QUANTIFICATION OF THE EFFECTS OF REINFORCEMENT DISTRIBUTION AND MORPHOLOGY ON FATIGUE IN Al-SiC$_p$ COMPOSITES

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ABSTRACT

Fatigue behaviour in particle-reinforced AA2124-18.7 vol% SiC has been investigated. Short crack growth was analysed in terms of reinforcement morphology and spatial distribution along crack paths, as well as in the surrounding microstructures. Reinforcement distribution was quantified in detail via 'finite body' tessellation. Of the numerous morphology and distribution parameters obtained, regression analysis particularly identified a combined influence on growth rates of reinforcement clustering (in terms of the spread of neighbouring particle separations) and alignment in the regions were crack growth occurred.

Keywords: *Fatigue, Short crack growth, Al-SiC composites, Clustering, Tessellation.*

INTRODUCTION

Discontinuously reinforced aluminium alloys are being considered for an increasing number of structural applications, including fatigue critical components where improvements in fatigue life commonly associated with particle reinforcements may be exploited (at least for load controlled situations) [1,2]. A detailed understanding of crack initiation and growth processes is therefore of considerable interest to reliably predict and optimise the fatigue resistance of these materials. Critical physical processes associated with ceramic reinforcement of a metallic matrix include local load transfer mechanics and associated stress/strain concentrations, the presence of matrix/reinforcement differential thermal contraction stresses and the modification of matrix microstructure by the presence of reinforcements (e.g. dislocation densities and precipitation characteristics). The extent to which reinforcements may affect crack growth processes may further particularly depend on interfacial strength, reinforcement morphology (size, aspect ratio, volume fraction) and spatial distribution. A number of authors have identified qualitatively the effects of particle distribution and morphology on crack growth processes, with, for example, clusters of particles and large particles both being associated with local reductions in growth rate and deflections of the crack path in the earliest stages of fatigue crack growth [3-6]. To date however, the effects of reinforcement distribution on crack growth behaviour have not been explicitly quantified.

The identification of Dirichlet cells around individual secondary phase bodies, such that every point within the cell is closer to the centroid of the associated body than any other, has been previously identified as a uniquely powerful analysis tool in describing distribution characteristics of particle-reinforced materials. The degree of clustering or regularity of overall distributions may then be evaluated via statistical analysis of specific cell characteristics [7-12]. Furthermore, the facility to quantify cell parameters on an individual, particle-by-particle basis may be extremely valuable in relation to 'nucleation'-type processes such as monotonic crack initiation and propagation [10,13]. In a separate publication by the present authors [14], such a tessellation process has been extended to finite bodies to provide a more physically meaningful description of non-spherical secondary phase bodies exhibiting a wide size range. A finite body tessellation consists of a network of cells such that every point within a cell is closer to the *interface* of the corresponding body than to any other. Initial results on the effects of particle distribution on short crack growth in a relatively low volume fraction Al-SiCp composite (6 vol.%) have shown that crack-reinforcement interactions occurred preferentially in small particle/low reinforcement content regions [15]. In this paper, the growth rates of microstructurally sensitive short fatigue cracks in a particle-reinforced aluminium alloy are examined in relation to the morphology and distribution of the reinforcement phase.

EXPERIMENTAL PROCEDURES

The material selected for this study was a 2124 aluminium alloy reinforced with 18.7 vol.% of particulate SiC with a nominal particle size of 6.5μm. The composite was powder-processed, forged, and cross-rolled. Tensile and fatigue samples were machined in the longitudinal direction, solutionised at 505°C for 1 hour, cold-water quenched, stretched to a plastic strain of 2% to minimise macroscopic residual stresses and aged to peak strength at 170°C for 16 hours. Corresponding tensile properties were measured as: yield strength, 534 MPa; tensile strength, 583 MPa, and total elongation, 4.6%. Fatigue testing of polished four-point bend bars was conducted in the L-S orientation under constant amplitude sinusoidal loading at a frequency of 20 Hz in air. A maximum top surface stress corresponding to 90% of the nominal yield strength and a loading ratio of 0.1 were used. Crack initiation and subsequent growth were monitored using acetate replicas. Stress intensity values for the various surface cracks were obtained from Scott and Thorpe's solution for semi-elliptical cracks [16].

Image analysis methods for characterising reinforcement spatial distribution have been detailed elsewhere [14]. An accurate and convenient method for generating finite body tessellations has been proposed, together with the implementation of a number of tessellation measurements. These include cell area, local area fraction (ratio of particle and corresponding cell areas) and a number of 'neighbouring particle' parameters based on the concepts of near-neighbour (defined as cells sharing boundaries) and near-neighbour distance (defined as the shortest distance between corresponding particle interfaces): number of near-neighbours, nearest-neighbour distance, mean near-neighbour distance and nearest-neighbour orientation. Further standard measures of reinforcement morphology were obtained, such as area, aspect ratio and orientation.

CRACK GROWTH ANALYSIS VIA TESSELLATION

Fatigue behaviour was specifically studied in the short crack regime, corresponding to maximum crack growth rates of ~ 10^{-5} mm/cycle. Replicas of specimen surfaces were taken prior to loading, and were used to produce tessellations of the regions where crack growth was seen to occur subsequently. Such regions surrounding individual cracks were analysed out to ~ 70μm on each side of the growth plane. Crack paths and tessellations of the surrounding microstructures were then overlaid, as shown in Figure 1. In assessing the effects of reinforcement distribution and morphology on crack propagation, local variations in image analysis measurements along crack paths were analysed, as well as the variations in these parameters in the associated surrounding microstructures (i.e. the region ± 70μm about each crack). Two types of crack interactions were identified: (i) cells containing particles directly intersected by the crack path and (ii) cells intersected by the crack path (independent of the associated particle being intersected or not). The latter measurement may then be seen as indicative of near-tip crack-particle interactions, rather than direct contribution of the reinforcement to crack advance. Approximately 50 crack-cell interactions occurred per 100μm of crack growth, with corresponding surrounding microstructures consisting of several thousands of cells.

Surrounding microstructures were further characterised in terms of reinforcement inhomogeneity by evaluating the coefficient of variation (ratio of standard deviation and mean) of specific tessellation measurements [9]. This may be illustrated for distinctly homogeneous and inhomogeneous regions as shown in Figure 2. Corresponding coefficients of variation of the tessellation measurements from these images are shown in Figure 3, highlighting the sensitivity of

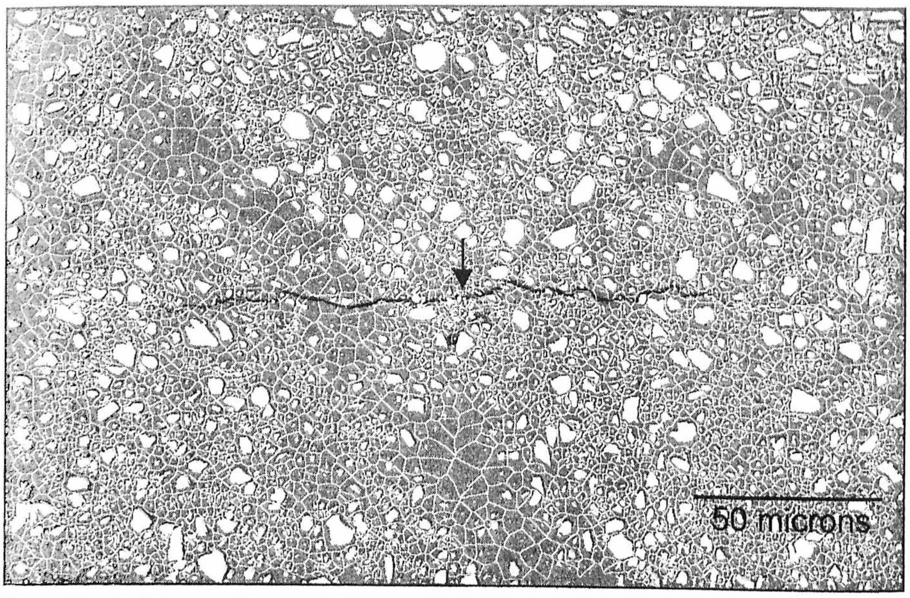

Fig. 1 : Typical short surface crack with superimposed tessellation (arrow indicates initiation site)

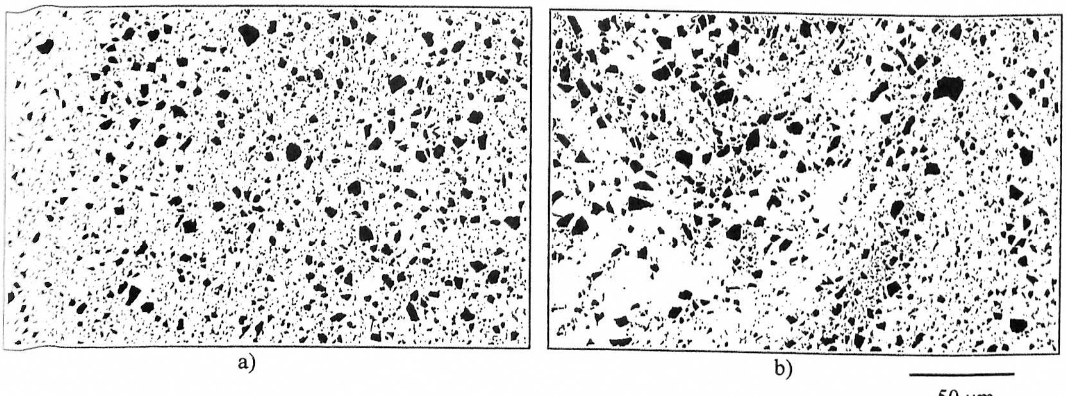

Fig. 2: Binaries of two distinct regions a) homogeneous and b) clustered

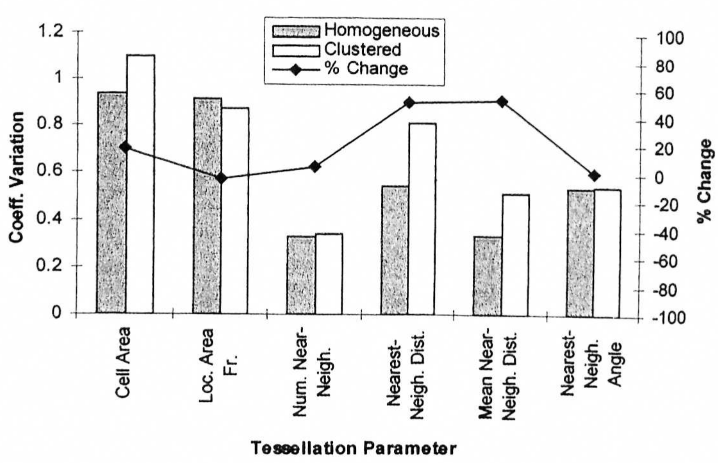

Fig. 3 Changes in coefficients of variation with particle distribution

nearest-neighbour and mean near-neighbour distances to the degree of clustering, with the coefficient of variation increasing with increasing inhomogeneity.

RESULTS AND DISCUSSION

Twenty-nine surface cracks were identified in the present study that had all, bar one, initiated in the first 25% of total fatigue life, growing to maximum lengths ranging from 54 to 1000 μm after 43,500 cycles. Initiation sites consisted predominantly of processing defects such as crack-like features (62%), porosity (17%) and intermetallics (3%). The remaining cracks (18%) nucleated within the matrix. These observations are broadly consistent with the literature [1,4], with the observed absence of particle cracking and decohesion amongst initiation sites attributable to fine particle size and high interfacial strength respectively. In terms of analysis, the growth of short cracks from multiple initiation sites was commonly observed, as shown in Figure 4, precluding direct comparisons of crack growth behaviour (i.e. crack tip driving forces being affected by the specific local arrangement of the initiation sites). Hence, detailed analysis was only possible on those 11 cracks which displayed single continuous paths from initiation onwards.

By plotting crack growth rates against stress intensity ranges (see Figure 5), two regimes of crack growth were identified. In the earliest stages of short crack growth ($\Delta K \sim$ 1-3 MPa√m, corresponding to surface crack lengths < 60μm), short cracks manifested classical intermittent growth and frequent arrests. At higher stress intensities ($\Delta K \sim$ 3-6 MPa√m, corresponding to surface crack lengths between 60 and 180 μm), more continuous crack growth was observed. Furthermore, in terms of average growth rates, variations of up to an order of magnitude were recorded for the first 60 μm of growth. As such this regime was of particular interest. Corresponding average growth rates and image analysis results were examined in terms of simple regressions and associated correlation coefficients of all the parameters collected, although no consistent effect was identified with any *one* parameter. Multiple regressions however identified a consistent combined influence on growth rates of the degree of clustering (measured as the coefficient of variation of mean near-neighbour distances) and the mean reinforcement orientation of the surrounding microstructures, as shown in Figure 6. Specifically, average growth rates rose with increased inhomogeneity and increased particle alignment in the loading direction. A strong underlying correlation between particle orientation and aspect ratio was identified in this material (presumably due to processing) and, as such, the two were in fact interchangeable in terms of growth rate influence.

It is interesting to note that whilst local reductions in crack growth rate have been associated with the size and arrangement of the reinforcement along the crack path [4-6], average growth rates were primarily dependent on specific characteristics of the surrounding microstructures. Furthermore, decreases in crack growth rates at reinforcement clusters reported by Li and Ellyin [6] are not reflected in the present results which consider overall growth rates through regions of varying homogeneity.

In terms of defining the surrounding microstructure to a crack, scale is clearly important. Specifically, over what distance may a given cluster influence crack tip behaviour. At one extreme, reinforcement distribution characteristics may vary within a material at a mesoscopic level (i.e. variations extending over hundreds/thousands of particles). Such variations will influence any crack growth that occurs within that region in terms of the bulk compliance of that region and associated load transfer interactions with its surroundings (e.g. a locally high volume fraction region may act as a stiff 'phase' in itself). At the finest scale, the spatial characteristics of a given particle will of course influence local stress/strain conditions [17]. The strongest correlation of reinforcement distribution and morphology with crack growth rates in the present work was associated with the microstructures immediately surrounding the crack, rather than the individual cells along the crack paths. In the first instance this implies that mesoscopic effects may be important. It is however surprising then that there was no correlation with mean volume fraction,

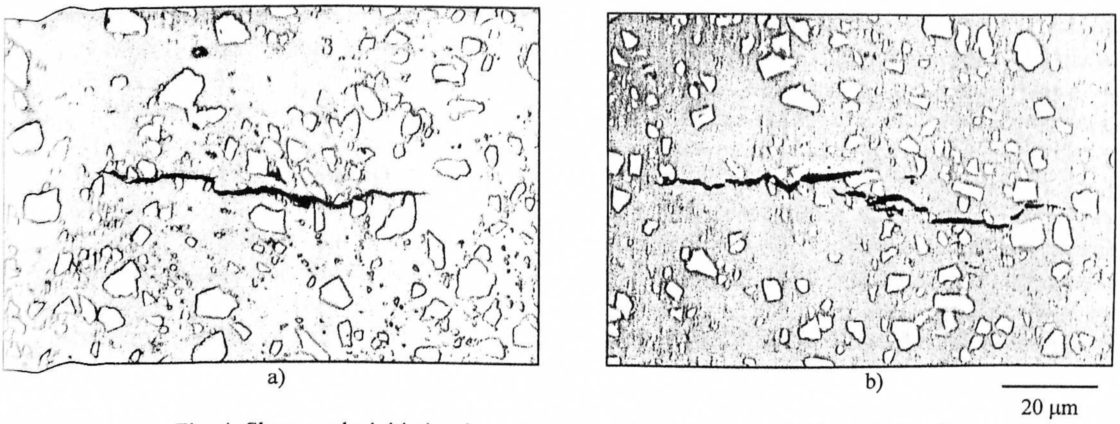

Fig. 4: Short cracks initiating from a) a single initiation site (crack-like defect) and b) multiple initiation sites (cluster of defects)

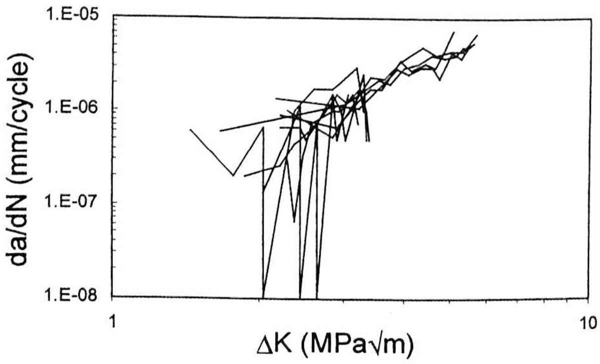

Fig. 5: Crack growth rate behaviour

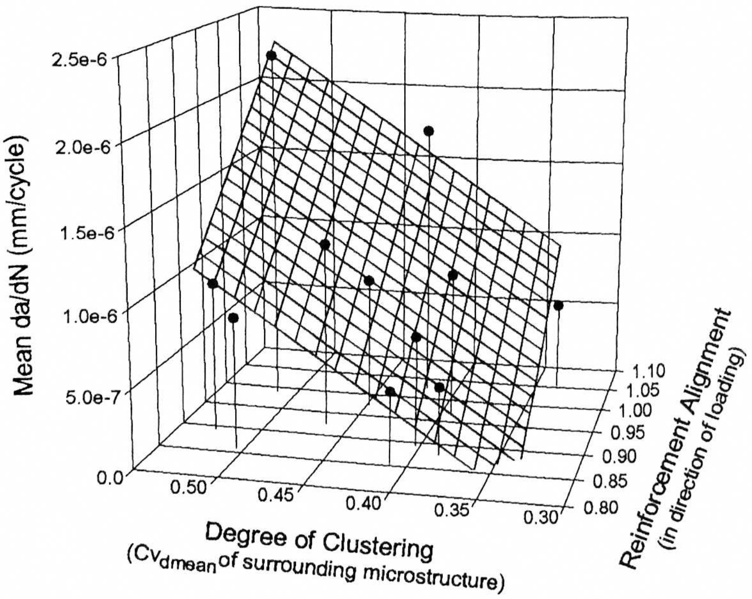

Fig. 6: Linear regression for average growth rates vs. image analysis measurements (Cv_{dmean} corresponding to the coefficient of variation of mean near-neighbour distances)

as this will have a first order influence on the behaviour of a given region, and hence any mechanical interactions with surrounding material during loading (and indeed, during fabrication). A single consistent effect that may be attributed to increasing clustering and particle alignment/aspect ratio in a given region is an increase in the local peak stress levels [18]. This would then be expected to influence crack growth at a very local scale, i.e. be reflected in the cell-crack and particle-crack interactions, which did not appear to be the case. In the first instance it may then be noted that defining near-crack interactions in terms of cells and particles that are directly associated with crack growth is not fully representative, and the neighbours of these cells should also be examined, as the environment of these particles may still be expected to have an influence on local stress and strain conditions at the crack tip. Further work is however required to clarify the scale over which these effects operate, and take into account any changes in the scale of the crack tip stress/strain fields with increasing crack length (i.e. the scale over which the crack 'samples' the surrounding microstructure, increasing as a function of K^2).

CONCLUSIONS

Tessellation has been identified as a valuable tool in characterising and quantifying the effects of reinforcement distribution and morphology on crack growth in particle-reinforced materials. For the short crack growth regime of interest here, the most consistent influence of reinforcement on crack growth rates was associated with the clustering and degree of particle alignment in the region surrounding the crack path, with no clear correlations being identified with the particles and cells that interact directly with crack growth. Increased clustering and particle alignment were both seen to increase average crack growth rates. The separation of microscopic and mesoscopic variations in reinforcement distributions is highlighted from these results, although the scale over which effects should be considered requires further clarification.

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