Mechanics of Materials 52 (2012) 69–77

Contents lists available at SciVerse ScienceDirect

Mechanics of Materials

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

Thermomechanical analysis of residual stresses in brazed diamond metal joints using Raman spectroscopy and finite element simulation

Mansur Akbari [a,*], Sebastian Buhl [a,b], Christian Leinenbach [b], Ralph Spolenak [c], Konrad Wegener [a]

[a] Institute of Machine Tools and Manufacturing, ETH Zurich, Tannenstrasse 3, 8092 Zurich, Switzerland
[b] Empa-Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Joining and Interface Technology, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland
[c] Laboratory for Nanometallurgy, ETH Zurich, Wolfgang-Pauli-Strasse 10, 8093 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 19 January 2012
Available online 28 April 2012

Keywords:
Thermomechanical analysis
Raman spectroscopy (RS)
Engineered grinding tool (EGT)
Creep
Plasticity
Full stress/strain tensor

ABSTRACT

Thermal residual stresses are one of the crucial parameters in engineered grinding tool (EGT) life and its consistency. Predicting failure of brazed diamond metal joints in EGTs is related to analyzing the thermal residual stresses during the cooling process. Thus thermal residual stresses have been simulated in a model with realistic materials properties, for instance isotropic hardening and a hyperbolic-sine creep law for SS316L and the silver–copper–titanium active filler alloy, named Cusil ABA™. Also, special modeling techniques such as tie constraint and sub-modeling have been used to model an intermetallic layer titanium-carbide (TiC) with dimensions in nanometers, where the rest of the model's dimensions are in millimeters. To verify the simulated stress state of the diamond, Raman-active optical phonon modes at three different paths in the diamond were measured. As the experiments with Raman spectroscopy (RS) do not deliver stress components, the solution is to directly compute the peak shift of Raman spectrum. The splitting in phonon frequencies and the mixing of phonon modes contain information about the thermal residual stresses in the diamond. Finally the shift in the phonon frequencies was calculated from the different numerical residual elastic strain components and compared to the experimental results.

1. Introduction

Brazed diamond–metal joints are used in EGTs, which can feature high performance grinding in addition to achieving desired and defined surface roughness of the ground workpiece. High performance grinding is needed in industry for machining hard or unconventional materials. Some of these materials are high-alloyed chromium steels, tungsten carbide, silicon nitride ceramics, superalloys and metal–matrix composites. The high bonding strength in diamond–metal joints results in an increase in grain protrusion and thus creates more chip storage space and improves the lubrication conditions. Furthermore diamond is the favored abrasive component for EGTs due to its high strength and high hardness. Therefore brazed diamond–metal joints signify an increase in service life of the EGTs, an increase in cutting speed and reduction of tool cost.

One of the major problems in brazed diamond–metal joints is the formation of residual stresses arising from the mismatch of thermal expansion coefficients between the parts. These thermal residual stresses change with brazing temperature and dwell time (Khalid et al., 2004; Klotz et al., 2006). Also it is revealed that low residual stresses are obtained by brazing at low temperature (Buhl et al., 2010). It should be noted that some researchers show that with having multiple ductile interlayers, residual stresses will relieve (Hao et al., 1995). In addition

---

[*] Corresponding author.
E-mail address: akbari@iwf.mavt.ethz.ch (M. Akbari).
URL: http://www.iwf.mavt.ethz.ch (M. Akbari).

0167-6636/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmat.2012.04.010

thermal residual stresses, due to a mismatch of the thermal expansion coefficients will differ with thickness changes of the TiC interface reaction layer between the diamond and the filler alloy in different brazing conditions (Klotz et al., 2008). The microstructure of brazed diamond–metal joints on brazing with different brazing parameters is investigated in Buhl et al. (2010). The large difference in length scale is a challenge for the modeling part. Since the thickness of the interfacial reaction layers are in the order of nano- or micrometers, e.g. 0.2 μm, and the rest of the model is in the order of millimeters, modeling techniques such as multiscale modeling, user-defined elements, tie constraints and sub-modeling should be used. Sub-modeling technique and tie constraint have been used in the current study.

Multiscale finite element thermomechanical analysis of brazed diamond–metal joints is complex and the rigorously analysis of the model is difficult, all the more so when considering creep and plasticity in steel and filler alloy. An earlier study by Chen et al. (2009) reports that the simulation and Raman spectroscopy stresses have similar trends, yet simulated stresses are larger than the experimentally measured stresses. Taken together, their straightforward model does not look after the intermetallic phases and the effect of creep and plasticity in filler alloy and steel. Other earlier studies (Torres et al., 1999) have shown that the thickness of the braze layer is directly proportional to the stress relaxation in a two dimensional model. However, the intermetallic interlayers in their study were neglected and the parts simplified to rectangular. Also maximum thermal residual stresses after brazing in ceramic–metal brazed joints are reported to be near the ceramic filler metal interface in a two dimensional model (Cazajus et al., 2008). Lixia and Jicai (2009) have studied the importance of the interfacial reaction layers on brazed TiC cermet–steel joints regarding thermal residual stresses and fracture of bonds, however, their model did not include the effect of creep. In order to reduce the thermal residual stresses and connect a single crystal diamond to copper as a monochromator, Takiya et al. (1999) have done brazing with active filler alloy, coating, soldering and also used a diamond platelet as a thermal buffer between diamond single crystal and copper. In their model the effects of thermal residual stresses due to the brazing and the influence of interface layers were not specified.

Raman spectroscopy is an efficient technique for strain tensor determination in Raman active materials with inherent advantages such as nondestructiveness, ease of implementation, speed and absence of sample preparation. When material is subjected to mechanical strain, the quantized lattice vibrations called phonons are selectively modified. Consequently, the scattered light from Raman microscope contains information about the modified lattice vibration which leads to identification of strain tensor (Ossikovski et al., 2008a, 2008b) used polarized off-axis Raman spectroscopy to measure the strain tensor in semiconductors. An approach has been presented by (Bonera et al., 2006) that compares the experimental Raman maps with a virtual experiment using a finite-element model during the manufacturing process. In their approach they used an analytical model beside finite element method (FEM) to calculate strain in microelectronic devices. In addition, strains in a silicon deposited layer have been simulated and compared to Raman spectroscopy results by (Bonera et al., 2009).

A complete three dimensional finite element model of brazed diamond metal joint with considering a TiC interlayer, creep and plasticity in the filler alloy and steel and validating the simulation results with experimental results was not found in literature. In this paper optical phonon Raman spectra and finally the wavenumber peak shifts have been computed from FEM simulation results and have been compared to experimental wavenumber peak shifts.

2. Experimental setup

The brazing process was carried out in a Torvac high-vacuum furnace (Cambridge Vacuum Engineering LTD, Cambridge, UK) at a brazing temperature of 910°C for a dwell time of 10 min. The vacuum was between 10^{-5} and 10^{-6} mbar. The specimen consists of a stainless steel substrate (X2CrNiMo 18-14-3, 30 × 10 × 5 mm), on which a block-shaped monocrystalline diamond (MT L 101005Q$^{\text{TM}}$, Element Six e6, Isle of Man, UK) with the dimension of 1.0 × 1.0 × 0.5 mm is brazed on top. The active filler alloy was Cusil–ABA™ with the denoted composition Ag-35wt%Cu-1.75wt%Ti, provided by Wesgo Metals (Hayward, CA, USA). More detailed description can be found in Buhl et al. (2010).

The measurement of the peak shift was done with a WiTec Confocal Raman Microscope 200 (WiTec, Ulm, Germany) with a laser as light source (wavelength 442 nm, Omnichrome Series 74, Melles Girot Laser Group, Carlsbad, CA, USA).

The test point No. 1 is situated in the middle of the diamond's lateral surface approximately 10 μm above the interface. The test points with the distances of 110 μm and 210 μm from the filler alloy–diamond interface are denoted with Nos. 2 and 3. Approximately every micrometer from the diamond surface a Raman spectrum was recorded and the wavenumber w of the Raman–Stokes peak was analyzed. The peak-shift Δw was calculated by $\Delta w = w - w_0$, where w_0 is the peak wavenumber of the unbrazed stress/strain free diamond.

3. Thermomechanical finite element analysis of the cooling process

In the thermomechanical FEM analysis of the cooling process, the diamond, the TiC interlayer, the active filler alloy and the stainless steel were modeled in Abaqus®. The model contains the block-shaped diamond with the dimension of 1.0 × 1.0 × 0.5 mm, the TiC interlayer with a thickness of 0.2 μm, a filler alloy of 16.8 μm thickness and the stainless steel substrate with the dimension of 5 × 5 × 5 mm. The dependency of the results on the stainless steel substrate size has been checked and the optimum size selected. Furthermore, different element shapes such as tetrahedron and hexahedron with linear and quadratic geometric orders, different numbers of integration points