Fatigue Behaviour of $Al/Al_2 0_3$ Metal Matrix Composites

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Abstract

Two new prototype composites containing a formulation of Aluminium 2618 alloy reinforced with a volume fraction of 20% aluminium oxide at T651 heat treatment and Aluminium 6066 alloy reinforced with volume fraction of 20% aluminium oxide at T651 heat treatment have recently been produced, both designed specifically to target brake rotor applications. In this study the fatigue behaviour of these MMCs is investigated. The fatigue behaviour was monitored and the corresponding S-N curves were experimentally derived for both composites. Microscopic studies reveal the damage accumulation mechanisms on the fracture surfaces of the composites.

Introduction

The use of particulate-reinforced aluminium alloy composites 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. The widely used reinforcing materials for these composites are silicon carbide and aluminum oxide in the form of particles or whiskers. The exceptional properties of metal matrix composites make it a prime candidate for light-weighting today's vehicles. The largest impact in lightweighing is unsprung weight. Replacing iron or steel brake rotors with MMC can result in as much as 50% reduction in unsprung mass. The mechanical behaviour of the aforementioned composites is dominated by the interface between the Aluminium matrix and the $Al_2 0_3$ 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 [1-3].

The response of the structural element to fatigue is critical for many applications. In the case of metal matrix composites (MMCs), the fatigue behaviour differs from that of unreinforced metals in several ways. 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 [4-6]. 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 [7]. A study by Davidson [8] concluded that there had been insufficient studies carried out on the fatigue crack initiation for alumina and silicon carbide, what was known at the time was that the larger the particulate reinforcement the more chance there was of fatigue cracks compared to reinforcements that had smaller sized particles. It was also known that poor particle dispersion in the manufacturing process would lead the formation of intrinsic cracks in the matrix. Recent studies by Myriounis et al. suggest that fatigue behaviour differs from that of un-reinforced materials [9].

Fatigue strength of aluminium alloy matrix composites has been reported to be mainly influenced by the thermo mechanical processing history of the composite. Recent studies have discussed the influence of heat treatment on the interfacial strength and the mechanical properties of reinforced aluminium alloy matrix composites [2]. The results indicated the interrelation between the heat treatment, the filler/matrix interface quality and the static failure mode of the composite. Further to the static properties, the heat treatment is expected to be of significant importance for the dynamic behaviour of these materials.

Material and heat treatment

The metal matrix composites studied in this work consisted of two different Al alloys 2618 and 6066 as matrix, reinforced with 20% volume Al_2O_3 particles. 2618 aluminium alloys are high strength alloys and due to the major alloying element being copper, additional strengthening can be achieved by precipitation hardening [10]. 6066 aluminium alloys are also high strength alloys like 2618 and can be strengthened further by precipitation hardening and offer excellent corrosion resistant properties and formability unlike 2618 alloys.
The composites were manufactured using stir casting technique and then cross hot rolled into sheets [11]. The average particle size is 18±1 μm. Table 1 shows the chemical composition of the matrix alloys. Both composites have been heat treated using T651 treatment. In particular 2618 MMCs were solution heat treated at 450^oC for two hours then water quenched; they were then aged for ten hours at 80^oC and air cooled, aiming in the formation of an equilibrium intermetallic phase (Al_2CuMg) [10]. These precipitate particles act as obstacles to dislocation movement and thereby strengthen the heat-treated alloys. For the 6066 samples higher solution temperature was used at 530 ^oC for 2 hours followed by water quenching and artificial ageing at 175^oC for 8 hours. Peak hardness occurs after 8 hours [12]. The main elements involved here are Mg and Si, and 6066 derives its strength from the precipitation hardening phase, Mg_2Si. As T651 heat treatment has been used the digits 51 indicate the composites have been stretched to relieve stresses within the materials.

Table 1. Chemical Composition of Aluminium

Elements (wt %)							
Material	**Cu**	**Mg**	**Fe**	**Mn**	**Ni**	**Ti**	**Si**
2618/Al_2O_3/20v/o%p	2.3	1.6	1.1	-	1.0	0.07	0.18
6066/Al_2O_3/20v/o%p	1.0	1.1	-	0.8	-	-	1.4

Experimental

Tensile testing

Prior to the fatigue testing tensile tests were performed in order to determine the yield stress of the composites. Tensile tests were conducted using hydraulic a universal testing machine and the strain was monitored using a clip gauge. The dimensions of the test coupons are shown in Figure 1. All the tensile tests were performed using 0.25 mm/min crosshead speed. At least three specimens were tested for each condition.

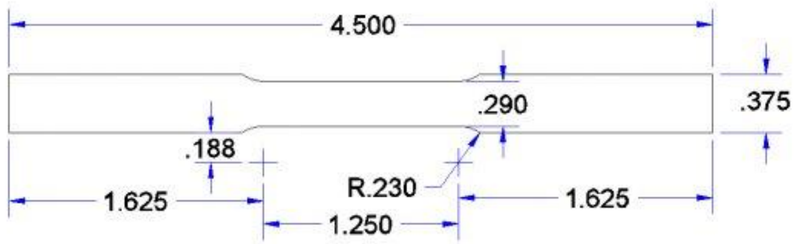

Figure 1. Specimen Configuration (All dimensions in Inches): Nominal Thickness: .080: Surfaces in As-Fabricated Condition, Edges Waterjet Cut.

Fatigue testing

Tension-tension fatigue tests were conducted using a 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 so-called Wöhler or S-N curves. Tests exceeding 10^6 cycles without specimen failure were terminated. The geometry of the samples was the same as those used for the tensile characterisation (see Figure 1).

Results and Discussions

Tensile testing

The results of the tensile tests for all the MMCs are shown in Figure 2 and the properties are summarised in Table 2.

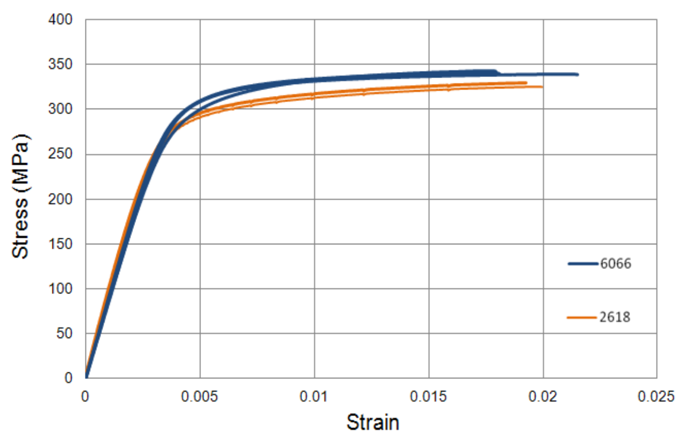

Figure 2. Stress vs. Strain Graph for 2618 & 6066 /Al_2O_3 Reinforced Composites

Table 2. MMC Average Mechanical Properties

	E (GPa)	σy (MPa)	UTS(MPa)
2618/Al_2O_3/20%p	97	293	328
6066/Al_2O_3/20%p	89	313	340

From the tensile testing results it can be concluded that the 6066/Al_2O_3/20%p composites exhibit slightly higher yield and UTS values compared with the 2618/Al_2O_3/20%p materials. The stiffness of these composites is definitely higher than the unreinforced aluminium (around 70 GPa) and this is mainly attributed to the harder particles which are reinforcing the soft and more ductile matrix. The aluminium matrix is also strengthened by the heat treatment precipitation processes. This allows the matrix to become stiffer and stronger. The strain to failure behaviour for both MMCs is similar with low values in comparison with unreinforced aluminium. The ductility is low for the Aluminium MMCs due to the hard and brittle Al_2O_3 particles.

In Figure 3 the fatigue behaviour of all studied systems is depicted. Both MMCs studied 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.

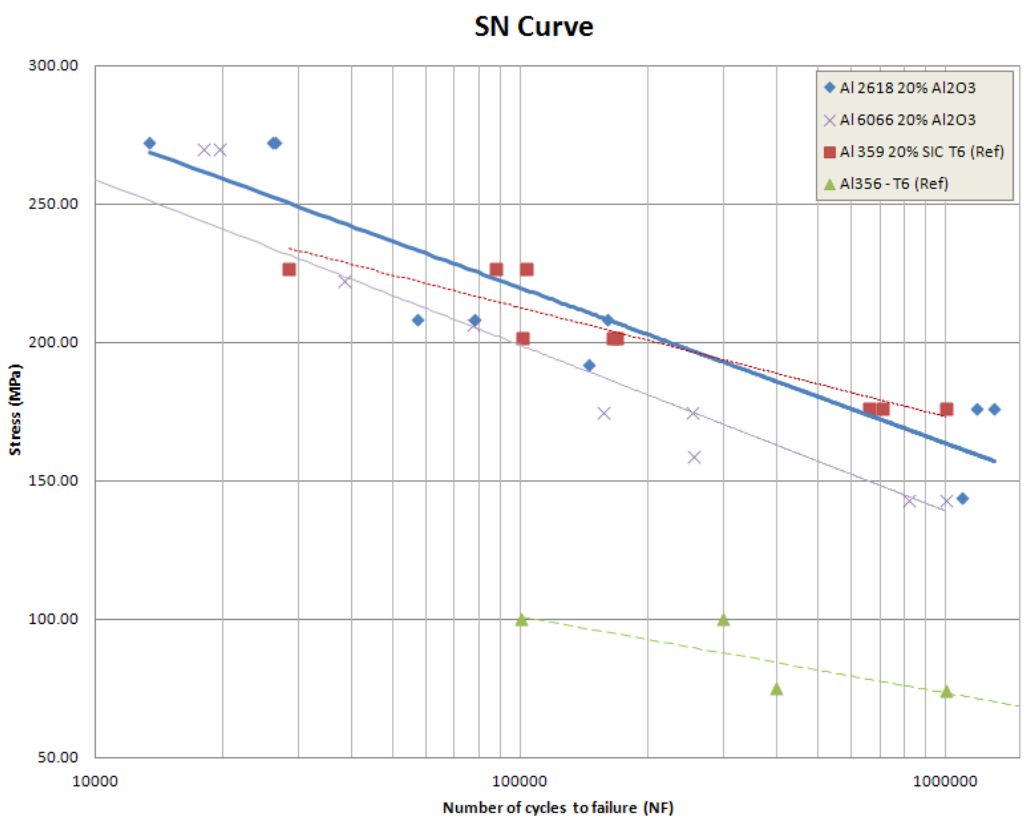

Figure 3. S-N curve for Al /Al_2O_3 Composites (Reference curves also shown)

From the S-N curve it can be observed that the 2618/Al_2O_3/20%p system was shifted to higher stress values than the 6066/Al_2O_3/20%p. In this context, 2618 MMCs have higher fatigue strength than the 6066 ones. Both composites exhibited low endurance limits ranging from 50% to 60% of their UTS. This is mainly attributed to the hard reinforcements which are reducing dramatically the fatigue strength after a critical point. Reference unreinforced Aluminium alloy exhibits very low fatigue strength in comparison with MMC values reported in this graph and in referenced ones [9]. As can be observed, the heat treatment had significant influence on the fatigue response of the composites. This is in agreement with previous observations [9], concluding that the heat treatment strongly affects both the static properties, as well as the failure mechanisms during quasi-static tensile loading. This mechanism relates to the precipitates appearing in the microstructure of the composite at the vicinity of the interface area, which results to the composite hardening.

Damage accumulation occurring during fatigue reflects within the materials microstructure leading to drop of fatigue strength and low but quick fatigue life behaviour. Microscopic studies helped to correlate the macro mechanical and microstructural mechanisms during the fatigue life of the material. SEM fractography studies reveal the damage accumulation mechanisms on the fracture surfaces of the composites. In Figure 4a-d fractured surfaces of the composites show some characteristic features. In Figure 4a cracked particles of alumina indicate excessive damage produced, leading to deformation of the softer and more ductile matrix and fracture of brittle particles (at a high cycle fatigue failure $>10^6$). In Figure 4c edge crack initiator shows that specimen design may affect the failure of the material. Also, large striations shown reveal the direction of the cracks along the fracture surface. Finally, in Figure 4d interfacial or/and interparticle crack shows the effect of excessive fatigue damage accumulation leading to the final fracture of the composite.

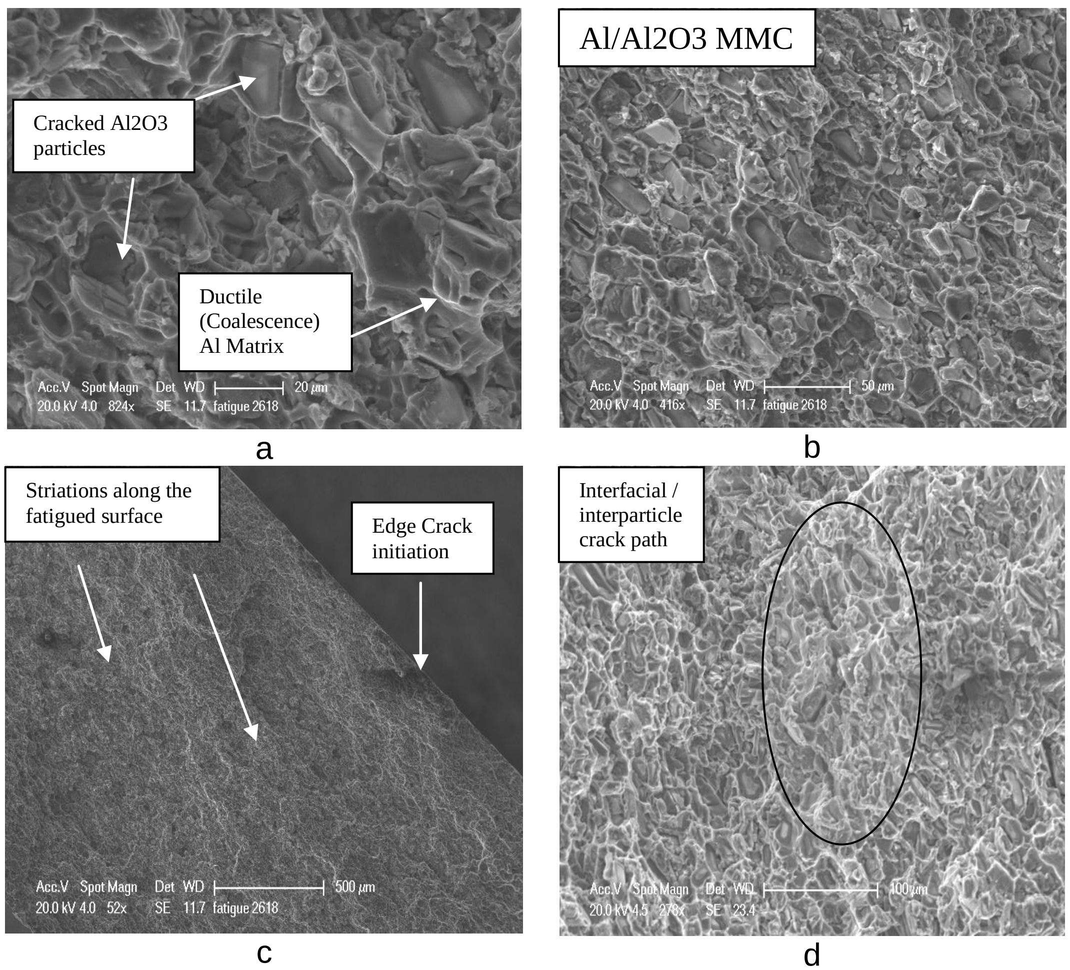

Figure 4. SEM fractographs of fatigued Al/Al_2O_3 composites at 10^6 cycles.

Summary

The tension-tension fatigue properties of Al/Al_2O_3 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 50% to 60% of their UTS.

The $Al2618/Al_2O_3$ composites performed significantly better in absolute fatigue strength values as well as fatigue limit which fell to around 60% of their ultimate tensile strength. The $Al6066/Al_2O_3$

composites fatigue strength and limit was slightly lower. This behaviour is linked to the microstructure and the matrix-particulate interfacial properties. The enhanced cohesion of the Al/ Al_2O_3 is mainly attributed to the strengthening mechanisms produced during heat treatment such as Al_2CuMg fully grown precipitates in the case of Al2618/Al_2O_3 composites which are reinforcing the matrix and produce a much better interfacial bonding.

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