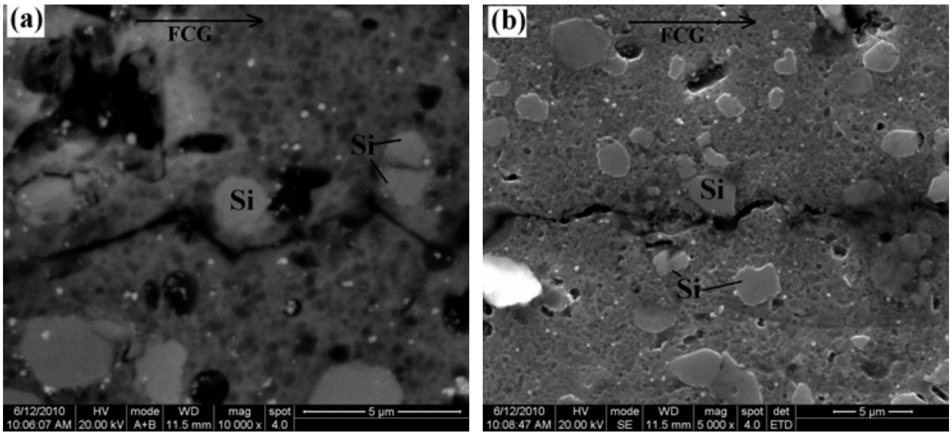


Figure 4. Fatigue crack extension observed on the polished surface of Al-7Si alloy sample, tested at R-0.1 for (a) ΔK_{th}=3.605 MPa•m$^{1/2}$ and (b) ΔK=5.0 MPa•m$^{1/2}$

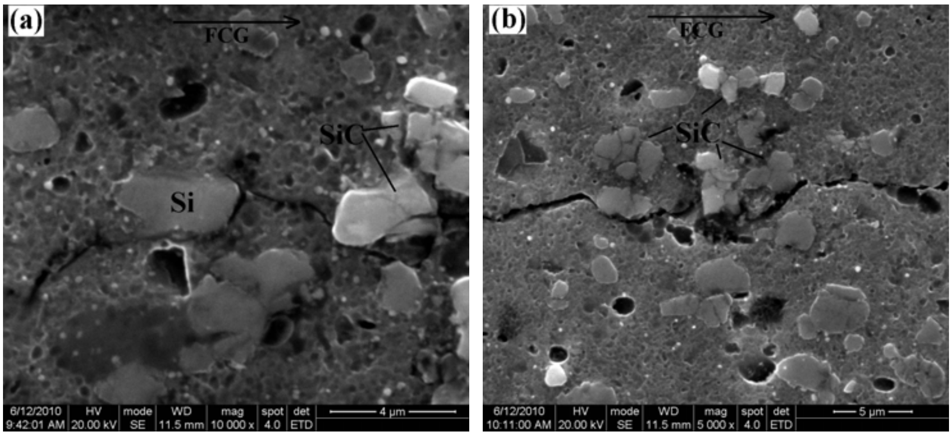


Figure 5. Fatigue crack extension observed on the polished surface of 4.5μm/Al-7Si alloy sample, tested at R-0.1 for (a) ΔK_{th}=3.878 MPa•m$^{1/2}$ and (b) ΔK=7.0 MPa•m$^{1/2}$

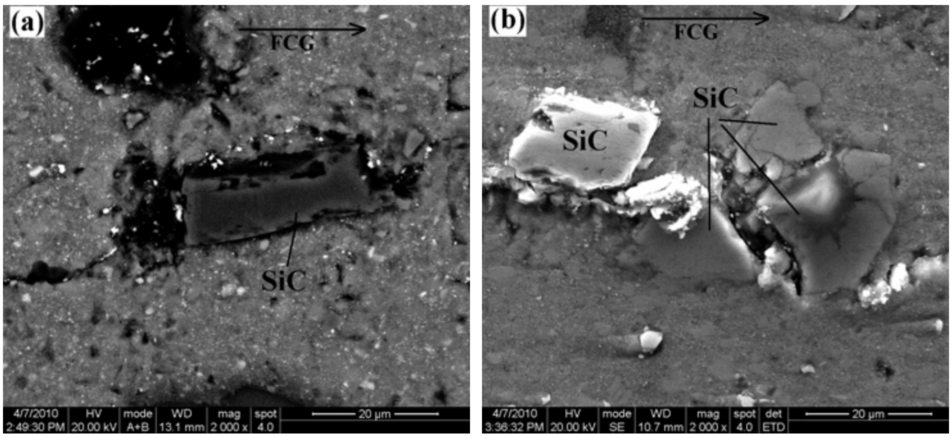


Figure 6. Fatigue crack extension observed on the polished surface of 20μm/Al-7Si alloy sample, tested at R-0.1 for (a) ΔK_{th}=3.630 MPa•m$^{1/2}$ and (b) ΔK=7 MPa•m$^{1/2}$

4. Discussion

In Al-7Si alloy, where fatigue cracks avoid Si particles, enhanced crack closure has been observed through roughness-induced crack closure. Crack deflection around

Si particles is the main fracture mechanism.

Corresponding crack path profiles are shown in Fig.5 and Fig. 6. At low Δ*K*, fatigue surfaces in the SiC/ Al-7Si composite exhibit a zig-zag crack propagation path, with crack deflection around the particles microcacking inside in the 4.5μm SiC along the side of the crack(Fig.5(a)), whereas in the 20μm SiC composite they exhibit only crack deflection around the large particles. The results has shown that in comparison with the composite with 20μm SiC, the FCG rate at 4.5μm SiC was significantly decreased by the development of a higher level of crack closure. The increased crack closure was accompanied by extensive small particle cracking evident. The opening of a microcrack formed from particle cracking under the combined action of the crack-tip stress can result in a local volume expansion around the microscrack, referred to as microcrack-induced crack closure. The effect of the closure force is similar to the reduction of crack-tip stress intensity by transformation toughening.

For the composite with 20μm SiC, the major effect of the large SiC reinforcement is to alter the fracture path, which enhanced crack closure through roughness-induced crack closure. However, roughness-induced crack closure diminishes at high stress intensities. The fatigue cracks do not avoid but run through the SiC particles. Therefore, the effectiveness of particles in crack deflection should be much smaller than the matrix alloy and 4.5μm SiC composite and would be further reduced because of the higher tendency of the large SiC fracture.

5. Conclusions

(1) The 4.5μm SiC/Al-7Si composite has the best fatigue crack growth resistance, i.e. lower fatigue crack growth rate and higher threshold stress intensity factor range ΔK_{th}. The ΔK_{th} is 3.878 $\text{MP}a \bullet \sqrt{m}$ for the 4.5μm SiC reinforcement composite, 3.630 $\text{MP}a \bullet \sqrt{m}$ fore the 20μm, and 3.605 $\text{MP}a \bullet \sqrt{m}$ for the Al-7Si alloy, respectively. The values of the fatigue crack growth rate for the 20μm are lower than the matrix alloy in the near threshold region and Paris regime, however, it become higher than those of Al-7Si alloy at the fast fracture state.

(2) For the unreinforced alloy, crack propagating around Si particles is observed in the near-threshold regime. Crack deflection caused by Si phase, gives rise to a higher degree of roughness of crack surface, and then results in the occurrence of crack closure effect.

(3) For the 4.5μm SiC reinforcement composite, crack deflections around SiC and microcracking inside SiC particles are the principle mechanisms of interaction between SiC particles and crack tip. Crack path analyses indicates that the extent of microcracking inside SiC particles induces a high level of fatigue crack closure ,which effectively reduces the crack growth driving force to slow down fatigue crack growth.

(4) For the composite with 20μm SiC particle, crack deflection caused by the SiC particles attributes the lower crack growth due to the high levels of roughness-induced crack closure at the low ΔK, then the propensity for the fracture of large SiC particles

increased with increasing ΔK resulted in a higher crack growth rate in the fast fracture state.

Acknowledgements

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