Effect of Polishing Load on Friction and Surface Quality in Diamond Chemical Mechanical Polishing

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Abstract. Chemical mechanical polishing (CMP) is an important process for diamond polishing. Polishing load is a key factor in CMP, which directly affects the surface quality of diamond. In this study, the friction force during in CMP was measured online under different loads. The coefficient of friction increases with the load before the load reaches 40 N. Then the coefficient of friction decreases with the load. This phenomenon is attributed to the fracture of abrasives under large load. In the polishing experiment, three different loads were applied on diamond specimens. The results of polishing experiment show that an ultra-smooth surface with no edge damage is obtained with a polishing load of 40 N. Increasing the load to 60 N, the effective abrasives are broke into smaller pieces and the surface roughness do not continue to decrease with the load. Therefore, the optimal polishing load for diamond CMP is 40 N.

Introduction

Diamond possesses the highest hardness [1], maximum breaking strength, excellent chemical, thermal and radioactive resistance property that is not found in any other material [2]. Therefore, diamond is widely used in the ultra-precision machining, electronic, optical and thermal fields [3]. Good surface integrity and low surface roughness of diamond are required in these applications.

Various techniques for diamond polishing are proposed, such as mechanical polishing [4], thermochemical polishing [5], plasma etching [6] ion beam polishing [7], laser polishing [8], ultraviolet-irradiated polishing [9], etc. However, most of these technologies cannot efficiently achieve ultra-smooth, low-damage surfaces. Chemical mechanical polishing (CMP) [10-12] is an effective technology for diamond polishing, which can provide a smooth and intact diamond surface, and unbroken crystal structure in general.

The polishing load on the diamond significantly affects the interface friction and diamond surface quality. The friction between the polishing plate and the diamond surface can not only directly remove the surface material, but also generate frictional heat that contribute to the interface chemical reaction. Therefore, the monitoring of the friction in the CMP process under different loads is critical for the study of removal mechanism and process optimization. This paper aims to study the relationship between friction force, coefficient of friction and polishing load, and further analyze the reason for the unusual changes in coefficient of friction. Optimum polishing load for diamond CMP is chosen, which provides guidance for the diamond polishing process.

Experiment

Synthetic single crystal diamonds of a size of 3 mm ×3 mm ×1 mm were used as specimens. In our work, diamond specimens must be lapped with 5μm and 2μm diamond abrasives successively before polishing.

The friction test was conducted on a CP-4 polishing machine from CET, USA, which can measure the friction force, coefficient of friction and acoustic emission signal of the polishing system online. The polishing machine was placed in the 1000 level ultra-clean room and the temperature was controlled at about 22 ℃. B_4C powders of 2 μm diameter were utilized as abrasives. Fenton reagent was used as oxidant to form polishing slurry. The diamond specimens were polished on a slick glass polishing plate under 20 N, 30 N, 40 N, 50 N, and 60 N loads for 5 min, respectively. The rotating speed of polishing plate is 40 rpm.

The CMP process was carried out on the UNIPOL-1200S Automatic Load Lapping/Polishing Machine. The polishing plates, abrasives, oxidants, and rotation speeds were selected as the friction test. The diamond specimens were polished with 20 N, 40 N, and 60 N loads for 120 minutes using a slick glass polishing plate.

The 3D surface profiler of Zygo Newview 5022 and the VHX-600E super depth of field microscope produced by the Keyence Corporation were used to measure surface roughness and characterize morphology of the diamond films under different loads, respectively. The different structures of carbon on diamond surface were identified by Raman spectroscopy (the excitation wavelength is 514.5 nm).

Result and analysis

In the friction experiment, the friction force and coefficient of friction were measured on-line under loads of 20 N, 30 N, 40 N, 50 N and 60 N. Figure 1 shows a linear increase of coefficient of friction with the load before the load reaches 40 N, which conforms to the general rules of tribology that the friction force is proportional to load. At this stage (from 20 N to 40 N), the increasing friction force induces the enhancement of mechanical effect between abrasives and diamond samples. And the asperities on diamond surface can be more quickly removed, thereby the surface roughness will be effectively reduced.

Figure 1 Friction force under different loads

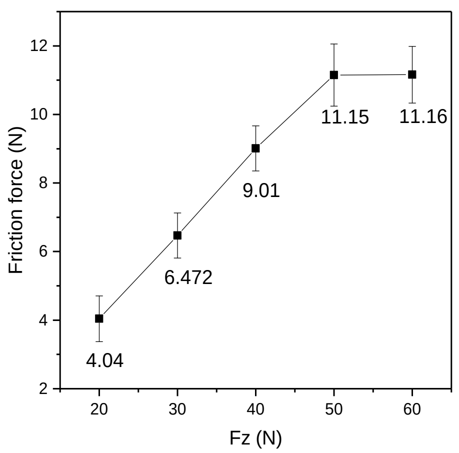
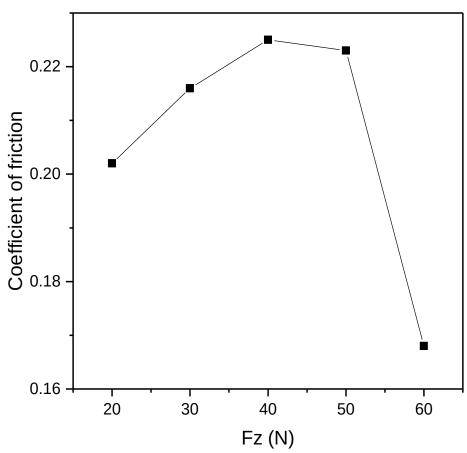


Figure 2 Coefficient of friction under different loads

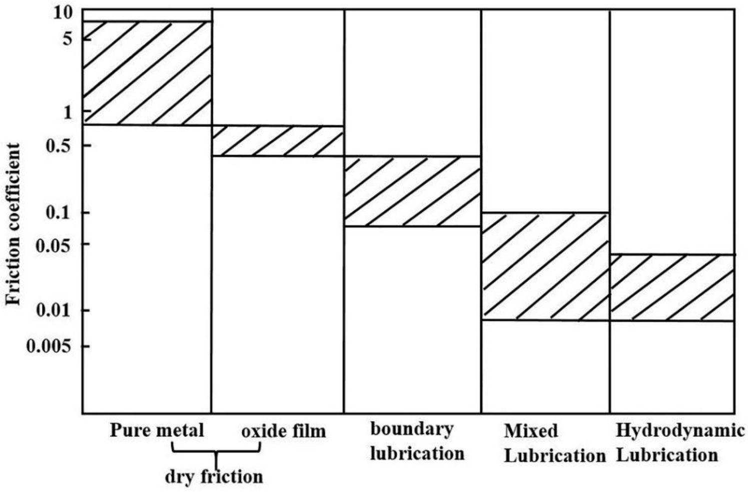


However, when the value of load is higher than 40 N, the friction force has no significant change with the load increase. The friction force is no longer proportional to the load. It indicates that the coefficient of friction μ at the interface has changed according to Eq. 1. Coefficient of friction of interface under different loads is showed in Figure 2. It shows the coefficient of friction begins to decrease under the load of more than 40 N.

$$f = \mu \times F. \tag{1}$$

While, f is known as the friction force. μ is the coefficient of friction. F is the load.

Figure 3 Typical friction coefficient under different lubrication conditions

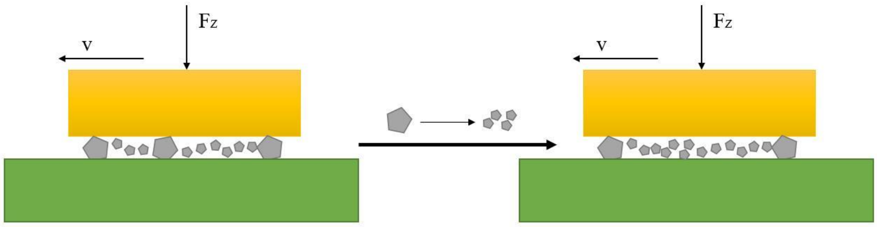


As shown in Figure 3, during the CMP process of diamond, the coefficient of friction is around 0.2. According to the typical coefficient of friction under different lubrication conditions shown in Figure 4, it is inferred that the polishing plate, diamond specimen and abrasives system are in boundary lubrication state during processing. Based on the famous Stribeck curve [13], the coefficient of friction decreases with S_0 in the boundary lubrication stage. Eq. 2 demonstrates that S_0 decreases with the load p_m. Therefore, in the boundary lubrication state, the coefficient of friction increases with the load. As shown in Figure 2, in the load range from 20 N to 40 N, the coefficient of friction increases with the load, which states that the polishing system is in the boundary lubrication state, consistent with the result above.

$$S_0 = \eta \times v/p_m. \tag{2}$$

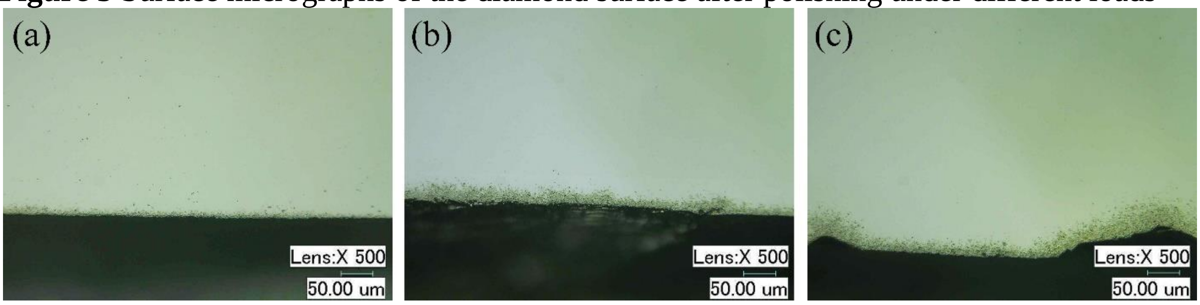
While, Somerfeld number (S_0) is known as the Hersey number. η is the fluid dynamic viscosity. v is the sliding speed. p_m is the couple loading load.

Figure 4 Three-body contact model of diamond, polishing plate and abrasive grains under low load and high load



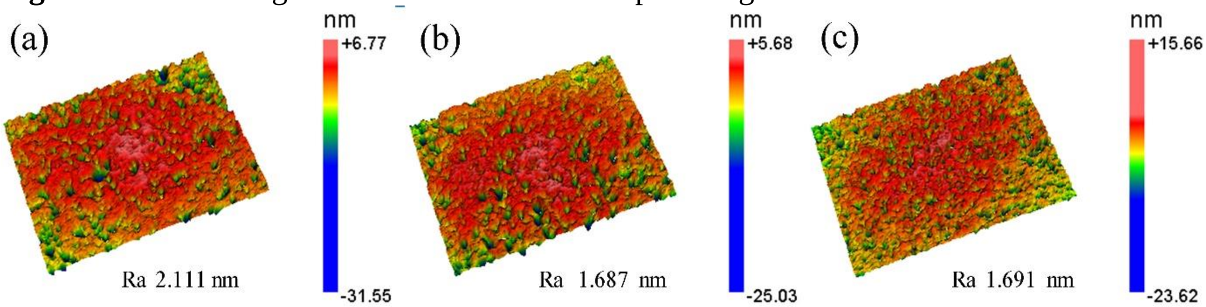
When the load is large enough, a part of the large abrasives that play main supporting role in the three-body contact system are subjected to crush by excessive stress. The large abrasives originally sandwiched between the plate and the diamond sample become small pieces suspended in the slurry, as shown in Figure 4, which results in a reduction in the effective contact area of the polishing plate, diamond and abrasive system. A portion of the boundary lubrication contact is converted into hydrodynamic lubrication contact, and the overall coefficient of friction comes to a lower value. Therefore, when the load is relatively high, the friction force does not go up linearly with the load. At this stage, the number of abrasives sandwiched between diamond and plate that play main mechanical role in polishing process is reduced. Although friction force increases with load, there is no significant increase in removal rate due to the decrease of effective abrasives. Besides, due to the increase of the overall load, the edge of diamond surface may be subjected to excessive impact and damaged.

Figure 5 Surface micrographs of the diamond surface after polishing under different loads



(a) 20 N (b) 40 N (c) 60 N

Figure 6 Surface roughness of the diamond after polishing under different loads

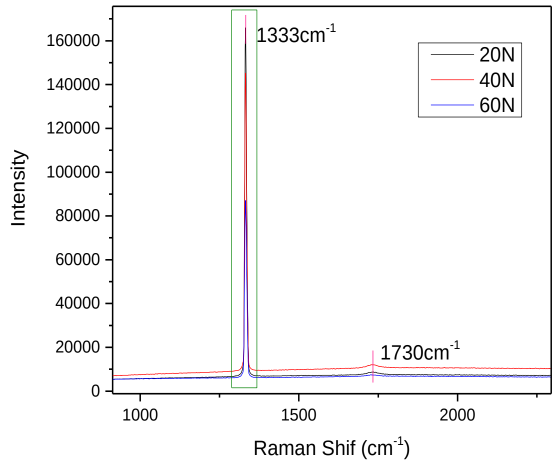


(a) 20 N (b) 40 N (c) 60 N

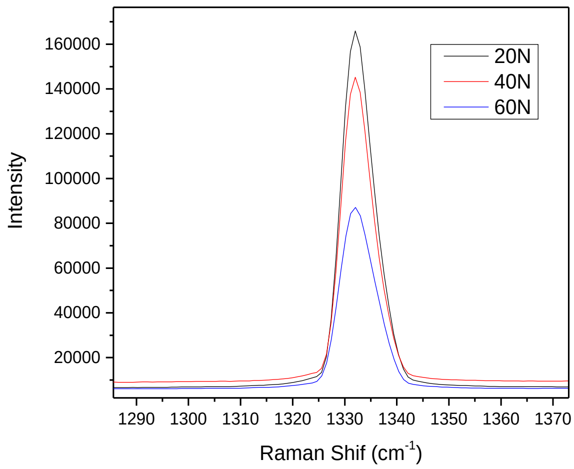
In order to verify the conjecture in the friction experiment that different loads lead to different diamond surface quality, three loads with the value of 20 N, 40 N and 60 N were selected as the polishing load for CMP. Figure 5 and Figure 6 show the morphology and surface roughness of diamond surface after polishing respectively.

As shown in Figure 5(a) and 6(a), the intact diamond edge is obtained with polishing load of 20 N, while the roughness of Ra cannot be reduced below 2 nm within 120 minutes. Under the load of 20 N, the friction force acting on the diamond is too small, so the asperities on surface cannot be quickly removed and the processing efficiency is low. Figure 5(c) and 6(c) show that the surface roughness drops to Ra 1.691 nm after polishing in 120 minutes, while obvious edge damages occur with the load of 60 N. Under the load of 60 N, the large abrasives get broken. The number of effective abrasives sandwiched between diamond specimen and polishing plate that play the main mechanical role in CMP reduces. Although friction force increases with load, there is no significant increase in removal rate due to the decrease of effective abrasives. Meanwhile, impact caused by excessive load fractures the diamond edge. When the load is 40 N, there is no obvious edge damages. Besides, the surface roughness after processing with the polishing loads of 40 N is Ra 1.687 nm that is close to the roughness under 60 N, as shown in Figure 6(b) and 6(c). Therefore, the polishing load of 40 N is suitable for diamond CMP.

Figure7 Raman spectrogram of diamond surface after polishing



(a) Global graph



(b) Local enlarged graph

Raman spectroscopy is one of the most used characterization techniques in carbon science and technology [14]. Figure 7 shows the Raman spectrogram of diamond surface after CMP, Figure 7(b) is a partial enlarged view of Figure 7(a). The polished surface presents an intense band at 1333 cm^{-1} which can be assigned to diamond, as the sharp Raman peak at 1332 cm^{-1} is the characteristic peak of the diamond structure [15]. The 1 cm^{-1} shift to a higher wave number indicates a compressive residual stress on the diamond surface. The diamond peak is shaper after polishing under the loads of 20 N and 40 N than 60 N, which demonstrates that the excessive load affects the crystallinity of diamond, as showed in Figure 7(b). The Raman spectrogram presents a characteristic peak near 1730 cm^{-1} in addition to the characteristic peak of diamond, where the characteristic peak is a Raman characteristic peak of the C=O bond, indicating that the active carbon atoms on diamond surface are oxidized during the CMP process.

Conclusion

(1) The coefficient of friction increases with the load before the load reached 40 N, which is accord with the general rules of boundary lubrication. When the load reaches more than 40 N, the effective abrasives are broke into smaller pieces and the coefficient of friction decreases with the load.

(2) The optimal polishing load for diamond CMP is 40 N. An ultra-smooth (Ra 1.687 nm) surface with no edge damage can be obtained with a polishing load of 40 N in 120 minutes.

Acknowledgments

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