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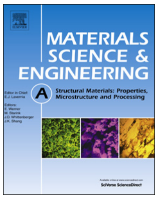

# Mechanical properties of cermet composites with various geometrical tortuosity of metal phase: Fractal characterization

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## ABSTRACT

Although the mechanical properties of cermet composites have been investigated extensively, how to quantitatively determine the relationship between the performances and the geometrical structures of the reinforcement phase is still one of the top challenging problems yet to be solved. To determine the influence of the geometrical structure of the reinforcement phase on the mechanical performances of composites, $Cu_2O$/Cu cermets were prepared with spherical or branch like Cu by the hot-pressing technology. Box-counting fractal dimension increasing rate with increasing filling content of reinforcement phase was first applied to quantitatively reflect the relationship between the geometrical structures of metal phase and the mechanical properties of composites. A simple model was developed by combining fractal theory and power law, in which the critical exponents were determined via experimental results. This study not only provides a pathway to understand the mechanisms of the geometrical structure of the reinforcement phase to the mechanical properties of composites, but also sheds light on the geometrical tortuosity characterization by using fractal approach in cermet composites.

## 1. Introduction

Cermet composites have been widely applied in many fields. They can be used as promising materials for solar energy conversion [1], cutting tools [2], anti-corrosion coating under marine environment [3], inert anode materials for aluminum production [4], electrical devices [5] or sensors [6]. Most of the cermet composites are composed of metal phases embedded in ceramic matrixes. With respect to properties, both advantages and disadvantages of the ceramic phase and the metal phase will be inherited in the final cermet composites. As one of the basic properties, the mechanical performance is always the first priority that needs to be considered before the using. It was found that the mechanical properties are governed by the microstructures of both ceramic phase and metal phase which were determined by many factors, including the properties of the raw materials, preparation approaches, chemical reaction and wetting and bonding conditions between the metal and ceramic interfaces, and the atmosphere during the preparation process [7–11].

The mechanisms of ceramics reinforced by metals, polymers or carbon materials have been investigated for decades, and many successful results have been extensively reported to demonstrate the relationship between the final mechanical properties and the reinforcement phases. The most widely accepted model is the mixture model expressed as

$$\rho_{mix(p)}=\rho_r f_r+\rho_m f_m \tag{1}$$

where $\rho_{mix}$ is the mechanical properties of composite, such as Young's modulus, strengths, or fracture toughness, $f_r$ and $f_m$, and $\rho_r$ and $\rho_m$ are the volume or weight contents and the mechanical properties of the reinforcement phase and the matrix, respectively. Especially, if the reinforcement materials are fibers or carbon nanotubes, this model will be modified as [12]

$$\rho_{mix(p)}=\mu_1\mu_2\rho_r f_r+\rho_m f_m \tag{2}$$

where $\mu_1$ represents the length efficiency factor, and $\mu_2$ represents the orientation efficiency factor.

Other models based on the rule of mixture were further developed in fiber or nano tube reinforced composites. The elastic modulus of the composites can be expressed as [13]

$$E_{c/m}=(E_{r/m}-1)V_r \quad (\text{lower bound}) \tag{3}$$

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$$E_{c/m}=\frac{(E_{r/m}-1)V_r}{E_{r/m}+(1-E_{r/m})V_r} \quad \text{(upper bound)} \tag{4}$$

where $V_r$ is the volume fraction of the reinforcement, $E_{c/m}=(E_c-E_m)/E_m$, $E_{r/m}=E_r/E_m$, and $E_c$, $E_r$ and $E_m$ are the longitudinal elastic moduli of the composites, reinforcement phase, and the matrix, respectively. However, some experimental data reported that the mechanical property of composites as a function of the filling content of the reinforcement is not linear, especially when the filling content takes large values. Consequently, a revised form of the rule of mixtures was developed with exponential form [13]:

$$E_{c/m}=(\varepsilon_l\varepsilon_o\varepsilon_w E_{r/m}-1)V_r\exp\alpha V_r \tag{5}$$

where

$$\alpha=\frac{\ln\beta}{\hat{V}_r},\quad \beta=\frac{\hat{E}_{c/m}}{(\hat{\varepsilon}_l\varepsilon_o\varepsilon_w E_{r/m}-1)\hat{V}_r},\quad \hat{E}_{c/m}=(\hat{E}_c-E_m)/E_m \tag{6}$$

The hat sign means that the values need to be determined by experimental results, and $\varepsilon_l$, $\varepsilon_o$, $\varepsilon_w$ are constants.

Another well accepted model is Halpin–Tsai equation [14–16] which gives the prediction of tensile modulus of nano-composites, expressed as

$$E_c=\left[\frac{3}{8}\frac{1+2(l/d)\rho_L V_r}{1-\rho_L V_r}+\frac{5}{8}\frac{1+2\rho_D V_r}{1-\rho_D V_r}\right]E_m$$
$$\rho_L=\frac{(E_r/E_m)-(d_m/4t)}{(E_r/E_m)+(l_m/2t)},\ \rho_D=\frac{(E_r/E_m)-(d_m/4t)}{(E_r/E_m)+(d_m/2t)} \tag{7}$$

where $E_c$ and $E_m$ are Young's moduli of the composite and the matrix, respectively, $l/d$ and $V_m$ represent the aspect ratio and the filling content of the nano-fibers or nano-tubes, $t$ is the thickness of the graphite layer.

Apart from the above mentioned models, the "composite sphere method" (CSM) was also used to predict the modulus of composites, which can be expressed as [17]

$$K_{com}=K_r+\frac{V_m}{(1/K_m-K_r)+(3V_r/(3K_r+4G_r))} \tag{8}$$

$$G_{com}=G_r+\frac{V_m}{(1/K_m-K_r)+(6V_r/(3K_r+2G_r)/(5G2(3K_r+4G_r)))} \tag{9}$$

where $K_{com}$ and $G_{com}$ are the bulk and shear modulus of composites. $V_m$ and $V_r$ are volume contents of the matrix and the reinforcement phase, $K_m$, $G_m$, and $K_r$, $G_r$ are the bulk moduli and shear moduli of the matrix and the reinforcement phase, respectively.

Although the mechanical performances of composites were extensively studied, and numerous methods were applied to characterize the relationship between the reinforcement phase and the final properties, the disagreement between the some experimental results and theoretical models, which was resulted from the complexity of the reinforcement phase, is always a problem that needs to be solved, especially how to quantitatively predict the mechanical properties of the composites with different geometrical structure of the reinforcements is still one of the top challenge topics in composite science and technology.

Recently, $Cu_2O/Cu$ cermet has gained significant interests due to its potential applications in solar energy conversion [18], electrode materials [4,19], sensors [20], and catalysis [21]. The physical properties of $Cu_2O/Cu$ cermets with different geometrical

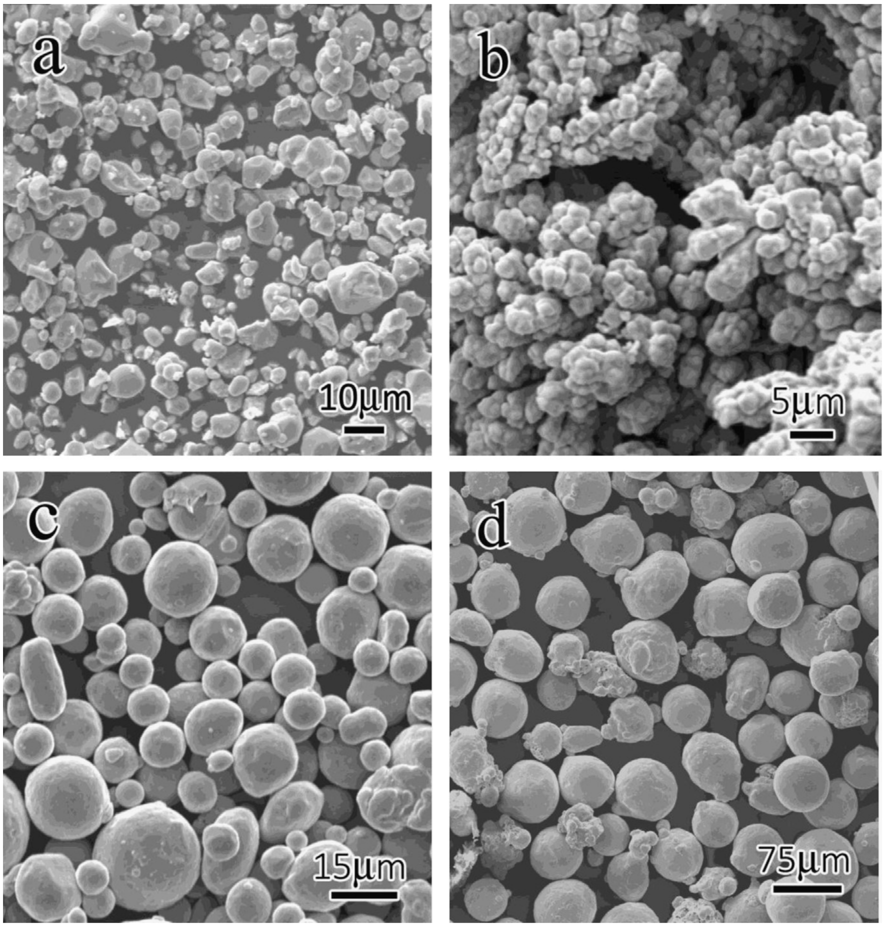

**Fig. 1.** SEM morphology of (a) $Cu_2O$ powder, (b) branch like Cu, (c) spherical Cu powder with size of 15 μm, and (d) 75 μm.