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Modeling of thermally induced damage in the processing of Cr–Al_2O_3 composites

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ABSTRACT

Thermal stresses induced during the cooling of Cr–Al_2O_3 (MMC) processed by sintering are modeled numerically using the FEA. The composite microstructure is modeled as (i) random distribution of ceramic particles (voxels) in the metal matrix, and (ii) using micro-CT scans of the real microstructure transformed into a FE mesh. Numerical simulations of the thermal residual stresses are compared with the test data measured by X-ray diffraction. A simple numerical model is then proposed to predict the overall elastic properties of the composite with account of the porosity and damage induced by the thermal stresses. Comparison of the model predictions with the measured data for Young's modulus is presented.

1. Introduction

The properties of metal-ceramic composites can be tailored for the targeted applications by varying the volume fractions and properties of the matrix and the type, shape, size, orientation and distribution of the reinforcement, and by controlling the reinforcement/matrix adhesion level [1,2]. One of the main problems that emerge during the processing of metal-ceramic composites are thermal residual stresses arising due to the mismatch in the coefficients of thermal expansion of the matrix and the reinforcement. These stresses may cause microcracking during the cooling of the composite from a higher processing temperature and, thus, may affect its elastic and fracture characteristics [3]. Compressive stress in the ceramic phase can close some microcracks, while tensile stresses can trigger initiation and growth of microcracks [4].

In the past, several different approaches were reported in the literature to model the thermal stresses in the MMC. Based on the Eshelby eigenstrain method the stress generated by an ellipsoidal inclusion in an elastic matrix can be determined. This methodology can be useful e.g. for the composites reinforced with spherical particles [5]. Analytical models of thermal residual stresses were presented by Hsueh and Becher for composite with ellipsoidal reinforcement [6] as well as short fibers [7]. In the case of fiber reinforcement, Yoda et al. [8] modeled the thermal stress as a result of the thermal expansion mismatch of the matrix and the fibers. Takao and Taya [9] computed the stresses inside and around a short anisotropic fiber. The influence of the thermal residual stresses on the constitutive behavior of fiber reinforced composites for different arrangement of fibers was investigated by Tsai and Chi [10]. Arsenault and Taya [11] developed an analytical model for thermal residual stresses in a short whisker MMC. Hu and Weng [12] proposed a model based on the secant moduli and eigenstrain principals. FEM was employed for computation of the thermal residual stress and strain in particle reinforcement composites in [13,14]. For metal-ceramic infiltrated composites (Al–Al_2O_3, Cu–Al_2O_3) Agrawal et al. [4] computed the thermal residual stresses by FEM using the concept of the effective processing temperature and representative unit cell.

For the calculation of the effective elastic moduli of a multiphase material a number of analytical models are available in the literature. In the case of regular microstructure (particulate or fiber reinforced composites) fast estimates can be obtained using the effective continua or effective field models like the self-consistent scheme, the differential model or Mori–Tanaka model [15–19]. Other analytical [20–23] or numerical [24–30] models of the effective properties are also available.

As for the modeling of damage mechanisms in MMC the debonding of a fiber from the surrounding matrix was considered and modeled by many authors (e.g. [31–33]). In the ceramic-matrix composites (CMC) a toughening bridging effect of the growing cracks by a particulate or fiber reinforcement is often observed. Kotoul [34] and Kotoul and Profant [35] developed models for the bridging mechanism in brittle matrix composites reinforced by ductile particles.

In this paper we consider Cr–Al_2O_3 composites processed by the powder metallurgy technique. The microstructure of this composite does not show any regular reinforcement shapes (e.g. particles, fi-

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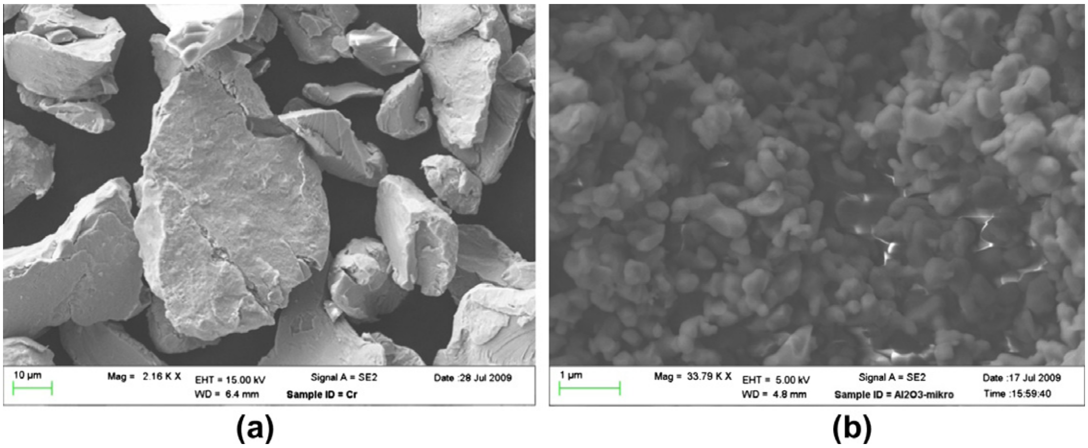

Fig. 1. SEM images of starting materials: (a) chromium powder, and (b) aluminium oxide powder.

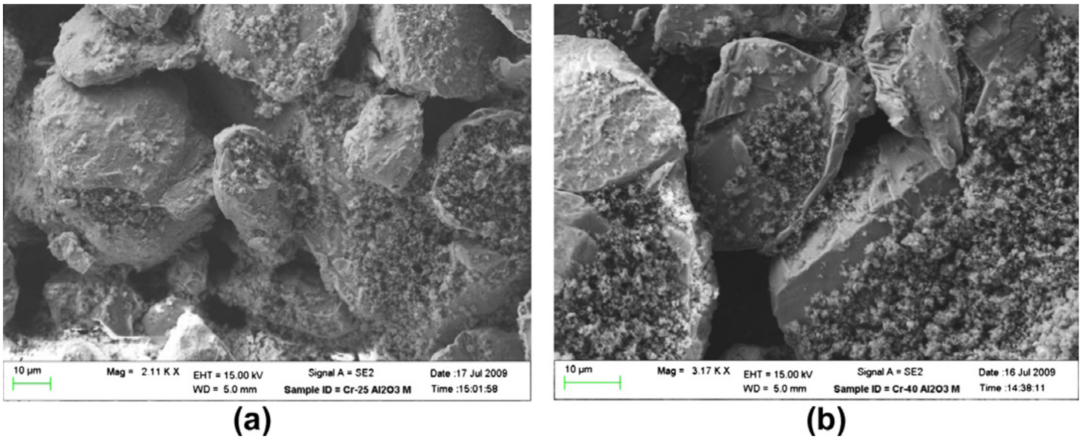

Fig. 2. SEM images of powder mixtures after 4 h of mixing: (a) $75Cr/25Al_2O_3$, and (b) $60Cr/40Al_2O_3$.

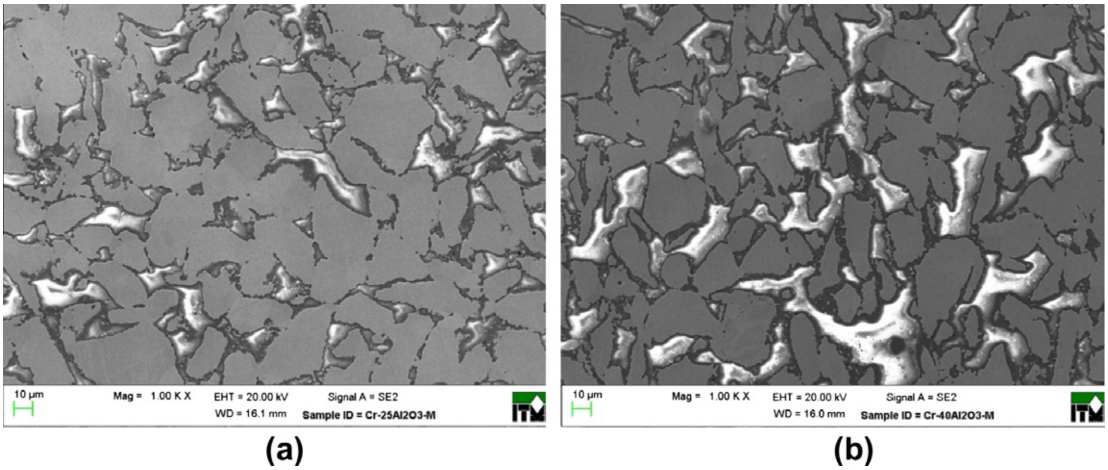

Fig. 3. SEM images of sintered composites: (a) $75Cr/25Al_2O_3$, and (b) $60Cr/40Al_2O_3$.

bers or whiskers) what makes the already existing models of limited utility. Consequently, the thermal stress generated during the cooling process will be calculated numerically using the Finite Element Method.

The objective of this paper is to model the thermal residual stresses and their influence on the overall Young modulus of the $Cr–Al_2O_3$ composite with account of the porosity and microcracking induced upon cooling from the high processing temperature to room temperature. For the prediction of the effective Young modulus a simple tensile test is simulated using a commercial FEM code. The FE mesh is modified in order to take into account the influence of the microcracks generated by the thermal stress.