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Multiresolution modeling of ductile reinforced brittle composites

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ABSTRACT

Tungsten carbide–cobalt (WC–Co) is an important ductile reinforced brittle composite used in a range of important applications. The relationship between microstructure and mechanical properties of WC–Co is truly multiscale; micromechanical processes interact at different scales, resulting in permanent plastic deformation, damage accumulation and final failure of the composite. The goal of the current paper is to develop a continuum-based model, which captures the progressively finer scales of strain localization observed in WC–Co composites during plastic deformation and failure. This is achieved via a set of multiresolution governing equations; a micro-stress is introduced at each scale of strain localization, which represents the resistance to inhomogeneous strain localization at that scale. The extra constitutive models associated with these microstresses can be elucidated from the average response of separate computational cell models of a representative microstructure. The final multiresolution continuum model is capable of capturing the important length scales of deformation during the plastic stage of deformation without resorting to modeling microstructural scale features directly. The result is a more realistic continuum model; in particular the fracture toughness prediction is more physical when these length scales are incorporated compared to a conventional continuum approach.

1. Introduction

Tungsten carbide–cobalt (WC–Co, cemented carbide, hardmetal or cermetal) is an important ductile reinforced brittle composite composed of a population of hard tungsten monocarbide (WC) grains (hexagonal crystal structure) 'cemented' together by a tough cobalt alloy binder (FCC structure) via a liquid-phase sintering process. The resulting composite has excellent hardness, toughness, and compressive strength, transverse rupture strength (resistance to bending failure) and wear resistance. It is particularly well known for its use in cutting tools, metal-forming tools, mining tools, and wear resistance surfaces.

The key microstructure parameters are assumed to be (Kim, 2004; Gurland, 1988; German, 1985):

(i) *Cobalt volume fraction f*: The ratio of cobalt phase to the total volume.
(ii) *Cobalt grain size d*: Interpreted as the average distance a dislocation can travel in the cobalt before hitting a carbide grain, i.e. the typical size of a cobalt pool. It is closely related to the carbide grain size.

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Cobalt volume fraction f is simply given by

$$f = \frac{V_{Co}}{V} \tag{1}$$

where V_{Co} is the volume of cobalt contained in a sample of volume V.

The high hardness and strength of cemented carbides is due to the high carbide volume fraction—see Table 1. The high fracture toughness is due to the highly ductile cobalt. Toughness is directly related to the volume fraction of ductile cobalt f, which absorbs energy via plastic deformation. However, a larger cobalt fraction f is accommodated by a decreased fraction of the much harder carbide phase, resulting in a reduction in strength.

To a lesser extent, large cobalt grains also increase toughness as the area over which plastic deformation occurs is controlled by the cobalt grain size d; as the cobalt grain size increases plastic deformation ahead of a crack tip spreads over a larger area. However, larger grains d have lower strength according to the Hall–Petch effect. In general, a larger cobalt grain size d and a greater cobalt fraction f result in a tougher behavior but with a lower strength. The effects of cobalt volume fraction f and grain size d on hardness and toughness are shown schematically in Fig. 1.

The processes that control the mechanical properties and failure mechanisms within the WC–Co composite's microstructure are truly multiscale in nature. In the cobalt phase of the composite, deformation is facilitated by atomic scale dislocation induced plasticity, atomic scale vacancy diffusion leading to nanoscale void nucleation, microscale void growth, coalescence and ductile failure. In the carbide grains, brittle fracture occurs. Ductile failure of the cobalt and brittle fracture of the carbide grains combine to form macroscale cracks which penetrate through the cobalt and carbide components.

The goal of the current paper is to develop a homogenized continuum model for WC–Co that retains each of the important length scales associated with the deformation and damage mechanisms. In the current model, the important length scales are observed to be the size of the cobalt grains, the crack opening displacement of a brittle crack in the carbide grains and the typical size of a nucleated microvoid. By including these length scale parameters, the resulting continuum model can replicate the progressively smaller length scales at which strain localizes as the material degrades. This multiresolution approach results in a more physical prediction of the energy released during composite failure, i.e. the fracture toughness. In terms of computational implementation, the embedded length scales ensure that the post-instability deformation is independent of the discretization used during finite element analysis. However, the mesh must be fine enough to resolve the smallest length scale of localizing strain that the user wishes to capture.

Table 1
Comparison of density, Young's modulus and hardness for cemented carbide components (memsnet.org., 2006).

	Density ($kg\,m^{-3}$)	Young's modulus (GPa)	Hardness (GPa)
WC	15,800	700	19.61
Co	8900	209	0.7
WC–Co	~15,000	~600	~16
Stainless steel	7900	200	5.84

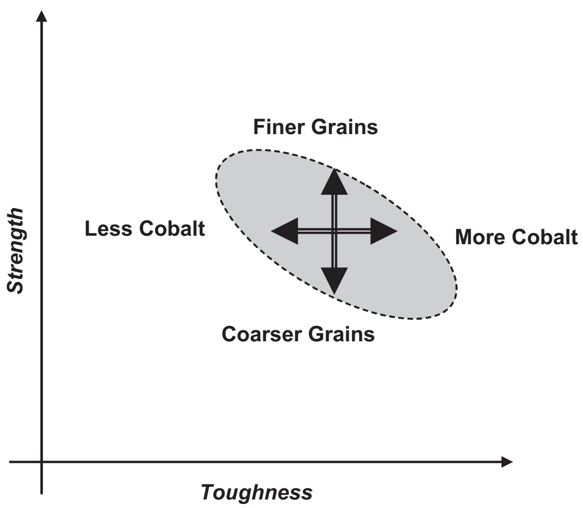

Fig. 1. Strength versus toughness for cemented carbide; coarse grains and more cobalt increase toughness to the detriment of strength and vice versa.