Journal of the Mechanics and Physics of Solids 57 (2009) 1781–1800

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

Particle fracture in high-volume-fraction ceramic-reinforced metals: Governing parameters and implications for composite failure

Aude Hauert, Andreas Rossoll, Andreas Mortensen *

Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Mechanical Metallurgy, Station 12, CH-1015 Lausanne, Switzerland

A R T I C L E   I N F O

Article history:
Received 22 December 2008
Received in revised form
9 July 2009
Accepted 20 August 2009

Keywords:
Fracture mechanisms
Particulate-reinforced material
Mechanical testing
Probability and statistics
Weibull strength distribution

A B S T R A C T

Weibull parameters of angular alumina particles are determined from experimental tensile test data on high-ceramic-content metal matrix composites using a micromechanical model that accounts for internal damage in the form of particle cracking, the dominant damage mode in these composites. The fraction of broken particles is assessed from the drop of Young's modulus and particle fracture is assumed to be stress controlled. Two extreme load-sharing modes, namely a purely local and a global load-sharing mode, are considered to account for the load redistribution due to particle fracture. Consistent powder strength parameters can be thus "back-calculated" for particles that are embedded in different Al–Cu matrices. On the other hand, this calculation fails for pure Al matrix composites, which exhibit a much larger strain to failure than Al–Cu matrix composites. It is shown that for Al matrix composites, the role of plastic (composite) strain on particle fracture constitutes a second parameter governing particle damage. This finding is rationalized by particle–particle interactions in these tightly packed ceramic particle-reinforced composites, and by the increase of matrix stress heterogeneity that is brought with increasing plastic strain. Failure of the alloyed matrix composites is well described by the (lower bound) local load-sharing micromechanical model, which predicts a catastrophic failure due to an avalanche of damage. The same model predicts failure of pure aluminium matrix composites to occur at the onset of tensile instability, also in agreement with experimental results once the role of plastic strain on damage accumulation is accounted for.

1. Introduction

The tensile failure of particle-reinforced metal matrix composites (PRMMCs) is preceded, and largely governed, by the evolution of internal damage during straining. In order to predict the failure of such materials, it is thus necessary to characterize and model the evolution of damage as they deform. Among the different damage modes present in PRMMCs, particle fracture is commonly encountered for composites containing brittle particles that are strongly bonded to a strong and tough matrix.

Typically reinforcements are made of ceramic; fracture of ceramics is generally considered to be stress controlled and to follow a Weibull distribution (Kingery et al., 1976). Whereas experimental assessment of intrinsic fracture properties of bulk ceramic structures or fibre reinforcements is relatively straightforward, this is difficult or impossible in the case of ceramic particles, since testing of individual particles is far more challenging (a pioneering effort can be found in Yoshida et

* Corresponding author. Tel.: +41 21 693 2912; fax: +41 21 693 4664.
E-mail address: andreas.mortensen@epfl.ch (A. Mortensen).

0022-5096/$ - see front matter
doi:10.1016/j.jmps.2009.08.005

al., 2005). Particle strength data have thus to be determined in an indirect way, i.e. by testing composites and inferring the desired properties via a more or less sophisticated model. For instance, some authors have related the fraction of broken particles to the average particle stress using Weibull statistics (Majumdar and Pandey, 2000; Mochida et al., 1991a). Others have related the cracking propensity to the particle aspect ratio and size (Bréchet et al., 1991; Derrien et al., 1999; Lewis and Withers, 1995; Llorca et al., 1993; Wallin et al., 1987). Also using Weibull statistics, Babout et al. (2004) studied different particle cracking criteria, namely the average particle stress in the loading direction (i.e. the largest principal stress within the particles), the average elastic energy stored in the particle, or the average Tresca stress within the particles (these values were calculated from single-particle axisymmetric finite-element cells). The fraction of broken particles was measured by X-ray microtomography for two composites containing different volume fractions of reinforcement. The authors showed that both the principal stress criterion and the elastic energy criterion are appropriate: these yield similar intrinsic particle properties for both composites. This was on the other hand not the case for the Tresca criterion.

It is known that ''back-calculated'' particle Weibull parameters depend strongly on the micromechanical model used to assess particle stress and on further assumptions made, such as accounting or not for particle size and aspect ratio (Lewis and Withers, 1995). Furthermore, indirect assessment of in-situ particle strength does not always yield a stress-type Weibull distribution. This was for example found by Mummery, Derby, Zong, and co-workers, who conducted acoustic emission experiments on composites with matrices of different strengths (Mummery et al., 1993; Zong et al., 1997). In the studied composites, particle fracture could be better described as controlled by composite plastic strain than as controlled by stress.

The aim of the present work is twofold: we first examine whether particle fracture in high-volume-fraction PRMMCs is stress controlled and obeys Weibull statistics. To this end we study damage of angular alumina reinforcements of one type embedded in several different matrices. Damage is monitored via the evolution of Young's modulus. The stress state in the particle phase is assessed using a micromechanical model accounting for load redistribution due to particle failure by either of two different load-sharing mechanisms, namely global or local load sharing (Hauert et al., 2009a). In a second step, using the phase properties calculated with the model, we use the same micromechanical model to predict failure of the composites to show that it predicts well the ductile-to-brittle transition that is observed in these composites as the matrix flow stress is increased. We also show that at higher composite strain, a new damage mode appears, namely particle damage linked, not with average particle stress, but with composite strain.

2. Experimental procedures

2.1. Materials

The present work focuses on damage by particle failure, and we thus choose materials where this damage micromechanism is dominant, in which the interface is strong (such that there is no decohesion) and the particles sufficiently brittle so that they crack before there is extensive matrix voiding. These are PRMMCs made of one of three matrices (Al 99.99%, Al–2 wt% Cu, or Al–4.5 wt% Cu) reinforced with angular alumina particles, which are known to crack within composites of these metals (Kouzeli et al., 2001; Miserez and Mortensen, 2004; Miserez et al., 2004). Pure aluminium was purchased from Hydro Aluminium GmbH (Grevenbroich, Germany) and Al–Cu alloys were produced by Alusuisse SA (Neuhausen, Switzerland). Angular-shape alumina powders, Alodur® WSK F320, were purchased from Treibacher Schleifmittel (Laufenburg, Germany). The mean particle size was measured by centrifugal sedimentation and equals $33.3 \pm 8\,\mu m$ (Miserez, 2002).

Composites were produced in house by gas pressure infiltration. This process involves forcing, under pressurized argon gas, the liquid metal into a loose preform of particles, packed to their maximum tapped density. Details of the process can be found in Despois et al. (2003) and Mortensen (2000). The resulting material presents a high density of homogeneously distributed ceramic reinforcements in a pore-free and metallurgically simple matrix; also, interfaces in these composites are strong and free of interfacial reaction products (Kouzeli et al., 2001; Miserez and Mortensen, 2004). The different castings used in this study will be referred to as *XY*, where *X* is a casting designation number and *Y* identifies the matrix (A for 99.99% pure Al, A2C for Al–2 wt% Cu, and A45C for Al–4.5 wt% Cu).

Composite density was measured with an immersion technique, using a high-precision Sartorius MCP 210P microbalance (IG Instrumenten-Gesellschaft, Zürich, Switzerland). Knowing the density, the volume fraction of reinforcement (V_r) in the composites was calculated for each sample.

2.2. Tensile tests and damage monitoring

Dogbone tensile specimens were made by electro-discharge machining in the longitudinal direction from as-cast composite billets. The geometry of the pure aluminium matrix specimens corresponds to ASTM E-8M (1999). These subsize dogbone samples have a reduced section length of 32 mm, a width of 6 mm, and a thickness of 2.5 mm. For composites with an alloyed matrix, the specimens are slightly shorter with a reduced section length of 25 mm, other dimensions being identical to the pure aluminium matrix specimens. Alloyed samples were then heat treated to the T4 or T6 condition (solutionized for 10 h at 515 °C, water quenched, and, for the T6 treatment, artificially aged to peak hardness at 100 °C for 12