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The influence of transition phases on the damage behaviour of an Al/10vol.%SiC composite

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Abstract

In particle reinforced metal matrix composites (MMCs) such as Al/SiC$_p$, there exist microscopic inhomogeneities due to the different elastic–plastic behaviour of the phases. As a result, stress and strain concentrations emerge at these inhomogeneities, the capacity for the deformation of one phase can be exceeded and local damage of the material and even macroscopic failure may occur. In order to investigate the damage behaviour of the ductile matrix, the damage parameter D, which was introduced by Rice and Tracey, and modified by Arndt et al., is used. Furthermore, cracking of the particles is the most commonly observed damage mechanism concerning the ceramic inclusions. In this case, a normal stress criterion is exploited to describe such kind of failure. As a third and more complex failure mechanism, delaminations between particles and matrix can take place. Frequently, there exists a transition phase between matrix and the inclusions with both, a ductile or a brittle material behaviour. To analyse the damage behaviour of the transition zone, both damage models (D-parameter and normal stress criteria) are applied into this region. Subsequently, this microstructure is modelled regarding the inclusion arrangement and the transition phase characteristics and parameter studies with respect to different transition interphase dimensions, material properties and critical failure stresses are performed. The damage behaviour of the microstructure is evaluated in consideration of the path and the amount of damage as well as stress–strain performance of the microstructure. In addition, residual stress effects on the damage behaviour are examined for various situations. In the light of these, the critical failure parameters that affect the damage behaviour of the microstructure are determined by comparing the results of several cases. It has been found, that transition phase material properties and dimensions possess an undeniable influence on the damage mechanisms of Al/SiC$_p$ composites.

Keywords: Metal matrix composites (MMCs); Microstructure; Damage parameter D; Normal stress criterion; Interface effects; Residual stresses; Finite element analysis

1. Introduction

Various techniques for the production and design of composite materials have been developed over the last few years in order to improve the mechanical properties of the materials and thus obtain more effective outcomes, low-cost and a weight reduction in structural applications. Metals reinforced by brittle particles such as silicon-carbide (SiC$_p$) offer numerous advantages over conventional engineering materials due to excellent strength to weight ratio, their high elastic modulus and tensile strength, superior creep resistance and ease of being machinable and workable using well-known methods. These properties make this type of composite attractive for a wide-range of application fields such as automotive, electronic and aerospace industries [1–3]. Research activities in recent years have been centered on relating to inclusion shape and location, matrix hardening, interface behaviour, residual stress effects and microstructural damage behaviour of MMCs, so as to optimize the mechanical characteristics of this kind of materials [4–6]. However, the accurate modelling of the mechanical behaviour of actual heterogeneous materials is not an easy task due to the irregular microstructural geometries that

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exist in real composites [7]. The mechanical behaviour of MMCs is strongly dependent on the microstructure. For instance, damage evolution and the failure properties are influenced by the spatial distribution and local volume fraction of particles in MMCs, hence it is essential to take care of the arrangement of the reinforcement during processing. In addition, the microstructural heterogeneity is an extremely crucial issue for MMCs. It has undeniable effect on the macroscopic mechanical properties of such composites. Therefore, it should be observed very cautiously.

In spite of several benefits associated with MMCs, their widespread use is limited primarily because of having low strains to failure, their poor ductility and poor fracture toughness behaviour. For instance, the addition of ceramic particles or fibres reduces the ductility of an aluminium (Al) matrix by a factor two [9]. Therefore, drastic damage behaviours (ductile failure, brittle failure or delaminations between matrix and particle) are sometimes recognized in the microstructures of MMCs at early loading stages, as shown in Figs. 1–3.

Since the transition phase between the reinforcement and the matrix plays an important role primarily for damage initiation and propagation [4], it should be also analyzed carefully and their impact on damage of MMCs ought to be clarified in all important aspects. Furthermore, residual stresses are present in the matrix and the inclusions owing to the difference of thermal expansion coefficients between ductile matrix and brittle inclusions. The cooling provokes frequently radial tensile stresses in the matrix and radial compressive stresses in the inclusions during processing and the yield stress as well as initial hardening of composites are influenced mainly by these residual stresses [8,9].

Many research activities have been focused on this field adopting crystal plasticity, continuum theory and micromechanical approach. In order to describe the deformation of composites containing small concentrations of submicron second-phase particles, dislocation plasticity models are exploited, whereas continuum approach gives reasonable results for composites having large-scale reinforcements [11]. Furthermore, a micromechanical approach to the damage in matrix, particles and at the interface between matrix and inclusion makes the mechanical behaviour of the whole structure evident. Thus, the future development of MMCs depends strongly upon succeeding improvements in their fracture and damage-related properties without increasing the cost of the final product.

In the light of these facts, a damage study for an Al/10vol.%SiC MMC microstructure considering the matrix, inclusion and interface phases separately is carried out in this study. First, the micrograph of an Al/10vol.%SiC cut-out is converted to a pixel graph in order to separate the SiC-inclusions (black pixel) and the Al-matrix (white pixel). After that, by examining the black–white binary microstructure picture, a new pixel area (transition phase) around the inclusion regions is produced with the developed pixel code. After generating the transition phase, a mesh code is developed to construct matrix, inclusion and transition phase meshes automatically for the finite element analyses using ABAQUS [15]. Finally, a subroutine is created to apply damage models for the ductile matrix,

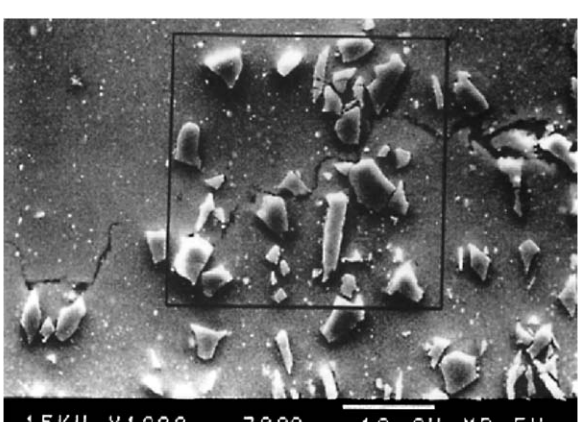

Fig. 1. Ductile failure inside the matrix of an Al/20vol.%SiC MMC [17].

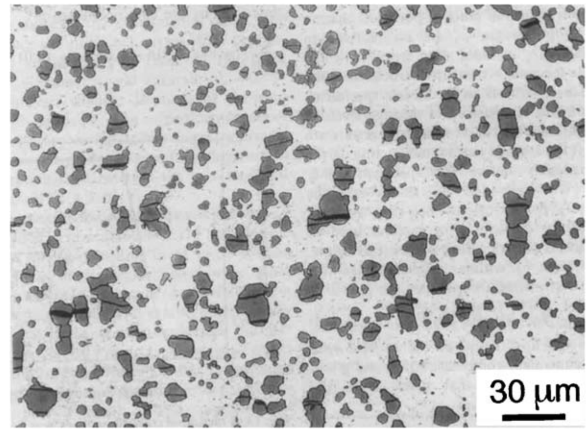

Fig. 2. Brittle failure in particles perpendicular to the tensile loading direction in an Al/SiC_p MMC [10].

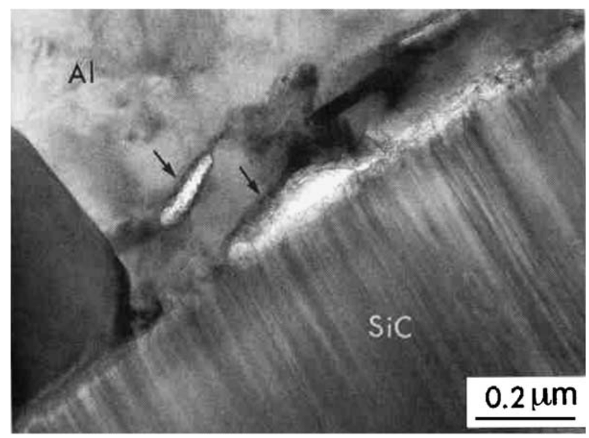

Fig. 3. Debonding in an Al/SiC_p MMC during tensile deformation (arrows indicate the sites where debonding occurred) [12].