Two-D Analysis of the Thermo-Mechanical Properties of ZrO₂-Based Composites

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ABSTRACT

In this paper, a fast and efficient tool for predicting a set of physical and mechanical composite properties such as thermal expansion coefficients, thermal and electrical conductivity, stiffness, and thermal residual stress is developed based on the analysis of a representative volume of ZrO₂-based composite. Such an analysis allows an engineer to assess the mechanical and physical properties to design an optimum composite composition in terms of advantageous mechanical properties and at the same time a good electrical discharge machining performance. Thermal residual stresses in the constituent phases and thermal and electrical conductivity of ZrO₂-based composites are assessed by a Finite Element (FE) model using 2-dimensional SEM micrographs. The FE models are verified by comparing numerically calculated results with experimentally measured data.

Keywords: 2 Dimensional SEM Micrographs, Finite Element Model, Physical and Mechanical Properties, Thermal and Electrical Conductivity, Thermal Residual Stresses, ZrO₂-Based Composite

1. INTRODUCTION

One of the main material removal mechanisms in Electrical Discharge Machining (EDM) of ZrO₂ based ceramics is melting/evaporation (Lauwers, 2004). A low thermal conductivity promotes keeping generated heat (due to electric discharge) in the surface zone and enhances the material removal rate by improving the melting/evaporation mechanism. Furthermore, a sufficient electrical conductivity is a prerequisite for EDM.

Thermal residual stresses have great influence on the mechanical properties of ZrO₂ based composites. Typically occurring tensile residual stress on the ZrO₂ increases ZrO₂ transformability (Rühle, 1989) and consequently improves the transformation toughening mechanism. Typically occurring compressive residual stresses
on the secondary phase in general also cause an increase in the toughness (Taya, 1990).

The purpose of the analysis described in this chapter is to develop a fast and efficient tool for predicting a set of mechanical and physical properties such as thermal expansion coefficients, thermal and electrical conductivity, stiffness and thermal residual stress based on analysis of a representative volume of ZrO$_2$-based composite. Such an analysis will allow an engineer to make an estimation of the mechanical and electrical properties in order to design an optimum composition; optimum in terms of having a ZrO$_2$-based composite with most advantageous mechanical properties and at the same time a good EDM performance.

Thermal residual stresses on the constituent phases and thermal and electrical conductivity of ZrO$_2$-based composites were modelled by Finite element (FE) modelling using 2 dimensional SEM pictures. FE models were verified by comparing numerically calculated data with experimentally measured data. This work includes three parts, modelling of 1) thermal conductivity, 2) electrical conductivity, and 3) elastic properties and thermal residual stresses.

2. EXPERIMENTAL PROCEDURE

The density of the samples was measured in ethanol, according to the Archimedes method. The electrical resistivity of the samples was measured according to the 4-point contact method. The elastic modulus, E and Poisson ratio, $\nu$, of the ceramics was measured using the resonance frequency method (ASTM, 1994). The resonance frequency was measured by the impulse excitation technique.

The thermal expansion coefficient of the samples was determined with commercial thermomechanical analyser equipment (model Q400, TA Instruments, USA). Experiments were conducted in a temperature range from 25 to 900°C with a heating and cooling rate of 2°C/min on rectangular shaped samples of about 20 × 2 × 4 mm$^3$ with ground parallel lateral surfaces. The TA instrument was calibrated with a pure aluminium test sample from room temperature up to 500°C.

Thermal residual stresses through the thickness of the ceramic discs (43 × 4 mm) were measured by neutron diffraction. The neutron diffraction experiments were performed on the high-resolution SPN100 neutron stress scanner available at the medium-power reactor LVR-15 at NPI in Řež (Czech Republic). The measurement method is based on an experimental examination of the two components of the lattice strain tensor and conversion of the measured lattice strains to stresses (Lukáš, 2005). Expansion or contraction of the lattice constant compared to measured lattice constant on pure phases is translated to residual thermal stresses due to mismatch between thermal expansion coefficients of constituents in the composite.

Thermal properties were measured by the laser flash technique (LFA427, Netzsch, USA). In this technique, a polished plane parallel disc with 1-4 mm thickness and 13-30 mm diameter is exposed to a short flash laser from one side. The temperature variation of the upper sample side is measured by an infrared detector and is monitored based on time and location. The sample itself is supported and placed inside a furnace with Ar environment and temperature control. Thermal diffusivity $\alpha_d$ (m$^2$/s) can be calculated from the following equation:

$$\alpha_d = 0.1388 \frac{L^2}{t_{1/2}} \tag{1}$$

Where L is the sample thickness and $t_{1/2}$ is the necessary time needed to reach half of the temperature variation observed before and after the flash on the upper sample side. Knowing weight and density of the sample, the specific heat $C_p$ (J kg$^{-1}$ °C$^{-1}$) (the amount of heat needed to increase the temperature of 1 g of material by 1 degree) of the sample can be measured in the laser flash equipment as well. Thermal conductivity $K$ (W m$^{-1}$ °C$^{-1}$) is related to the thermal diffusivity and the specific heat by the density (kg m$^{-3}$) as can be seen in the following equation: