International Journal of Refractory Metals & Hard Materials 71 (2018) 239–245

Contents lists available at ScienceDirect

International Journal of Refractory Metals & Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

Real microstructure-based simulation of thermal residual stresses in cemented carbides and the related strengthening and toughening consideration

Ji-fei Zhu[a,b], Li Zhang[a,*], Hua-dong Zhang[a], Zhi-qiang Zhong[a], Lei Zhou[a], Yi Chen[a]

[a] *State Key Laboratory of Powder Metallurgy, Central South University, Changsha 410083, China*
[b] *Achteck Tool Technology Co., Ltd., Ganzhou 341000, China*

ARTICLE INFO

Keywords:
Cemented carbide
Image processing
Finite element analysis
Thermal residual stress
Strengthening mechanism
Toughening mechanism

ABSTRACT

Realistic representation of the stress and its distribution in a composite material requires the use of a model based on the real microstructure. In this work, an image processing technique for transferring scanning electron microscope image into a finite element (FE) model is introduced in detail. Based on the aforementioned FE model, thermal residual stresses (stresses for short) in the hard and binder phases in a WC–Co alloy are assessed and presented mainly in a form of distribution contour. The parameters include the average stresses and their evolution with temperature, the mean stress frequency distribution of each element in the FE model, the maximum and the minimum principal stress distributions and the corresponding stress directions, as well as the Von Mises stress distributions. Based on the results concerning the existing positions of the innate microstructure defects, the strengthening and toughening mechanism of cemented carbides and the Martensitic transformation mechanism of the Co based binder phase are discussed.

1. Introduction

WC–Co based cemented carbides are well recognized for their easily tailored properties combination of high hardness provided by the WC hard phase (WC phase) and desirable toughness and strength by the ductile Co based binder phase (Co phase) [1–4]. Thermal residual stresses (stresses for short) are established within the hard and binder phases upon cooling from the sintering temperature due to the pronounced difference in their respective thermal expansion coefficients [5,6]. Non-destructive methods including conventional X-ray diffraction [7], energy dispersive synchrotron X-ray diffraction [8,9], neutron diffraction [10,11] and Raman spectroscopy [12,13] can be used in the stresses investigation. Alternatively, stresses can be quantificationally estimated by finite element (FE) modeling, by which additional insight into its distribution in composite materials can be provided.

As the importance of the stress is well recognized, the relationship among the microstructure, stress and properties has been intensively investigated for cemented carbides [5–8,14–20]. In the present study, to aim at the strengthening and toughening design for cemented carbides, we investigate the stresses in a WC–10Co alloy based on a real microstructure-based FE model. Different from the peer reports, the main contributions of our work include: (1) an image processing procedure for transforming SEM image into accurate FE model is presented in detail; (2) precise stress distribution contours for the WC phase and Co phase are obtained; (3) innate microstructure defects are revealed from different aspects and levels, i.e., the maximum and the minimum principal stress distributions and the Von Mises stress distributions; (4) based on the locations of tensile stress in the WC phase, compressive stress in the Co phase, and high shear stress, the strengthening and toughening mechanism of cemented carbides and Martensitic transformation mechanism of the Co phase are discussed.

2. Specimen preparation

A WC–10Co alloy (in mass fraction, %) was prepared by a conventional sinter-HIP process. At the final sintering stage of 1430 °C, Ar pressure was kept to 5.6 MPa for 40 min; the total soaking time at 1430 °C was 60 min. After the sintering, the specimens were cooled down to around 80 °C with an average cooling rate of 4 to 5 °C/min in Ar. A structure of WC + β (Co phase) was identified by scanning electron microscope (SEM) observation, shown in Fig. 1a. The microstructure parameters based on the SEM image shown in Fig. 1a, i.e., average WC grain size of 1.2 μm, Co phase mean free path of 1.0 μm and WC grain contiguity of 0.76 were determined by applying Image J

* Corresponding author.
E-mail address: zhangli@csu.edu.cn (L. Zhang).

https://doi.org/10.1016/j.ijrmhm.2017.11.014
Received 14 October 2017; Received in revised form 17 November 2017; Accepted 17 November 2017
Available online 22 November 2017

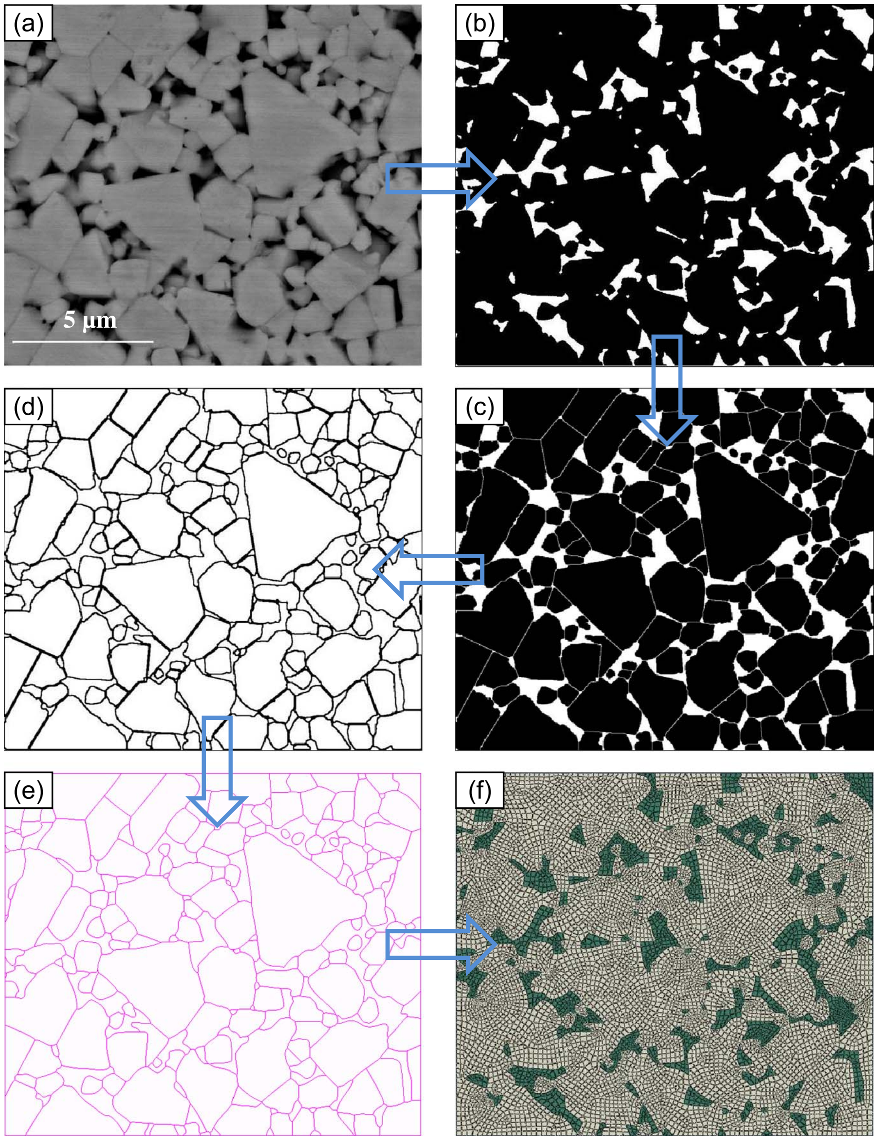

Fig. 1. Schematic representation of image processing procedure used to transform SEM image to FE model automatically. Presented images correspond to: (a) original SEM image of WC–10Co alloy, (b) binarization of original image, (c) segmentation of WC grains, (d) outlining of WC grain boundaries, (e) vectorization of WC grain boundaries and (f) meshing.

Table 1
Material properties [35] adopted in our FE analysis.

Material	Young's modulus/GPa	Poisson's ratio	TEC/10^{-6}/K
WC	719–0.05 (T–T_{room})	0.19	5.2
Co	213–0.05 (T–T_{room})	0.31	13.3

TEC refers to thermal expansion coefficient.
T_{room} refers to room temperature, and T refers to current temperature.

package. The process for the determination of the microstructure parameters was described in details in Ref. 21.

3. Microstructure-based FE analyses

3.1. Image processing

An open source finite-element software OOF (object-oriented finite element software) and its updated version OOF2 were often used to create finite element meshes based on optical or SEM micrographs [22–29]. Nevertheless, OOF runs only on Unix operation system [30] and it does not support Windows operation system at the current time. Taking the advantage of the popularity of Windows operation system, in this work, we employed an ABAQUS software [31] to create finite element meshes.

The SEM image was treated by means of a series of algorithm operations based on ImageJ and CAD software, demonstrated in Fig. 1. The following steps were included:

(1) Noise reduction. Despeckle filter for removing noise from the original image was applied. In this step, the gray value of each pixel was replaced with the median value in its 3 × 3 (pixels) neighborhood to reduce the over-segmentation in the watershed algorithm.
(2) Image binaryzation. The gray-scale image was converted to a black and white binary image by adjusting the threshold operation, based on a modified ISODATA algorithm, shown in Fig. 1b. Here, a global thresholding method was employed for the determination of the threshold. Then, the pixels gray values below and above the threshold were made white and black, respectively.
(3) Segmentation of WC grains. A watershed algorithm was performed, by which the Euclidian distance map (EDM) and ultimate eroded points (UEPs) were achieved sequentially. A dilation operation was performed for each UEP, i.e., the peak or local maximum of the EDM, either until the edge of the particle is reached, or the edge touches a region of another (growing) UEP [32]. Admittedly, this