Fatigue life estimation of Aluminium Alloy reinforced with SiC particulates in annealed conditions

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Abstract

The use of SiC particulate-reinforced aluminium alloy composites (MMCs) as a substitute of monolithic aluminium alloys in structural applications, especially in the aerospace and automobile industry, is becoming increasingly attractive. This is due to their superior strength, and stiffness, which is combined with their good performance in low cycle fatigue, corrosion fatigue and wear. In this work the fatigue behaviour of silicon carbide (SiC_P) reinforced A359 aluminium alloy matrix composite is described, considering its microstructure, and thermomechanical properties. A variety of heat treatments have been performed for the 20 vol. % SiC_p composite, which resulted in different mechanical behaviour of the material. The fatigue behaviour was monitored and the corresponding S-N curves were experimentally derived for all heat treatments. The fatigue strength of silicon carbide (SiC_P) reinforced A359 aluminium alloy matrix composites has been reported to be mainly influenced by the thermomechanical processing history of the composite. Subsequent microscopical studies revealed that the thermally tailored microstructure dominates the macroscopic behaviour of the composites via precipitation hardening, phase segregations which affect the particle-matrix interfacial strength.

1. Introduction

The mechanical behaviour of the aforementioned composites is dominated by the interface between the Aluminium matrix and the SiC particles. While strengthening relies on the load transfer at the interface, toughness is influenced by the behaviour of the crack at the boundary between the matrix and the reinforcement and ductility is affected by the relaxation of peak stresses near the interface due to the plastic flow ahead of the crack tip. As a result, the non-elastic behaviour of the composite is dominated firstly by the time dependent stress field i.e. the imposed stress rate, and secondly by the induced changes in the microstructure because of the presence of the reinforcement [1]. These changes consist of segregation and precipitation phenomena caused by the thermal treatment which in turn are expected to drastically affect the fatigue strength and the fatigue life behaviour of the Al/SiC$_p$ composites.

In the case of particle reinforced metals, numerous studies have focused on understanding the influence of the reinforcing particle on the matrix microstructure and the corresponding effect on the fatigue behaviour of the MMCs [1-5]. The size and percentage of the reinforcement are also affecting the fatigue life. In some cases, the fatigue strength may deteriorate by the addition of the reinforcement [6-7].

Previous work results indicated the interrelation between the heat treatment, the filler/matrix interface quality and the static failure mode of the composite [8]. Further to the static properties, the heat treatment is expected to be of significant importance for the dynamic behaviour of these materials.

The scope of the present study, involved the application of two different heat treatment protocols on stripes of Al/SiC$_P$ 20% specimens with the aim of tailoring the fatigue properties of the composite.

2. Material and microstructure

The metal matrix composites studied in this work consisted of aluminium – silicon – magnesium alloy matrix A359, reinforced with silicon carbide particles. Hot rolled A359 Aluminium alloy with 20% SiC particles per weight with an average particle size of 17±1 μm was used. In Table 1, the chemical composition of the matrix alloy is shown.

Table 1. Chemical Composition of the Al/SiC$_P$ composite

Material	Elements (wt %)					
	Si	Mg	Mn	Cu	Fe	Zn
A359 /SiC$_P$-20%	*9.5*	*0.5*	*0.1*	*0.2*	*0.2*	*0.1*

The Al-Si-Mg alloys are the most widely used in the foundry industry due to their good castability and high strength to weight ratio. By adding magnesium, an Al–Si alloy becomes age hardenable through the precipitation of Mg_2Si precipitates.

The microstructure of the examined MMCs in the as-received condition has four distinct microphases as clearly marked on the image micrograph, which are as follows: the aluminium matrix, the SiC particles, the eutectic region of aluminium and silicon and the Mg phase (Fig. 1).

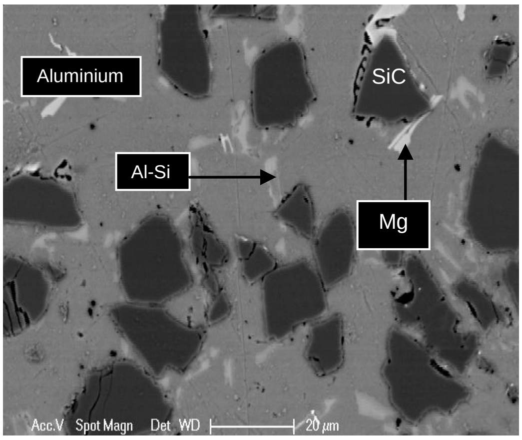

Fig.1. Aluminium/Silicon Carbide particulate Composite

3. Experimental

3.1 Heat Treatment

Two different heat treatments were used for this study; T6 and modified-T6 (HT-1) [9-10]. The T6 heat treatment process consisted of the following steps: solution heat treatment, quench and age hardening. In the solution heat treatment, the alloys were heated to a temperature just below the initial melting point of the alloy for 2 hours at 530±5 ºC. Next, the composites were heated to a temperature of 155 ºC for 5 hours and subsequently cooled in air. The second heat treatment process was the modified-T6 (HT-1) heat treatment, where the alloys in the solution treatment were heated to a temperature lower than the T6 heat treatment that is 450±5 º C for 1 hour, and then quenched in water. Subsequently, the alloys were heated to an intermediate temperature of 170 ºC for 24 hours in the age hardened stage and then cooled in air.

3.2 Tensile properties

Prior to the fatigue testing tensile tests were performed in order to determine the UTS of the composites. Aluminium A359 with 20 vol. % SiC particulate composite specimens were tested in tension in the as received state, and after two heat treatments: the as previously described modified T6 (HT-1) and the standard T6 heat treatment. Tensile tests were conducted using a 100KN Instron hydraulic universal testing machine and the strain was monitored using a clip gauge.

3.2 Fatigue testing

Tension-tension fatigue tests were conducted using a 100KN Instron hydraulic universal testing machine with complementary data acquisition computer and software. The system was operated under load control, applying a harmonic tensile stress with constant amplitude. Throughout this study, all fatigue tests were carried out at a frequency of 5 Hz and at a stress ratio R = 0.1. Different stress levels between the ultimate tensile strength (UTS) and the fatigue limit were selected, resulting in S-N curves.

4. Results and discussion

The results of the tensile tests for all the heat treatments of the MMCs are summarised in Table 2. The microhardness results of the samples for three heat treatments are also tabulated. Details on the microhardness testing are reported in a previous publication [11].

Table 2. Al/SiC$_p$ 20 mechanical properties results

Material	Condition	$\sigma_{0.2}$(MPa)	σ_{uts}(MPa)	ε (%)	E	$HV_{0.5}$
	(T1)	***141***	***151***	***1.5***	***101***	***114***
	HT-1	***127***	***163***	***4.0***	***104***	***172***
Al/SiCp20%	*T6*	***210***	***252***	***2.1***	***129***	***223***

In Fig. 2 the fatigue behaviour of all studied systems is depicted. All systems exhibit typical S-N behaviour, reaching the fatigue limit before 10^6 cycles, which was set as the run-out point for the fatigue experiments. While the HT1 system failed at approximately the same absolute stress level as the T1 system, the S-N curve of the T6 system was shifted to considerably higher stress values. In this context, the T6 heat treatment yielded higher fatigue strength than both the T1 and HT1 systems. As can be observed, the heat treatment had significant influence on the fatigue response of Al/SiC composites. This is in agreement with previous observations [11], concluding that the heat treatment is strongly affected by both the static properties, as well as the failure mechanisms during quasi-static tensile loading.

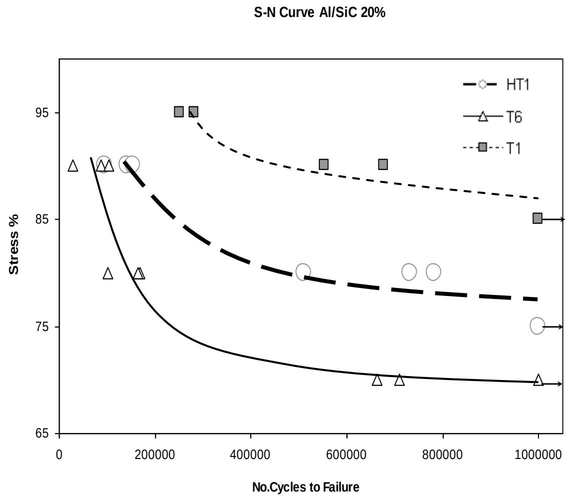

Fig. 2. S-N Curve of Al/SiC 20% Composite

In the T6 condition, due to the strengthening of the matrix and interface region with hard precipitates of Mg_2Si phases, the interface is much stronger. As the crack approaches the interface area, the crack energy tends to be absorbed by the SiC particles, leading them to fracture and an overall rapid failure. Thus the reinforcement no longer plays the role of stress relief site but behaves in a brittle manner, with the crack propagating through it. In lower stress levels the composite behaves in a different manner as the crack is arrested by the interface.

Fractography has been employed in order to verify the aforementioned mechanisms. In the T6 condition, SiC particles seem to be cracked but not debonded (Fig. 3) indicating good interfacial bonding. As the fractographic examination revealed for the T6 condition, the fractured surface at 28000 cycles at 95% of UTS fatigue (Fig. 4) showed striations formed in the aluminium matrix. This further supports the fact that high local stresses induce plastic flow of the matrix.

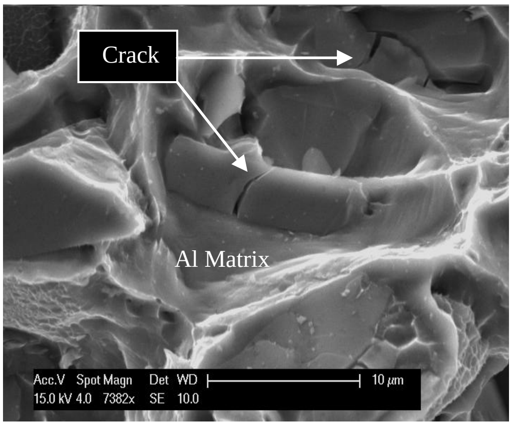

Fig. 3. Cracked SiC particles-Mg_2Si precipitates

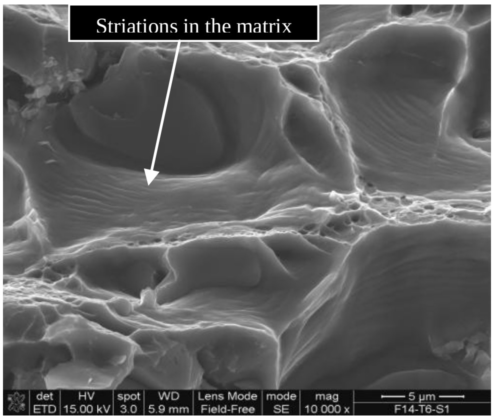

Fig. 4. T6 condition sample fractured surface at 226MPa stress level fractures around 28000 cycles-Striations shown in Al matrix

The fractographic examination for HT1 conditions revealed that the interface bonding is not as good as in case of the T6 condition. In this case, the crack is propagated mainly through the interface region leaving the reinforcement intact (Fig. 5a). The above postulation was validated by the clear evidence of debonded SiC reinforcement and the mark caused by the sliding of the reinforcement on the soft matrix (Fig. 5b).

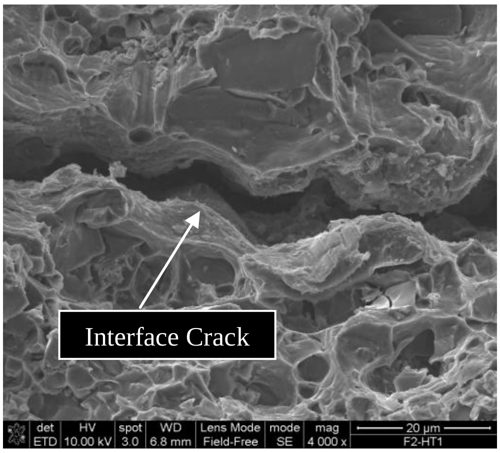

Fig. 5a. Al/SiC -HT1 condition- cracking through interface

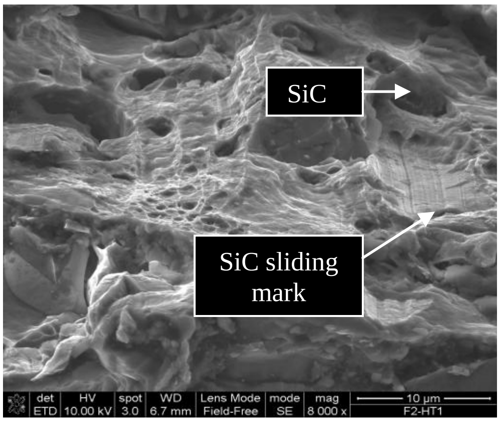

Fig. 5b. Sliding of SiC on the Al matrix showing weak interface

5. Conclusions

The tension-tension fatigue properties of Al/SiC composites have been studied as a function of heat treatment. The possible damage development mechanisms have been discussed. The composites exhibited endurance limits ranging from 70% to 85% of their UTS. The T6 composites performed significantly better in absolute values but their fatigue limit fell to the 70% of their ultimate tensile strength. This behaviour is linked to the microstructure and the good matrix-particulate interfacial properties. In the case of the HT1 condition, the weak interfacial strength led to particle/matrix debonding. In the T1 condition the fatigue behaviour is similar to the HT1 condition although the quasi static tensile tests revealed a less ductile nature.

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