# Fatigue and Fracture Behaviour of Al-SiC$_p$ MMC NDE by IR detection

***D.P.Myriounis, S.T.Hasan***

*Sheffield Hallam University, ACES, Engineering and Mathematics, City Campus, S1 1WB, Sheffield, UK*
*Corresponding author: d.myriounis@shu.ac.uk*

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## Abstract

In this study the fatigue and fracture toughness behaviour of Aluminium reinforced with SiC particles is examined. The Al/SiC$_p$ composites were subjected to heat treatments. The microstructure is tailored by introducing strengthening mechanisms such as precipitates and improved interfacial cohesion strength. The fatigue and fracture toughness behaviour was monitored and the corresponding S-N curves were experimentally derived for all heat treatments. The fatigue strength was found to depend strongly on the heat treatment. Infrared thermography (IR) was used to monitor the fatigue crack propagation as well as the fracture toughness behaviour of the composites. The heat wave, generated by the thermo-mechanical coupling and the intrinsic dissipated energy during mechanical and cyclic loading of the sample, is detected by a thermal camera. This technique will give us a better understanding of the materials performance and failure behaviour.

## 1. Introduction

Aluminium alloys are attractive base materials which, with the addition of discontinuous ceramic reinforcements, can achieve enhanced mechanical performance, i.e. strength, wear resistance and coefficient of thermal expansion [1-3]. The major drawback of the inclusion of the ceramic reinforcement in aluminium matrix composites is their tendency to brittle behaviour, i.e. low fracture toughness values, due to the brittle nature of the ceramic reinforcement in an otherwise ductile matrix [4-6]. The microstructure-dependent fracture mechanisms and their correlation to the macroscopical mechanical behaviour are not yet well understood in the case of particulate-reinforced metal matrix composites (MMCs).

To further understand the mechanisms involved with the fatigue and fracture toughness of MMCs, microstructural strengthening mechanisms such as precipitation hardening, need to be addressed. The strengthening micromechanical mechanisms of MMCs are very complicated due to the several parameters involved. Some of the factors affecting significantly the fatigue and fracture properties of particulate MMCs, are the particles size, interparticle spacing, and volume fraction of the reinforcement [7]. Furthermore, the MMCs performance can be influenced by complex microstructural mechanisms such as precipitation hardening achieved by heat treatment processing. Using appropriate heat treatment conditions, precipitates are formed in the matrix material leading to an improvement of interfacial strength of the composite, thereby enhancing the overall strength of the material [8].

The scope of the present study, involved the application of different heat treatment protocols on stripes of Al/SiC$_P$ 31% specimens with the aim of tailoring the fatigue and fracture toughness properties of the composites. Simultaneously, the stress field on the samples was monitored non-destructively as imaged by the transient temperature gradient per fatigue cycle using IR thermography.

## 2. Materials and Heat Treatments

The materials studied in this study are aluminium – silicon – magnesium alloy matrix A359, reinforced with silicon carbide particulates. Hot rolled A359 Aluminium alloy with 31% SiC particles per weight with an average particle size of 17±1 μm was used. The chemical compositions of the matrix alloys are shown in Table 1.

**Table 1** Compositional data of Aluminium matrix

| Material | Elements (wt %) | | | | | |
|---|---|---|---|---|---|---|
| | **Si** | **Mg** | **Mn** | **Cu** | **Fe** | **Zn** |
| **A359** | *9.5* | *0.5* | *0.1* | *0.2* | *0.2* | *0.1* |

The microstructure of the as received (T1) materials was modified using T6 and HT1 heat treatments [9]. In the T6 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 °C. Thus, all the solute atoms were allowed to dissolve to form a single-phase solid solution before being quenched in water. Next, the composites were heated to a temperature of 155 °C for 5 hours so as to allow the precipitation hardening mechanisms to grow. The expected phase was the $Mg_2Si$. In the modified HT-1 heat treatment the alloys were heated for 1 hour to a temperature lower than the T6 heat treatment that is 450±5 ° C, 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. Experimental Procedure

### *3.1 Fatigue testing*

Tension-tension fatigue tests were conducted 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. Tests exceeding $10^6$ cycles without specimen failure were terminated. Specimens that failed in or close to the grips were discarded. The samples were rectangular strips of 12.5mm width, and 1.55mm thickness.

### *3.2 Fracture Toughness $K_{IC}$ Testing*

Fracture toughness tests were conducted according the ASTM E399 standards using a 100 KN servo-hydraulic universal testing machine with data acquisition controller. The system was operated on load control for the fatigue pre-cracking stage, and on position control for the crack opening displacement (COD) testing. The fatigue test for pre-cracking in tension – tension at a load ratio of R = 0.25 was conducted at a frequency of 1 Hz due to the brittle behaviour of the material and the testing nature, that requires a slow crack propagation. The COD was monitored by a clip gauge attached to the specimen with a testing rate set at 1 mm/min. Compact tension (CT) specimens were prepared for fracture toughness tests according to ASTM E399. The thickness of the specimens was 9.2 mm.

### *3.3 Infrared Thermography*

Infrared thermography was used to monitor the fatigue crack propagation, the plasticity zone and the fractured area during testing. The deformation of solid materials is almost always accompanied by heat release. When the material becomes deformed or is damaged and fractured, a part of the energy necessary to initiate and propagate the damage is transformed in an irreversible way into heat [10] The principal advantage of infrared thermography is its noncontact, non-destructive character.

## 4. Results and discussion

### 4.1 Fracture Toughness

Fracture toughness data for Al/SiC$_p$ and unreinforced aluminium alloys are detailed in Table 2. From the results shown in Table 2, it becomes obvious that T6 heat treated specimen exhibit the highest $K_Q$ values compared to the other two heat treatment conditions. Although these results provide some insight regarding the fracture behaviour of the materials examined, specific validity criteria have to be satisfied in order to obtain $K_{IC}$ values. In summary, in the tests performed for all MMC specimens, heat treated in three different conditions, all validity criteria were met. Therefore, $K_Q$ values could be considered as $K_{IC}$ valid fracture toughness values. Also, the $K_{IC}$ values for all heat treatment conditions were higher than other MMC values documented in the literature, even having lower weight percentage of silicon carbide particles. Furthermore, the thermal images shown reveal the process zone formed (Fig.1a). As the crack propagates (shown in red region) plastic zone region ahead of the crack tip is also visible (Fig1b).

**Table 2** Fracture toughness results of MMCs

| **Material** | **Heat Treatment** | **E (GPa)** | **$Rp_{0.2}$ (MPa)** | **B (mm)** | **a/W** | **$\alpha_{eff}$ (mm)** | **$K_Q$ (MPa √m)** | **Valid** |
|---|---|---|---|---|---|---|---|---|
| **A359/SIC/31** | T1 | 108 | 158 | 9.20 | 0.45 | 20.7 | 19,28 | Yes |
| **A359/SIC/31** | **T6** | **116** | **290** | **9.21** | **0.46** | **20.1** | **22,05** | **Yes** |
| **A359/SIC/31** | HT1 | 110 | 155 | 9.20 | 0.46 | 21.3 | 20.75 | Yes |
| **A357/SIC/20** [11] | - | - | 215 | - | - | - | 18.60 | - |
| **A359/SIC/10** [11] | - | - | 300 | - | - | - | 17.40 | - |

4.2 Fatigue

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.

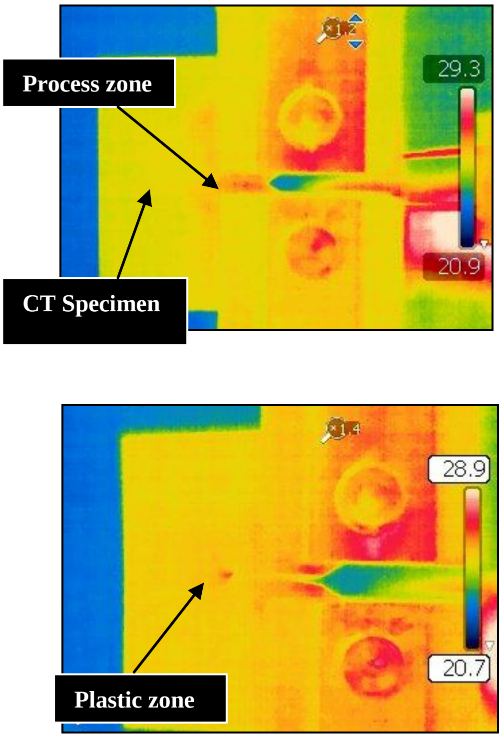

**Fig1a, b** Thermal images showing the process zone and plastic zone.

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 [12], concluding that the heat treatment is strongly affecting the static properties, as well as the failure mechanisms during dynamic testing.

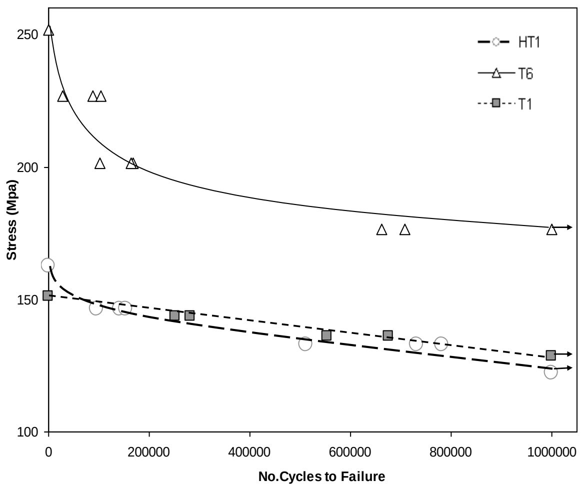

**Fig. 2** S-N Curve of Al/SiC 31% Composite

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.

In Fig. 3a, b, c, thermographic images are presented to demonstrate the development of damage close to the vicinity of the fracture area.

As can be seen in Fig. 3c, just prior to fracture, the plasticity area is clearly delineated on the specimen's surface as a round heated region which may be readily attributed to local plastic deformation. This real-time thermographic characterisation allowed the prediction of the fracture location of the specific sample approximately 25 minutes or 4493 cycles before failure.

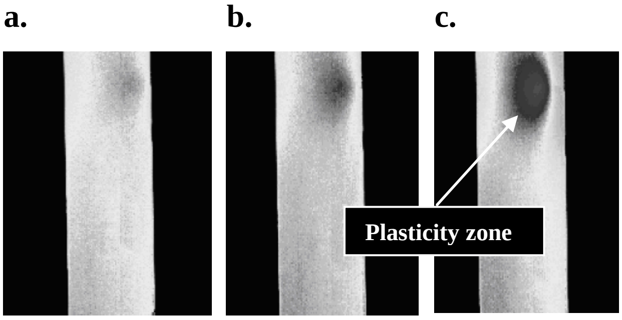

**Fig. 3** Thermographic images of fatigued Al/SiC composite specimen showing the formation of plasticity zone before fracture occurs, (a) at *246500* cycles, (b) at 248600 cycles, and (c) at *251000* cycles, which corresponds to the specimen's fracture point.

## 5. Conclusions

The determination of valid plane strain fracture toughness ($K_{IC}$) for particulate-reinforced aluminium matrix composites subjected to different heat treatment conditions has been achieved by satisfying all the validity criteria as per ASTM E399 standard. It was found that $K_{IC}$ values reported in this paper are higher than other MMC values documented in the literature, even with lower weight percentage of silicon carbide particles.

The endurance limit of the composites in the fatigue tests ranged between 70% and 85% of their UTS. The T6 composites performed significantly better in absolute values. This behaviour is linked to the microstructure and the good matrix-particulate interfacial properties.

Heat treatment processing is the key to this improvement, with the T6 heat treated composite to convene the highest fracture toughness value. This can be attributed to a dominant mechanism associated to microstructural changes in the composite. This mechanism relates to the precipitates appearing in the microstructure of the composite at the vicinity of the interfacial region, which results to the composite's hardening.

The plastic zone actually gets smaller due to heat treatment therefore improved cohesion strength has been achieved. There is more crack closure during crack propagation therefore the resistance of the structure to the crack is higher than the as received composites.

Infrared thermography was used to monitor in real-time the various stages of crack growth up to the specimen's final fracture, in order to demonstrate that linear elastic fracture mechanics approach was satisfied and support the validity of fracture toughness measurements. Thermographic examination of the materials showed that heat treated composite samples exhibit regular crack propagation behaviour. Stress concentration, due to the presence of particle reinforcements, produces controlled crack growth and higher stresses, which are related to regular energy release by the material during fracture, indicative of brittle fracture behaviour. The need for higher stresses for a crack to propagate reveals the material's microstructural strength.

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