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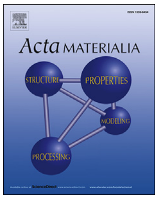

Full length article

Multi-axial response of idealized cermets

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The yield response of two *idealized cermets* comprising mono and bi-disperse steel spheres in a Sn/Pb solder matrix has been investigated for a range of axisymmetric stress states. Proportional stress path experiments are reported, from which are extracted the initial yield surfaces and their evolution with increasing plastic strain. The initial yield strength is nearly independent of the hydrostatic pressure but the strain hardening rate increases with stress triaxiality up to a critical value. For higher triaxialities, the responses are independent of hydrostatic pressure. Multi-axial measurements along with X-ray tomography were used to demonstrate that the deformation of these idealized cermets occurs by two competing mechanisms: (i) a granular flow mechanism that operates at low levels of triaxiality, where volumetric dilation occurs under compressive stress states, and (ii) a plastically incompressible mechanism that operates at high stress triaxialities. A phenomenological viscoplastic constitutive model that incorporates both deformation mechanisms is presented. While such multi-axial measurements are difficult for commercial cermets with yield strengths on the order of a few GPa, the form of their constitutive relation is expected to be similar to that of the idealized cermets presented here.

1. Introduction

Cermets are composite materials that contain a high volume fraction of ceramic particulates (typically carbides, nitrides, and oxides, in the range of 50%–95% by volume) within a ductile metal binder phase (e.g. Mo, Ni, Co, Al) [1,2]. They offer a good compromise between the hardness of ceramics and toughness of metals, e.g. typical values for WC/Co composites are in the range of 500–2000 HV and 8–20 MPa $m^{1/2}$ respectively [3]. This combination of mechanical properties makes them suitable for lightweight ballistic armour applications, where the high hardness value results in the erosion/destruction of the projectile [4], and the improved toughness increases the ability of the structure to sustain multiple impacts [5]. More commonly, cermets are used as hard coatings for tools and high-pressure components, in order to reduce wear and increase the service life [6,7].

The elastic properties of ceramic particle reinforced metals with low particulate volume fractions (e.g. less than 50%) have received extensive attention. These include their uniaxial response [8–10] as well as their multi-axial behaviour [11]. By contrast, investigations of the inelastic properties of cermets have mainly been restricted to the influence of the particulate volume fraction on the uniaxial compressive response [10,12], indentation hardness, and toughness. Little information exists about the dependence of the multi-axial response of these materials on stress triaxiality, possibly because the extremely high yield strength impedes instrumented measurements of the deformations involved. Several studies have used metal jacket confinement tests [13,14] to provide a qualitative estimate of the behaviour of these materials under multi-axial stress states. These studies suggest that both the compressive strength and ductility increase with increasing lateral confinement [13,14]. Notched tensile specimens have also been used to examine the influence of triaxial stress on the ductility and failure of cermets, with an increase in tensile triaxiality observed to increase the failure stress and decrease the failure strain [15]. However, since the precise multi-axial stress state is not straightforward to extract, such measurements cannot be used to estimate the yield surfaces of cermets or the corresponding plastic flow rules.

Uniaxial compression tests of cermets suggest that they behave like high cohesive strength granular materials with shear band formation and associated dilatancy [16,17]. For example, Getting et al. [12] observed that WC/Co cermets dilate under uniaxial loading, and Bele and Deshpande [16] demonstrated via experiments on idealized cermets that this dilation was primarily confined to shear bands. These deformation mechanisms are similar to those of granular media [17], where an initial compaction

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phase occurs as inter-particulate voids collapse and the particulate density increases. The newly-packed granular assembly contains a network of force chains formed by contacting particles [17]. The maximum compressive strength of the material is governed by the buckling of these force chains and the formation of a localised shear band [16], and volumetric dilation within the shear band is due to the progressive buckling of the force chains. Correspondingly, increasing the confining pressure will delay the onset of volumetric dilation within the shear band [13,14,17]. The effect of these force chains is further illustrated by the marked difference in compressive and tensile failure stresses observed for high volume fraction cermets [18]. By contrast, low volume fraction cermets of the same composition displayed negligible tension-compression asymmetry.

In order to investigate the mechanical properties of cermets in more detail, idealized model materials have been used, e.g. composites comprising steel spheres in a soft Sn/Pb solder matrix [16]. These idealized materials possess the same particle/matrix contrast in elastic moduli and yield strengths as commercial cermets, but have a simpler microstructure and significantly lower macroscopic yield strength, thus facilitating standard instrumented laboratory-based mechanical testing. Uniaxial compression of these materials has demonstrated that (a) percolation of the steel spheres and the associated formation of force chains leads to a compressive strength that is significantly higher than what is predicted by models of uniformly distributed aggregates, and (b) deformation under uniaxial compression is due to the formation of shear bands, with significant dilation occurring within these bands [19].

There is thus considerable evidence that commercial cermets behave like granular materials [12,16,17,19]. Therefore, their multi-axial yield response is not expected to be governed solely by the von-Mises equivalent stress. In this study, we take advantage of the relatively low compressive strength of idealized cermets to measure their multi-axial plastic response, with the aim of elucidating the constitutive behaviour of commercial materials. A triaxial load cell is used to conduct axisymmetric compressive experiments over a range of stress states (triaxialities). The experimental set-up allows simultaneous control of the stress triaxiality, and direct measurement of axial and radial strains. These measurements, along with X-ray tomography, are used to clarify the dependence of deformation mechanisms on the triaxial stress state, and to extract a phenomenological constitutive model for the yield surface and plastic flow rule of these materials.

2. Experimental investigation

The overall aims of the experimental program are to (i) determine the stress-strain responses of the idealized cermets under proportional compressive axisymmetric loading, and (ii) investigate the shape of the initial yield surface and its evolution under proportional compressive load paths.

2.1. Materials and manufacture

Two types of idealized cermets, comprising AISI 52100 steel spheres in a Sn/Pb solder matrix (Sn 60, Pb 38, Ag 2 wt%), were manufactured as in Ref. [16]: (i) mono-dispersed specimens, with spheres of 2 mm diameter packed to a volume fraction $V_f \approx 65\%$ in the solder matrix, and (ii) bi-dispersed specimens, with spheres of diameters 4 mm and 0.5 mm (70% and 30% by volume respectively[1]), packed to an overall volume fraction $V_f \approx 0.75$.

Cylindrical specimens of diameter 18.5 mm and height 40 mm were manufactured for both types of idealized cermets. The spheres were first packed into a cylindrical crucible of the appropriate diameter and vibrated under a low applied axial compressive stress of ≈0.1 MPa to maximize the packing density. High temperature magnets were then placed around the periphery of the crucible to maintain the skeleton structure of the steel spheres, and solder powder (of average particle size 25–38 μm) was infiltrated into the interstitial sites. A small amount of ZnCl flux was added to improve interfacial adhesion, and the assembly was pressure-cast at a pressure of ≈0.1 MPa and temperature of 200 °C for 1 h.

Optical images of the cross-section of representative mono and bi-disperse specimens are included in Fig. 1. Some voids are visible in both types of specimens; X-ray tomography measurements (discussed in Section 3) indicated that the void volume fraction was in the range of 1.5%–5% in both types of specimens. Vickers hardness tests were conducted to measure the mechanical properties of the two phases and revealed that the AISI 52100 steel had a Young's modulus of 210 GPa and yield strength of 2.1 GPa, while the Sn/Pb solder had corresponding modulus and yield strength values of 32 GPa and 39 MPa respectively (uniaxial compression tests on the matrix material reported in Ref. [16] confirmed these properties of the Sn/Pb solder).

2.2. Apparatus and measurement protocol

A high-pressure apparatus (Fig. 2a) was used to subject the specimens to triaxial compression tests. It consists of a pressure cell with a maximum capacity of 100 MPa, and a piston for the application of axial force. Hydraulic fluid was used as the pressurising medium, and axial load was applied by displacing the piston via a screw-driven test machine. A submerged load cell provided readings of the axial load independently of the pressure of the surrounding fluid. Two linear variable differential transformer (LVDT) transducers were attached to the specimen as shown in Fig. 2a in order to measure the axial displacement imposed on the specimen. A third LVDT was attached to the mid-height of the specimen to measure the change in specimen diameter.

The applied stresses are sketched in Fig. 2b: p denotes the fluid pressure and σ_a the axial stress, defined as the ratio of the applied axial load (as measured by the submerged load cell) to the initial cross-sectional area of the specimen. With p taken to be positive in compression, the mean (hydrostatic) stress σ_m, and von Mises effective stress σ_e are

$$\sigma_m = -p + \frac{\sigma_a}{3}, \tag{2.1}$$

and $\sigma_e = |\sigma_a|$, respectively. Note that the radial Cauchy stress on the specimen equals the fluid pressure p. The corresponding work-conjugate strains (mean strain ε_m and effective strain ε_e) are given in terms of the axial strain ε_a and radial strain ε_r as

$$\varepsilon_m = 2\varepsilon_r + \varepsilon_a, \tag{2.2}$$

and

$$\varepsilon_e = \frac{2}{3}\left|\varepsilon_r - \varepsilon_a\right|, \tag{2.3}$$

respectively.

Prior to the start of each test, the specimen was consolidated within the triaxial cell by applying a pure hydrostatic pressure $p = 100$ MPa : this consolidation step was found to improve the repeatability of the measurements. The majority of tests were conducted along proportional stress paths with the direction of the

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[1] Readers are referred to [20] for a detailed discussion on the random packing of spheres, including maps that specify the sphere size distributions and volume fractions required in order to achieve a specified overall volume fraction of spheres.