Materials Science and Engineering A 393 (2005) 133–139

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Elastic properties of ceramic–metal particulate composites

C.L. Hsieh, W.H. Tuan*

Department of Materials Science and Engineering, National Taiwan University, Taipei, Taiwan

Received 12 July 2004; received in revised form 1 October 2004; accepted 6 October 2004

Abstract

In the present study, the experimental data on the elastic properties of several ceramic–metal systems, Al_2O_3–NiAl, SiC–Al, WC–Co and glass–W, are compiled and compared with several theoretical predictions. These theoretical predictions offer upper and lower bounds on the elastic constants. The elastic moduli of the ceramic–metal composites fall well within the Voigt–Reuss bounds and Hashin–Shtrikman (H–S) bounds. Though most the Poisson's ratio of ceramic–metal composites falls within the modified H–S bounds, the values of the composites with low second-phase concentration deviate from model predictions. The deviation shows strong dependence on the interconnectivity of each phase in the composites.

Keywords: Composites; Elastic modulus; Poisson's ratio

1. Introduction

The elastic properties of monolithic materials (ceramics or metals) depend strongly on their bonding characteristics [1]. For example, the elastic modulus of monolithic ceramics reflects their cation-oxygen bonding length and strength under tension [2]. The bending strength of inter-atomic bonds determines the magnitude of shear modulus. Among these elastic constants, Koester and Franz suggested that the Poisson's ratio provided more information about the character of the bonding forces [3]. Furthermore, the elastic constants are sensitive to the composition change. The presence of solute can alter the bonding characteristics as well as the elastic constants of materials [2].

The bonding characteristics of ceramics are different from those of metal. The addition of ceramic into metal or vice versa introduces heterogeneous interfaces. To be demonstrated later, the elastic properties of the two-phase materials often deviate from the prediction made by using the rule of mixtures. It may be related to the presence of heterogeneous interface.

Though the properties of ceramics and metals are different, the combination of two materials to form composite exhibits many potential applications. For example, the hardness of tungsten carbide (WC) is very high; nevertheless, the sintering between WC particles is not possible below 1500 °C. Metallic cobalt can bond WC particles strongly together at a relatively low temperature [4]. The WC–Co composite can thus be applied as cutting tool. The addition of Al into SiC can result in improved thermal stability [5]. The addition of NiAl improves the toughness of Al_2O_3 [6]; the presence of ZrO_2 particles enhances the high temperature strength of NiAl [7].

The knowledge about the elastic properties of two-phase systems is essential for designing new composites and functionally graded materials [8–13]. With the knowledge of the elastic modulus, other properties such as hardness and creep resistance can then be estimated [14,15]. There are many theoretical models available to predict the elastic constants of two-phase materials [16–38]. Some models contain one or two adjustable variables that have to be determined experimentally [19–23,25–38]. Some models need only the properties of the two constituents to predict the elastic constants [8,16–18,24]. Among these models, several models can offer fixed values for the elastic properties of two-phase materials [8,19–21]. Several models propose upper and lower bounds instead [8,16,17,19–21,32–36]. All these models claim that

* Corresponding author. Tel.: +886 2 23659800; fax: +886 2 23634562.
E-mail address: tuan@ccms.ntu.edu.tw (W.H. Tuan).

0921-5093/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2004.10.009

they can match the experimental data well. However, the pre-existed experimental data cover only part of the composition range for a certain composite. A recent study reported the elastic constants of Al_2O_3-NiAl system for whole range of composition [37], which makes comparison between experimental data and theoretical predictions possible. Apart from the data of Al_2O_3–NiAl system, the available data for other ceramic–metal composites, SiC–Al, WC–Co and glass–W, are also compared in the present study to verify the model predictions.

2. Theoretical models

Most theoretical models are made under the assumptions of perfect bonding at the interface, strain compatible and negligible elastic interaction between particles [16–38]. These models further employed simplified geometries, as shown in Fig. 1, to derive their mathematical equations. In the present study, experimental data are compared with the theoretical predictions. A comprehensive data collection on the ceramic–metal composites has been carried out. These experimental data vary within a range instead of a specific point. The model predictions that can provide upper and lower bounds to cover the experimental data seem more plausible. Therefore, the following three models are chosen: (1) Voigt–Reuss, (2) Hashin–Shtrikman (H–S) and (3) Ravichandran models.

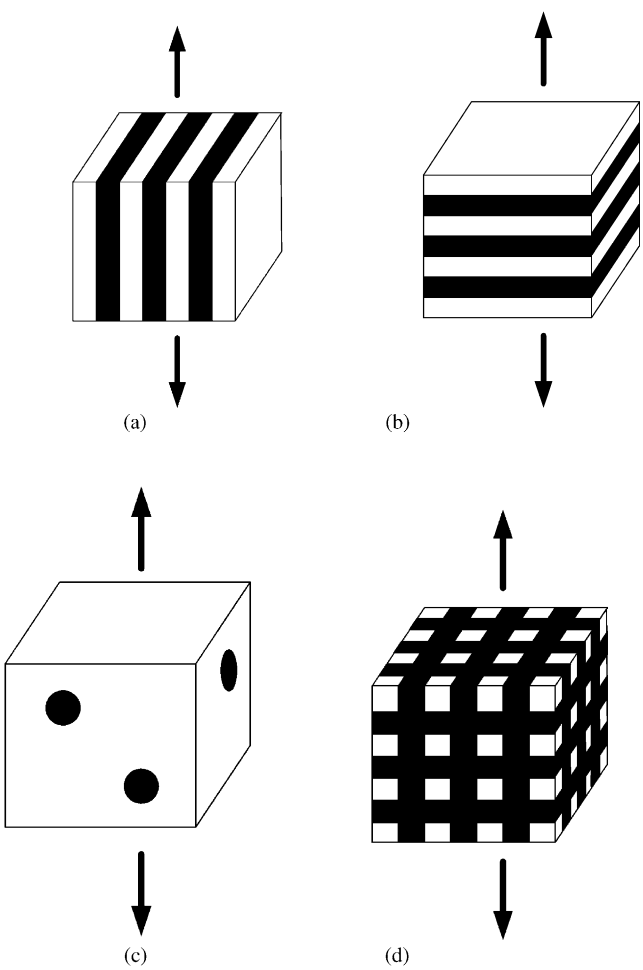

Fig. 1. The unit cell proposed in (a) iso-strain (Voigt) state and (b) iso-stress (Reuss) state. The geometrical models employed by (c) Hashin–Shtrikman (H–S) and (d) Ravichandran models. The arrows indicate the direction of the external load.

2.1. Voigt–Reuss bounds

Fig. 1(a) shows the case that the strain of the two phases in the composite under an external load is the same. The loading direction is parallel to the interface. The elastic modulus of the composite, E_c, as proposed by Voigt [16] is

$$E_c^u = E_m V_m + E_p V_p \tag{1}$$

with $V_m + V_p = 1$, V_m and V_p are the volume fraction of matrix and particle, respectively. Eq. (1) follows the rule of mixtures. When the composite is under an iso-stress state as proposed by Reuss [17], as shown in Fig. 1(b), the elastic modulus is expressed as

$$E_c^l = \frac{E_m E_p}{E_m V_p + E_p V_m} \tag{2}$$

The superscripts u and l denote upper and lower bounds, respectively. As pointed out by Hill [22], neither iso-strain nor iso-stress assumption is realistic. The tractions at interface are not at equilibrium under the Voigt condition; the interface could not remain bonded under the Reuss condition. Though the equality in Eq. (1) is true only when the Poisson's ratios of the two phases are the same; the values predicted by Eqs. (1) and (2) are widely treated as the upper and lower bounds of the elastic modulus of any two-phase materials, respectively [5]. The Voigt–Reuss bounds are thus used in the present study to compare the experimental data.

Each value of elastic modulus (E), shear modulus (G), bulk modulus (K) and Poisson's ratio (ν) can be calculated by knowing any two elastic constants. However, it should be noted that it is not suitable to calculate the Poisson's ratio under the iso-strain and iso-stress assumptions.

2.2. Hashin–Shtrikman (H–S) bounds

Hashin and Shtrikman treated the two-phase system composing of one randomly distributed particulate phase and one continuous matrix phase, Fig. 1(c). The model provides bounds for the elastic constants of a two-phase material with a random isotropic distribution of phases from the properties and volume fraction of each phase [19–21,36]. The "minimum energy" principle was employed to show the bounds on the bulk modulus and shear modulus as

$$K_C^l = K_m + \frac{V_p}{(1/K_p - K_m) + (3V_m/3K_m + 4G_m)} \tag{3}$$