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Effect of manufacturing parameters on polycrystalline diamond compact cutting tool stress-state

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ABSTRACT

Residual stresses and stress transients in a polycrystalline diamond compact tool were numerically predicted for different pressure and temperature manufacturing conditions. Results showed maximum tensile and compressive stresses of about 500 MPa and −125 MPa, respectively. However, stress transients during the manufacturing process were up to 2–3 times higher. These depend on how pressure and temperature are removed following the sintering process. Rapid cooling and pressure removal result in high stress transients and vice-versa. These transients can lead to the formation of micro-cracks and delamination of the polycrystalline diamond layer from its substrate, contributing to premature failure of the tool. On the other hand, lower cooling rates and gradual pressure removal offer low stress transients and a favourable final residual stress-state of the PDC tool.

Introduction

Polycrystalline diamond compact (PCD) cutting tools are widely used in a variety of cutting applications including oil and gas drilling and non-ferrous materials machining [1–5]. They consist of a polycrystalline diamond layer in-situ bonded onto a tungsten carbide substrate as shown in Fig. 1 via a high temperature and high pressure sintering route [2]. PDC tools can present in different shapes and formats. For oil and gas drilling, they are usually cylindrical shaped with a tungsten carbide to polycrystalline diamond layer thickness ratio ranging from 4 to 6. The high abrasion resistance of PDC cutting tools has been recognised as the key contributor to the increased economy of oil and gas drilling [1]. On the other hand, these tools still present a high susceptibility to fractures due to low fracture toughness [2–7]. This is especially the case when drilling through highly interbedded hard rock formations and during dynamically unstable drilling [6].

Residual stresses pre-existing from the tool manufacturing process have been identified to play an important role in the behaviour and performance of PDC tools during application [8–11]. These stresses are due to the coefficient of thermal expansion (CTE) and stiffness mismatch between the polycrystalline diamond layer and the tungsten carbide substrate. They are generated as the tool is cooled down from sintering temperature to room temperature and pressure reduced to the atmospheric one. Sintering conditions are typically about 1400 °C for temperature and 5 GPa for pressure. As the tool cools down, the carbide substrate shrinks more than the polycrystalline diamond layer. This results in the diamond layer being predominantly under compression and the carbide under tension. Tensile stresses of as high as 690 MPa in a PDC cutter sintered at 1450 °C and 5.5 GPa have been reported [8]. Compressive stresses have also been measured in a diamond layer using neutron diffraction [9]. Values ranging from −250 to −582 MPa were reported for a PDC tool manufactured under similar conditions. However, none of these or any other similar study has looked at stress transients in the tool during the manufacturing process. These transients can be very high depending on how pressure and temperature are reduced from sintering conditions to atmospheric pressure and room temperature, respectively.

The disadvantage of high stress transients during the manufacturing process is that they may induce undesirable defects in the PDC tool. Examples of such defects would include delamination of the polycrystalline diamond layer from its carbide substrate due to very high stresses at the interface and formation of micro-cracks. Such defects, if unidentified following the manufacturing process i.e. micro-cracks, can significantly compromise the performance of the tool during application and lead to premature failure. Any existing micro-cracks are more likely to grow under loading and cause catastrophic failure. The current study looks at the magnitude of stress transients during the manufacturing process and how they can be minimised by appropriate choice of manufacturing conditions. In addition the study also looks at the benefit of cooling rate on the final residual stress-state of a PDC tool and possible "annealing" of the stresses. A numerical model employing a coupled elastic–plastic–creep analysis is used in this study.

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Fig. 1. Geometry of a typical PDC cutting tool used in oil & gas drilling.

Numerical analysis

Residual stresses and stress transients in a PDC tool during and after the manufacturing process are predicted using numerical modelling. The model assumes an elastic–plastic–creep behaviour of the material components forming the PDC cutting tool. This is particularly important for tungsten carbide which has been reported to exhibit significant plasticity and creep at temperatures above 800 °C and 1000 °C, respectively [12,13]. On the other hand, plastic and creep deformations in polycrystalline diamond are expected to be insignificant in comparison to the carbide for the range of temperatures and pressures used. Fig. 2 shows the temperature dependency of yield strength and Young's (E) modulus of tungsten carbide with 6 wt% cobalt and average grain size of 2 μm.

Numerical model

The Cauchy momentum balance equation for a continuous media, neglecting body forces, is given by

$$\rho\left(\frac{\partial u_i}{\partial t} + u_k\frac{\partial u_i}{\partial x_k}\right) = \frac{\partial \sigma_{ij}}{\partial x_j}, \tag{1}$$

where ρ is the density, $u_i = \partial D_i/\partial t$, D_i is the displacement, u_k is the convective velocity and σ_{ij} is the stress tensor defined by the constitutive law. For small deformations, the convection term can be neglected (u_k is always zero for Lagrange formulation), and the Lagrange and Euler formulations can be considered equivalent. The energy balance equation, with no internal heat generation, is given by the Fourier's transient heat conduction equation as shown in Eq. (2).

$$\frac{\partial T}{\partial t} = \frac{\mathrm{k}}{\rho \mathrm{C_p}}\left(\frac{\partial^2 \mathrm{T}}{\partial {x_i}^2}\right), \tag{2}$$

where T is the temperature, k is the thermal conductivity and C_p is the specific heat capacity of the material. Hence, the coupled thermo-mechanical constitutive model for isotropic solids, assuming infinitesimal strains, can be expressed by the Duhamel–Neumann's linear theory of thermo-elasticity [14];

$$\dot{\sigma}_{ij} - \dot{p}\,\delta_{ij} = 2\mu\dot{\varepsilon}_{ij} + \lambda\dot{\varepsilon}_{kk}\delta_{ij} - 3K\alpha\dot{T}\delta_{ij}, \tag{3}$$

where $\dot{\sigma}_{ij}$ is the time derivative of the stress tensor, μ and λ are the shear modulus and second lame coefficient, respectively, $\dot{\varepsilon}_{ij} = 0.5 * (\partial\dot{U}_i/\partial x_j + \partial\dot{U}_j/\partial x_i)$, $\dot{U}_i$ is the time derivative of the displacement, K is the bulk modulus, α is the coefficient of thermal expansion (CTE), δ_{ij} is the Kronecker delta, and $\dot{T}$ and $\dot{p}$ are time derivatives of the temperature and pressure, respectively. The terms '$3K\alpha\dot{T}\delta$' and '$\dot{p}\delta_{ij}$' in Eq. (3) respectively account for residual stresses due to the thermal and elastic expansion mismatches between the polycrystalline diamond layer and tungsten carbide substrate as the high temperature and pressure applied during the manufacturing process (i.e. sintering) are removed. When cooling down, polycrystalline diamond and the carbide substrate contract at different rates due to the differences in their CTE. Likewise, as the pressure is reduced from sintering conditions to atmospheric pressure the two materials expand at different rates due to the differences in their elastic modulus. Therefore, the pressure and thermal effects offset each other.

For elastic–plastic–creep analysis, the total strain rate can be treated as a sum of the elastic ($\dot{\boldsymbol{\varepsilon}}^e_{ij}$) and inelastic ($\dot{\boldsymbol{\varepsilon}}^{in}_{ij}$) components as expressed in Eq. (4).

$$\dot{\boldsymbol{\varepsilon}}_{ij} = \dot{\boldsymbol{\varepsilon}}^e_{ij} + \dot{\boldsymbol{\varepsilon}}^{in}_{ij} \text{ or simply } d\boldsymbol{\varepsilon}_{ij} = d\boldsymbol{\varepsilon}^e_{ij} + d\boldsymbol{\varepsilon}^{in}_{ij}, \tag{4}$$

where $d\boldsymbol{\varepsilon}^e_{ij}$ and $d\boldsymbol{\varepsilon}^{in}_{ij}$ are the elastic and inelastic strain increments, respectively. The inelastic strain rate can further be decomposed into the plastic ($\dot{\boldsymbol{\varepsilon}}^p_{ij}$) and creep ($\dot{\boldsymbol{\varepsilon}}^c_{ij}$) strain rate components. This decomposition depends on the type of the model used. For example, $\dot{\boldsymbol{\varepsilon}}^{in}_{ij} = \dot{\boldsymbol{\varepsilon}}^p_{ij} + \dot{\boldsymbol{\varepsilon}}^c_{ij}$ for the extended Maxwell model and $\dot{\boldsymbol{\varepsilon}}^{in}_{ij} = \dot{\boldsymbol{\varepsilon}}^p_{ij} = \dot{\boldsymbol{\varepsilon}}^c_{ij}$ for the Bingham model. In the current analysis, the extended Maxwell model was adequate based on the initial validation with experimental data (Fig. 3). It is also commonly used in similar analyses [15,16]. In addition the PDC

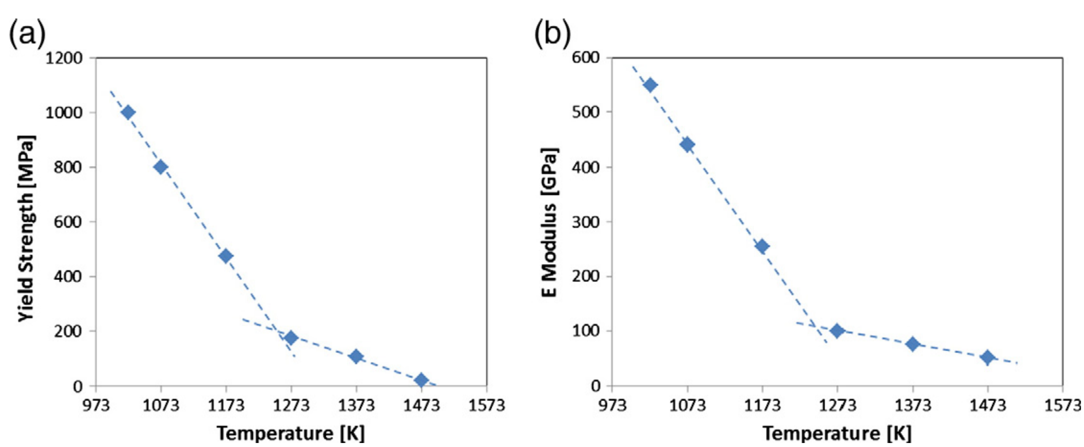

Fig. 2. Temperature dependency of (a) yield strength (in tension) and (b) elastic modulus derived from experimental data for tungsten carbide [13,14].