Diamond & Related Materials 45 (2014) 34–42

Contents lists available at ScienceDirect

Diamond & Related Materials

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

Investigation of fatigue-type processes in polycrystalline diamond tools using Raman spectroscopy

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ARTICLE INFO

Article history:
Received 3 November 2013
Received in revised form 31 January 2014
Accepted 15 February 2014
Available online 22 February 2014

Keywords:
Synthetic diamond
Mechanical property characterization
Mechanical properties
Cutting tools

ABSTRACT

Polycrystalline diamond (PCD) cylindrical tool-bits used in oil well drilling are susceptible to fracture due to the hostile environment of randomly occurring impact loads to which they are subjected. The fact that the tool-bits fail after repeated use suggests the possibility of fatigue type processes in PCD. The study of stress fields on the surface of the PCD thus becomes crucial in the quest to have extended lives for these tool-bits. Since the diamond Raman peak reveals both the nature and magnitude of the stress present in the material, this technique can be employed as a non-destructive measurement tool to investigate these stress fields. Raman stress measurements at room temperature were carried out using a 36 point mapping array in area close to the size of the PCD samples. The mapping points provided histograms of the magnitude and nature of these small individually stressed regions showing a general compressive stress for the lower numbers of fatigue cycles which deteriorates to a high proportion of tensile regions. The data are also illustrated by 2-D surface maps as an alternative mode of presentation again confirming the change from surface stresses being dominantly compressive to dominantly tensile with exposure to the higher numbers of fatigue cycles. Whereas a general compressive stress is desirable in the PCD layer as it inhibits the propagation of cracks, on the contrary tensile stresses facilitate the formation of cracks ultimately leading to catastrophic failure of the tool-bits.

1. Introduction

Diamond is a remarkable material with unique properties resulting in numerous applications [1]. One of its industrial applications is in oil well drilling and the tool-bits employed generally have a polycrystalline diamond (PCD) layer sintered onto a tungsten carbide substrate. These PCD tool-bits are subjected to very harsh working environments where they are exposed to cyclic fluctuating impact loads. Such hostile environments induce cyclic stresses that often result in the formation and propagation of cracks which can inevitably lead to the premature failure of the tool-bits.

Fatigue behaviour of materials has been studied and investigated for a range of materials over a number of decades. Relaxation of residual stress under cyclic load in metals has been studied by e.g. Zhuang and Halford [2]. The paper by Pook [3] gives a multi-decade overview of three-dimensional effects at cracks and sharp notches, while Suryanarayana [4] reviews the mechanical properties of nanocrystalline and glassy materials, including how fatigue processes feature in these materials.

Fatigue behaviour in polycrystalline diamond has been previously reported [5]. Bell et al. [6] remarked that repeated indentations of a single crystal diamond surface by a spherical diamond indenter may result in the progressive build up of damage. Results obtained by Lin et al. [7] having conducted laboratory rock-cutting tests with single PCD cutting tools showed the progressive degradation of the tool-bits after cutting tens of linear metres of rock. In other research work Dunn and Lee [8] in investigating the fracture and fatigue of sintered diamond compacts concluded that the fracture stress of a diamond compact is reduced under cyclic loading. Paggett et al. [9] conducted studies on residual stress and stress gradients in polycrystalline diamond compacts and observed that the sintering process parameters can influence surface residual stress. Catledge et al. [10] did interesting work on micro-Raman stress investigations and concluded that residual stresses in polycrystalline diamond cutting tools can be accurately measured using this technique. These investigations indicate the importance of the stress state of the surface of PCD tool-bits in determining their lifetime.

In general, fatigue failure is considered to be the tendency of a material or structure to fracture by means of progressive brittle cracking under repeated stress of any intensity considerably below the normal strength of the material or structure [9]. It has been established that a

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http://dx.doi.org/10.1016/j.diamond.2014.02.012
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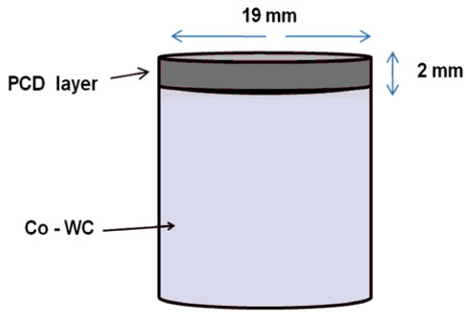

Fig. 1. A diagram of a typical cylindrical tool-bit showing the dimensions of the PCD layer.

compressive stress state on the surface of the PCD tool-bits inhibits crack initiation and propagation and this can possibly extend their life [11]. Conversely tensile residual stresses on the surface of the PCD tool-bits encourage the crack formation. Thus an understanding of the mechanism of fatigue crack growth and propagation in PCD materials is critically important for their improved lifetime.

2. The influence of stress on the Raman peak

Diamond has a triply-degenerate Raman peak at 1332.5 Rcm^{-1} [1]. The position of the Raman peak conveys information on the nature and structure of the material under study. Since the Raman effect is a result of the interaction between photons and Raman-active vibrational mode(s) in a crystal, any stresses present cause changes in an observed Raman band. If an applied stress results in the compression of the unit cell then the force constant of the vibration and consequently the frequency is altered. The same argument also holds when the exerted stress results in the unit cell dilating. Grimsditch et al. [13] showed that when a compressive stress is applied to diamond, the position of the Raman peak shifts linearly with stress to higher frequency. Conversely, a shift of the Raman peak position to lower frequency is associated with the presence of tensile stress in the diamond. Studies of this type have been carried out on PCD samples by Erasmus et al. [12].

The dependence of the Raman shift $\Delta\upsilon$ on the applied stress σ is given by the equation

$$\Delta\upsilon = \upsilon - \upsilon_0 = -\alpha\sigma, \quad (1)$$

where α is the piezo-Raman coefficient, υ_0 is the Raman peak frequency of the unstressed natural diamond and υ is the observed Raman peak frequency [13]. The reference for the Raman peak position of an unstressed diamond was a high quality type IIa natural diamond.

For the piezo-Raman coefficient α, the value reported by Bergman and Nemanich [14] was used, namely 1.9 cm^{-1}/GPa.

3. Experimental details

3.1. Specimen preparation

The source of the PCD samples used in the present fatigue experiments was the same production batch of tool-bits each consisting of a PCD layer of diameter 19 mm and thickness 2 mm sintered onto a Co–WC substrate. A diagram of a typical tool-bit is shown in Fig. 1. The PCD layers were detached from their respective substrates using Electron Discharge Machining (EDM) and slightly polished.

3.2. Transverse rupture strength measurements

Prior to conducting the fatigue studies, it was necessary to determine the average maximum strength of the sample PCD material. For this purpose Transverse Rupture Strength (TRS) measurements were made using the ball on three balls arrangement shown in Fig. 2 installed in a 5500R Instron test machine. Each of three typical PCD disc samples was respectively placed and supported as shown in Fig. 2, then loaded centrally until fracture occurred. The respective rupture strengths were recorded, leading to an average maximum strength of 3470 ± 150 N. The balls in the setup were made of stainless steel.

3.3. Fatigue studies

The fatigue studies were conducted under constant amplitude cyclic loading with load control at a frequency of 10 Hz. Each PCD disc specimen was held by the ball on three ball arrangement shown in Fig. 2, mounted within an Instron SYN 179 servo-hydraulic test machine and subjected to a predetermined number of fatigue cycles under standard room temperature and pressure conditions.

The choice of loading conditions for the fatigue experiments was selected by subjecting several test samples to different loads slightly lower than their measured average maximum strength. The aim was to identify the conditions under which a substantial number of loading cycles would not result in fracture of the PCD samples and thus ensure that the planned Raman studies could be performed. In practice the fatigue experiments were conducted with a load of 3100 N which is 89% of the measured average maximum strength of the sample material. Börger et al. [15,16] have performed finite element modelling for the three balls on ball arrangement and the expected stress field according to their calculations is given in Fig. 3. The percentage of the maximum tensile stress component in the disc (0–100%) is plotted, illustrating

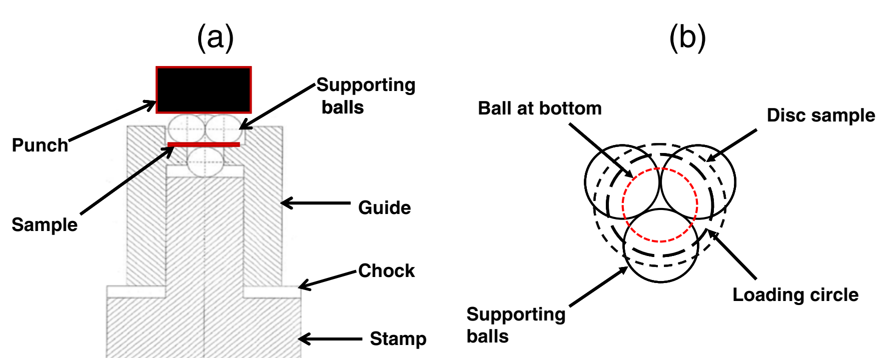

Fig. 2. (a) Shows the ball on three ball arrangement and the configuration of the sample and the balls. For the actual cyclic loading, the chock is removed, allowing the guide to slide downwards. This results in the sample being held only by the spherical balls and ensures a small vertical cavity such that the sample can flex vertically. The flexing distance in the experiments was 0.1 mm. (b) Shows a plan view of the positioning of the four balls and the diameter of the loading circle relative to the sample [15].