Materials and Design 87 (2015) 342–351

Contents lists available at ScienceDirect

Materials and Design

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

An investigation of residual stresses in brazed cubic boron nitride abrasive grains by finite element modelling and raman spectroscopy

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ARTICLE INFO

Article history:
Received 7 August 2015
Accepted 9 August 2015
Available online 13 August 2015

Keywords:
CBN abrasive grain
Residual stress
Finite element analysis
Ag–Cu–Ti alloy
Cu–Sn–Ti alloy
Raman spectroscopy

ABSTRACT

Joining cubic boron nitride (CBN) abrasive grains and tool body made of steel using brazing always creates residual stress due to thermal mismatch of the components when cooling down from the brazing temperature. A large tensile stress perhaps causes grain fracture during the grinding process with single-layer brazed CBN abrasive tools. To evaluate the residual stresses occurring in brazed CBN grains, values and distribution of residual stresses are calculated using the finite element method. Effects of bonding materials, embedding depth, gap thickness and grain size on brazing-induced residual stresses are discussed. Results show that the Cu–Sn–Ti bonding alloy always results in a larger tensile stress in the CBN grains, when compared to Ag–Cu–Ti alloy during the cooling phase of the brazing process. The maximum tensile stress is obtained at the grain–bond junction region irrespective of the choice of bonding material and embedding depth. When the grain side length is 100 μm, gap thickness is 10 μm and grain embedding depth is 30%, the maximum magnitude of the tensile stresses is obtained. The maximum stress is 401 MPa with Ag–Cu–Ti alloy and 421 MPa with Cu–Sn–Ti alloy. The brazing-induced residual stresses have been finally measured experimentally by means of the Raman spectroscopy. The current simulated results are accordingly verified valid.

1. Introduction

Over the last several decades, single-layer brazed cubic boron nitride (CBN) abrasive tools have found a wide range of applications in grinding difficult-to-cut metallic materials such as titanium alloys and nickel-based superalloys. This attractive property of single-layer brazed CBN tools arises due to their high grain protrusion and strong bond to grains [1,2]. However, Ghosh and Chattopadhyay [3] discovered that the brazed CBN grains fractured easily at the grain–bond junction region (macro-fracture) or at the grain vertex region (micro-fracture) during the grinding process. Furthermore, Buhl et al. and Hagiwara et al. reported that this type of fracture was not limited to brazed CBN abrasive grains and was also observed in the case of brazed diamond grains [4–7]. Fracture behavior of brazed CBN grains can be attributed to the residual tensile stress resulting from significant mismatch between thermal expansion coefficients, Young's modulus, and Poisson's ratio of the joined components during cooling from the brazing temperature [8]. This behavior is also similar to the brazed joint cracking of some brittle materials under quasi-static or cyclic loading conditions, such as cemented carbide and AISI 1045 steel [9], silicon nitride and AISI 1036 steel [10], SiO_2–BN ceramics and Invar alloy (Fe–36 wt.% Ni) [11].

Experiments to characterize brazing stresses in CBN or diamond grains are time consuming and expensive. Furthermore, stress measurements using the current techniques (e.g., Fourier Transform Infrared Spectroscopy (FTIR) [12], Raman spectroscopy [13–15]) merely obtain an average value over a fixed volume. This results in an error in the accuracy of the stress values due to the small grain size ranging from 100 μm to 400 μm. Alternatively, the finite element (FE) method can provide a numerical solution as well as a coupled multi-physics analysis of the thermo-elastoplastic behavior. FE analysis has been demonstrated as an effective tool, which was widely used to predict the residual stresses of brazed joints. De Weese et al. [16] applied FE analysis to predict brazing-induced thermal stress in ceramic–metal joints. They discussed details related to the modeling techniques, analytical assumptions and boundary conditions used. Analytically predicted stress distributions were experimentally verified at the location and along the direction of cracks observed in the ceramic component of the brazed sample test assembly. Torres et al. [17] conducted FE analysis to calculate thermal stresses generated during brazing diamond to tungsten carbide and minimized the thermal stresses at lower brazing temperatures. Meanwhile, increasing the thickness of the filler metal layer improved stress relaxation. Akbari et al. [18] carried out FE analysis to study residual thermal stresses occurring at the brazed joint between a stainless steel substrate and a block-shaped mono-crystalline diamond (1.0 × 1.0 × 0.5 mm) with Ag–Cu–Ti alloy as the bonding material. Zhou et al. [19], Eagar et al. [20] and Kim et al. [21] carried out FE

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http://dx.doi.org/10.1016/j.matdes.2015.08.039
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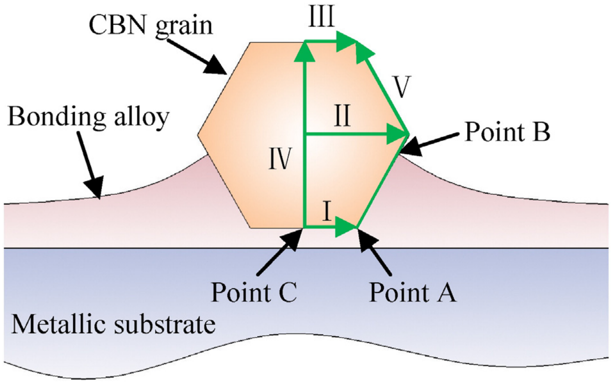
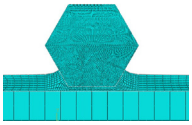
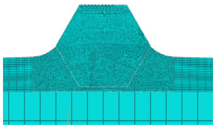
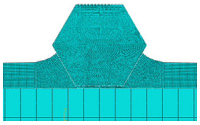
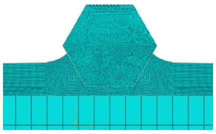
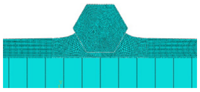
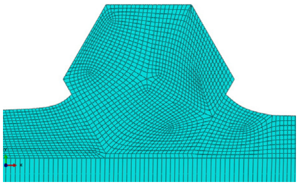


Fig. 1. Schematic of a brazed CBN grain sample with an embedding depth of 40%.

Table 1
Comparison of meshed models with different grain embedding depths, gap thicknesses and grain sizes.

Embedding depth	 20%	 50%
Gap thickness	 5 μm	 20 μm
Grain side length	 50 μm	 200 μm

modeling calculations to analyze thermal stress of the brazed Si_3N_4-metal joints. Based on the simulation results, the interlayer was optimized to reduce thermal stresses and maximize the joint strength. Zhang and Jin [22] studied residual stresses of the cemented carbide-steel brazing joints using FE numerical simulation. They found that the lower residual stress and higher shear strength of the joint were achieved by applying a compressive pressure on the brazed specimen during cooling. Jiang et al. [23] simulated the residual stress distribution in different stainless steel brazed joint samples, and three different materials of filler metal using nine different FE models. Materials of the stainless steel plate–fin structure were accordingly optimized to obtain the lowest residual stress. Additionally, Deibel [24], Wang et al. [25], Pintschovius et al. [26] and Kurita et al. [27] also pointed out that the residual stress distribution in brazed ceramic–metal joint can be reasonably understood within the framework of an elastic–plastic FE model based on the favorable agreement between the experimental data and FE calculations.

In various studies reported in literatures, effects of geometry and gap thickness of a given bonding material were taken into consideration to determine the brazing-induced residual stresses. De Weese et al. [16] analyzed the role of joint geometry to minimize the cool-down stress in brazed metal-ceramic assemblies. Izui et al. [28] and Gong et al. [29] experimentally evaluated the residual stresses obtained with different joint clearance or brazing gap.

Various researchers have also investigated the stress distribution in the grains using FE analysis. Chen et al. [30,31] calculated the residual stresses in brazed diamond grains. It was found that stress values obtained by simulation and measurements had similar trends although the stress magnitude was larger in simulations compared to stress values measured using Raman spectroscopy. Meanwhile, Zhou et al. [32] and Suh et al. [33] investigated stresses at the grain–matrix interface based on a two-dimensional FE model to understand failure in grain–matrix bonding. Spherical [30,31] and pyramidal [32,33] grains were used in the simulation to investigate the grain geometry effects.

Ag–Cu–Ti and Cu–Sn–Ti active alloys are typically applied nowadays as the bonding material to braze CBN grains. Using these alloys, a good bonding interface between the CBN grains, bonding materials and metallic substrate can be obtained [34,35]. However, a significant variation in the brazing-induced residual stress of the CBN grains can result due to the difference in the material properties of Ag–Cu–Ti alloy and Cu–Sn–Ti alloy. In this paper, FE analysis is used to compare residual stresses of the brazed CBN grains when Cu–Sn–Ti alloy and Ag–Cu–Ti alloy, respectively, are used as the bonding material. Effects of embedding depth, grain size and gap thickness on stress distribution are determined. Evolution of residual stress in the CBN grains during the cooling phase of the brazing process is discussed. Experimental verification of the simulated stresses is also made. This work is designed to act as a reference for the fabrication and application of single-layer brazed CBN abrasive tools.

2. Finite element modeling

2.1. Model formulation for brazing-induced residual stress simulation

The purpose of the current investigation is to simulate the residual stress distribution in a brazed CBN grain resulting from the thermal property mismatch of CBN grain/bonding alloy/metallic substrate. The

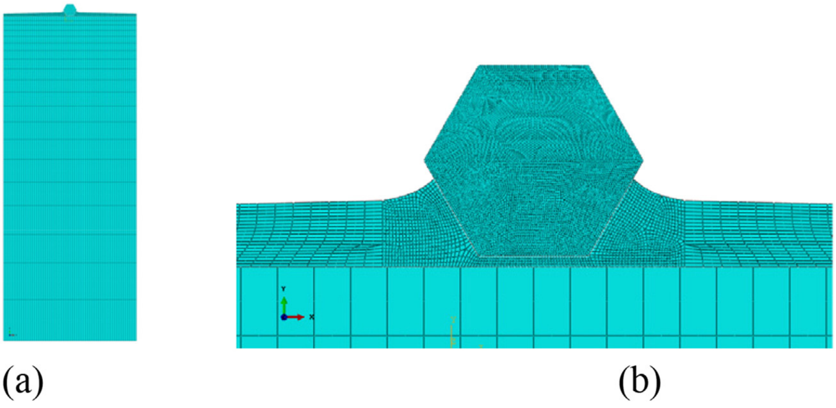


Fig. 2. FE model for residual stress analysis of a brazed CBN sample: (a) control volume, (b) regional volume.