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Wear process of single crystal diamond affected by sliding velocity and contact pressure in mechanical polishing

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ABSTRACT

In this work, the influences of sliding velocity and contact pressure on the wear rate of diamond substrate in mechanical polishing are investigated experimentally and theoretically. The experimental observations indicate that the wearing process only consists of the wear-in and stable wear periods. The removal thickness of diamond crystal first increases nonlinearly in the wear-in stage, but then linearly in the subsequent stable wear stage. A diamond carbon amorphization-dependent model is established to calculate the linear variations of removal thickness, which gives a satisfactory prediction accuracy as compared to the experimental data. Although the experiment results demonstrate that the higher sliding velocity or contact pressure will cause a higher wear rate of diamond substrate, the action laws are thoroughly different according to the theoretical prediction. A greater sliding velocity increases the amorphization rate of diamond carbons and the scratching frequency of diamond grits. However, a higher contact pressure produces a larger contact area, which forces more diamond grits to scratch on the surface of diamond substrate.

1. Introduction

Single crystal diamond has many unmatched mechanical and physical properties, such as the greatest hardness, excellent wear resistance and high thermal conductivity, and has been widely employed in different industrial sectors. Before subjected to practical applications, diamond crystal should be polished to achieve a smooth surface or a damage free cutting edge by the mechanical, chemical or tribochemical processing methods [1,2]. Considering the efficiency and economics, the mechanical polishing process still acts as one of the most popular methods. Due to the excellent hardness and wear resistance, however, diamond crystal is quite difficult to be processed mechanically. Therefore, the material removal relevant topics of diamond crystal are always challenging.

The pioneering scientific investigation on mechanical polishing of diamond crystal was carried out by Tolkowsky [3]. He paid great attention to the wear rate anisotropy of diamond crystal, and the relationship between the wear rate, applied load and rotational speed of scaife. Wilks et al. employed the optical technique to evaluate the wear rate of diamond crystal [4–6]. Their observations demonstrated that the differences in the resistance to abrasion of diamond crystal heavily depend on the crystalline orientation of the as-abraded facet. Hird and Field performed polishing experiments on the diamond surfaces to confirm the dependence of wear rate on the polishing velocity [7]. They suggested that the relationship between the wear rate and velocity is complex, and a high velocity will change the contact conditions. In 2005, Hird and Field constructed an Ashby-type wear map for the mechanical polishing of diamond crystal, which gave an insight into the complex wear process of diamond crystal [8]. Ramesh et al. [9] modelled a crack propagation-dependent equation to calculate the wear rate of diamond crystal. They stated that the wear rate of diamond crystal increases with the increment of applied contact pressure or diamond powder size. Grillo et al. fulfilled the friction and wear measurements on the diamond (100) plane in mechanical polishing [10]. They found that the <100> direction presents a higher friction coefficient than the <110> direction, and consequently a greater wear rate appears along the <100> direction. They declared that this is caused by the mechanically induced phase transformation of diamond cubic to sp^2 hybridizations along the <100> direction. However, the micro-fractures dominate the polishing along the <110> direction. Moseler et al. recently proposed an atomic scale model to describe the time-dependent evolution of amorphous carbons layer during nano-asperity sliding of diamond surface [11]. They claimed that, similar to other planarization processes, the diamond surface is chemically activated by mechanical means. They used molecular dynamics (MD) to reveal that the polished diamond undergoes a sp^3–sp^2 order–disorder transition, which results in an amorphous layer with a growth rate that strongly depends on surface orientation and sliding direction. The probabilities for amorphization of carbon atoms are thought to be responsible for the removal rate anisotropy.

Moreover, van Bouwelen and van Enckevort proposed a periodic bond chain (PBC) model to describe the wear rate anisotropy of

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diamond polishing [12]. This newly proposed model can qualitatively explain the anisotropy by means of the inner product between the PBC vector and the sliding direction vector. If the inner product is less than or equal to 0.7, then the polishing direction presents a high wear rate, i.e. the polishing is operated in the 'soft' direction. If the inner product is bigger than or equal to 0.9, the polishing direction is the 'hard' direction, along which a low wear rate appears. Klein and Cardinale proposed a Poisson's ratio model to compare the wear rate anisotropy [13]. This model predicts that the Poisson's ratio in the polishing direction and that in the orthogonal direction on the mechanically polished facet both approach their maximal values, the polishing direction is the 'soft' direction, along which a high wear rate presents. Zong et al. put forward a brittle–ductile transition theory to clarify the material removal mechanism of diamond crystal in mechanical polishing [14]. They concluded that the wear rate anisotropy of diamond surface is heavily dependent on the critical cutting depth for brittle–ductile transition under the same polishing conditions. The bigger the critical cutting depth, the higher the wear rate. The wear rate ratio of any polishing direction to the others is approximate to the ratio of their critical cutting depths.

However, above work only focused on either the material removal mechanism or the wear rate anisotropy of diamond crystal in mechanical polishing, and there is rather limited work concerning the effect of sliding velocity and contact pressure on the microscopic wear process of diamond crystal.

Therefore, in this work the diamond wear processes under different sliding velocities and contact pressures are investigated thoroughly. Furthermore, an empirical model is established for diamond crystal to analyse the wear process and wear rate.

2. Procedure of wear experiments

In this work, wear experiments of diamond crystal are carried out on the PG3B planetary grinding machine supplied by Coborn Engineering Co. Ltd. Fig. 1 shows the experimental set-up as employed. The infeed table of this machine is mounted on precision linear bearings, which use gravity acting on a fixed weight to provide a smooth and constant infeed movement. A linear encoder is used to provide the positional feedback, which provides the infeed table with a resolution of 0.1 μm. Therefore, the small wear volume of diamond crystal can be monitored by the high resolution linear encoder. Moreover, the successive measurements for the worn thickness of diamond substrate can also be on-line fulfilled by recording the positional feedback.

The wheel spindle is a high precision, high frequency and water-cooled air bearing cartridge spindle. The speed is controlled by a high frequency inverter, allowing smooth or continuously variable speeds up to 12,000 rpm. After rigorous balancing, a copper bonded diamond wheel with a grain size of 0.5 μm is installed on the fixture of wheel spindle.

All the wear experiments are performed on the diamond {110} plane and along the <100> direction. In order to keep an invariable contact pressure in any test as possible, the diamond substrate is shaped in advance for achieving a constant cross-section. Fig. 2 shows the configured cross-section, which can be reached easily by shaping a natural octahedral diamond. Moreover, a real-time X-ray directional instrument, i.e. the MWL 110 system supplied by Multiwire Laboratories Ltd., is employed to accurately find the orientation as required, in which a reshaping can be made for the cross-section to approach the perfect {110}<100> lattice direction. In such a way, the orientation of the tested cross-section is controlled rigorously before the wear tests, allowed an inclination angle error of less than 0.5°.

In wear tests, the average sliding velocities are configured as 6.0, 10.0, 15.0 and 20.0 m/s by altering the rotational speed of diamond wheel and the contact position of diamond substrate on the wheel surface. Contact pressures are set at 2.08, 3.10, 4.11, 5.10, and 6.08 MPa by selecting different weights for the infeed table. In each test, the worn thickness of diamond substrate is directly sampled by reading the position of infeed table, corroborated by a recording of evolution time. Fig. 3 presents a sampling close-up in the wear measurement.

In general, the wear rate can be evaluated in terms of the removal thickness and removal mass of worn material. For the diamond wear tests in this work, the mass loss is quite minute. If the quality of worn material is utilized to evaluate the wear rate, the diamond substrate should be frequently disassembled from the fixture for the necessary cleaning and accurate weighting operations. Resultantly, slight errors of inclination angle will be introduced inevitably to change the orientation of tested surface when the diamond substrate is reinstalled to the clamping system. In this case, the polishing conditions are varied as the multiple installations of diamond substrate are carried out, which in return leads to an inaccurate measurement [7]. Therefore, in this work, the thickness of worn diamond substrate is adopted to evaluate the wear rate, which can be sampled directly by a real-time continuous recording for the position of infeed table, as demonstrated in Fig. 3. In this case, however, the thermal expansion of the diamond substrate holder is inevitable due to the effect of frictional heat. A detailed discussion on this problem will be given in the following text.

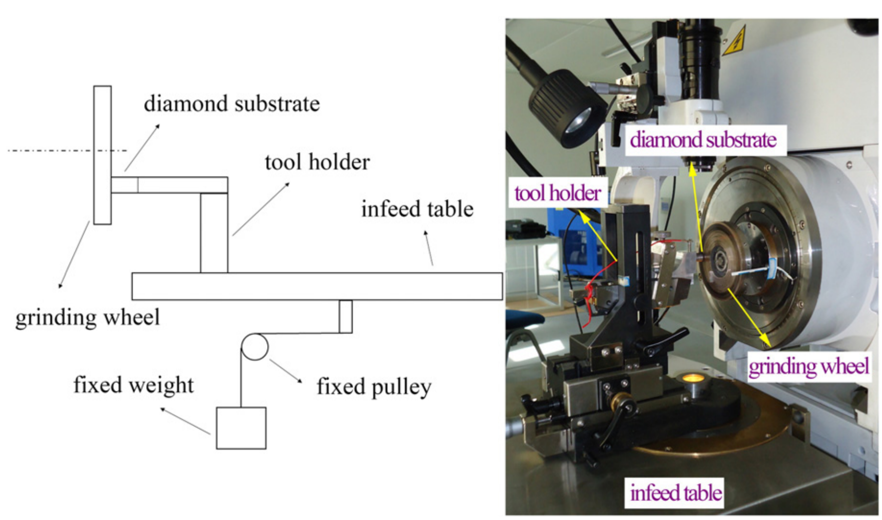

Fig. 1. Schematic diagram and photo of the experimental set-up.