STRENGTH PROPERTIES AFFECTING RELIABILITY OF DIAMOND TOOLS

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The paper describes some important strength properties for the design, manufacturing and proper use of highly reliable diamond cutting tools. Diamond strength is measured by the specially designed Hertzian fracture test. Based on the fracture criterion obtained, the anisotropy in the risk of fracture is analysed numerically on diamond cutting edges with various crystalline orientations. The remarkable size effect is observed in the strength. Although microcracks induced by polishing reduce the strength considerably, the microstrength is almost independent of surface conditions. Diamond microstrength shows close correlation with the spectra of infrared absorption and electron spin resonance which reflect some form of crystalline defects in diamond. Diamond specimens subject to temperatures higher than 800 K deteriorate in strength by surface crack elongation due to oxidation. Specimens heated at temperatures lower than 600 K show some improvement in strength due to crack healing.

1. Introduction

Ultraprecision metal cutting is a technique using a fine single-point diamond cutting tool on a specially designed precision machine tool to transfer the motion of the machine tool to highly machinable worksurfaces as repetition of the tool profile.

The machine tool, which is a key element in this technique, has attained an extremely high level in its performance. The accuracy of the machine tool for this purpose has reached the order of 10 nm on commercial machines and of 1 nm on an experimental one aided by advanced control techniques$^{1)}$. On the other hand, the design, manufacturing and proper use of the diamond cutting tools which are the other key element of ultraprecision metal cutting have been almost dependent on empirical rules.

In order to harmonize the quality of diamond tools with highly refined machine tools, and to satisfy the requirements for advanced tooling in the near future, the growing importance of the scientific approach to diamond tool technology is being recognized. Keeping this in mind, the paper describes some important strength properties which directly affect the reliability of diamond cutting tools.

2. Strength of diamond

Diamond is known as the ideal material for fine cutting tools because of its extremely high strength and hardness. However, the strength properties of diamond have not been understood well enough for specific purposes, possibly due to the difficulty in reliable measurement of the strength and to complicated characteristics such as the remarkable anisotropy, the size effect and the wide discrepancies in strength of individual stones.

Diamond strength is measured by the Hertzian fracture test, utilizing the acoustic emission (AE) technique with spherical-shaped diamond indenters of various tip radii. This measuring procedure has the distinctive feature of detecting the initiation of fracture by AE signal from the tiny Hertzian cracks of micron size induced on the specimen surfaces$^{2)}$. The average contact pressure of the indenter at the moment of crack initiation, p_0, is used as a characteristic strength value.

Fractures in diamond take place when the tensile stress normal to the (111) plane, $\sigma_{(111)}$, or the characteristic stress, which is effective to induce cleavage, reaches a certain level (or strength) inherent to the specimen. This fact automatically leads to the presence of "apparent" anisotropy in the fracture strength of diamond. Figure 1 shows

Science and Technology of New Diamond, edited by S. Saito, O. Fukunaga, and M. Yoshikawa, pp. 383–387.

pressure of diamond estimated from the indentation hardness. The maximum tensile stress normal to the (111) plane along the contact circle at the crack initiation, $\sigma_{a(111)}$, reaches the level of 20 GPa, which is a few tenths of the theoretical tensile strength.

3. Possible defects affecting strength

Figure 3 shows the effect of size on strength of fine polished surfaces compared with that on rough polished surfaces of some identical specimens as a function of the indenter radius$^{4)}$. Though there is little difference between the strengths of fine-polished and rough-polished surfaces under smaller indenters, the strengths of fine-polished surfaces under larger indenters are higher than those of rough-polished surfaces, especially with the indenter of 50 μm tip radius. The size effect in general is explained on the basis that the number of flaws in the stressed region decreases as the indenter radius decreases. However, this characteristic size effect on fine-polished surfaces cannot be explained statistically as above. This decreased strength under larger indenters on rough-polished surfaces recovers to the original level when measured again on a specimen finished by re-polishing to the original fine polishing. Considerable differences in the strength measured by the indenter of 5 μm tip radius, defined as the microstrength, are observed among different specimens.

It is considered from these results that the possible mechanism for the changes in this size effect may be found in the presence of two types of flaws with different strength distributions as the fracture nuclei. The microcracks induced by rough polishing reduce the strength considerably under the larger indenter. However, as the density of these weak macroscopic flaws may not be so high, the strength under the smaller indenters shows a negligible decrease. The strength of rough-polished surfaces under the larger indenter can be improved by the removal of weak flaws by fine polishing. On the other hand, the microstrength is almost independent of the surface conditions, and it may depend only on the microscopic defects inherent in the individual diamond specimen.

In order to identify the defect structures, analyses of a variety of specimens of different microstrengths were carried out on the infrared absorption spectra (IRA) and the electron spin resonance (ESR), both of which have been reported to characterize, by means of electromagnetic waves, some of the crystalline defects in diamond. A close correlation is found between the microstrength and the IRA at the 7.3 μm band, as shown in Fig. 4. The absorption coefficient at 7.3 μm has been reported to be proportional to the total area of the platelet, which is the disk-like defect with a diameter of less than 100 nm on the (100) planes$^{5)}$, in the unit volume of diamond$^{6),7)}$. Figure 5 shows the correlation between the microstrength and the relative intensity of broad P2 center ESR. The P2 center has been identified as a defect composed of three nitrogen atoms which, in substitution for carbon, locate most closely to each other in a (111) plane$^{7)}$. Although the correlation between the platelet and the P2 center has not been clarified yet, these defects can be assumed to be closely related to each other in the scope of present strength measurements.

The correlations as seen in Figs. 4 and 5 give the high possibility of non-destructive testing of the microstrength, and in turn the qualification of diamond.

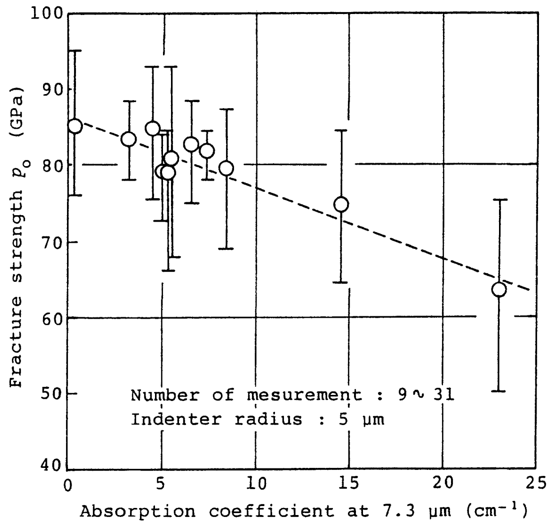

Fig. 4. Microstrength of diamond as a function of the infrared absorption coefficient at 7.3 μm.

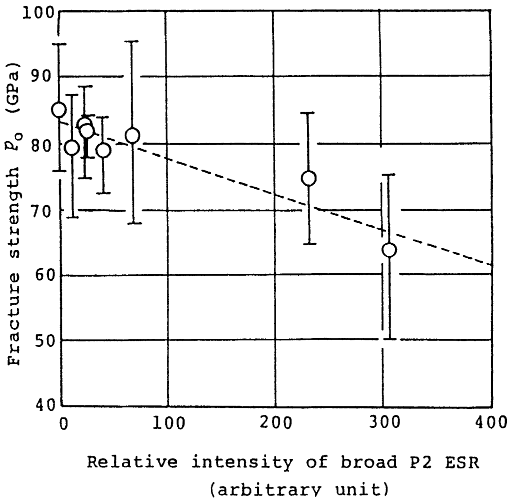

Fig. 5. Microstrength of diamond as a function of relative intensity of broad P2 ESR.

4. Thermochemical effects on strength

The thermochemical effect on the strength of diamond should not be overlooked. A cutting edge under attritious contact with workmaterial is inevitably subject to elevated temperatures in the metal cutting process. Therefore, the durability of diamond cutting tools may be affected by some thermochemical reaction, because diamond is known to be easily oxidized and/or graphitized under high temperature conditions.

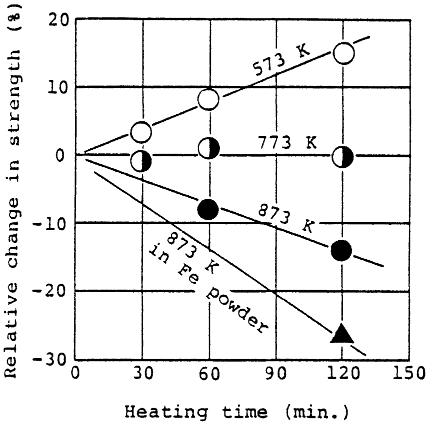

Fig. 6. Change in Hertzian strength on polished diamond surface by heat treatment in air.

Figure 6 shows the change in Hertzian strength of polished diamond specimens under the 50 μm tip radius indenter before and after various heat treatments. The specimens which are subjected to elevated temperatures higher than 800 K deteriorate in strength. Although the deterioration is enhanced when the specimen is heated in iron powder, no change in the strength is observed in the specimen heated in vacuum. From the results, the deterioration in strength is assumed to be caused by the elongation of surface cracks due to oxidation. On the other hand, the specimens heated at the temperatures lower than 600 K do not show any deterioration but rather some improvement in strength. At temperatures lower than 630 K, the surface of diamond is reported to be covered by a stable layer of adsorbed oxygen molecules[8]. In other words, there is no more oxidation to accelerate the crack elongation. The crack healing effect is considered to be the possible mechanism of strength improvement due to an atomic transfer process of thermally activated carbon atoms at the crack tip. In the range of temperature between 650 K and 800 K, the rate of crack healing and the oxidation of transferred carbon atoms can be in equilibrium.

Crystalline defects generally act as nuclei in thermochemical etching and also as obstacles reducing atomic mobility in solids. Therefore, the change in strength of heated specimens is considered to be affected by the defect density included in individual stones. Figure 7 shows the effect of the P2 center density evaluated by the ESR technique on the change in strength of specimens heated at 573 K and 873 K. The specimen with the higher defect density shows less deterioration and greater improvement in the strength. The results show that the thermal durability of cutting tools manufactured of diamond with lower defect densities may be better than those using stones with higher defect density.

5. Conclusions

Taking the scientific and systematic approach to the strength properties of diamond, some useful and fundamental data are obtained for the development of highly reliable diamond cutting tools.

Diamond strength can be reliably measured by

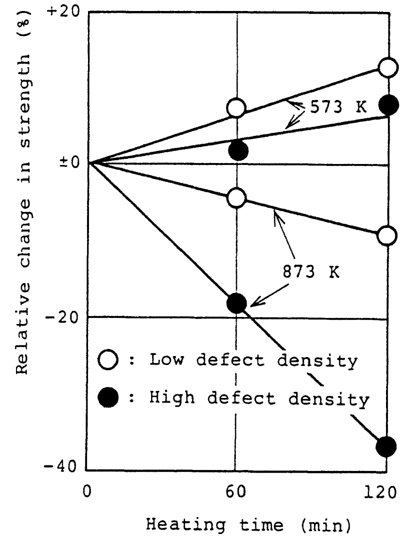

Fig. 7. Effect of defect density on relative change in strength.

the Hertzian fracture test aided by the acoustic emission technique. Fractures in diamond take place at the condition (fracture criterion) that the normal tensile stress on the (111) plane reaches a certain level inherent to the specimen. Based on the fracture criterion, the anisotropy in the fracture risk can be analysed numerically on diamond cutting edges with various crystalline orientations.

The stress level at the fracture in micron-sized cracks (the microstrength) reaches the level of a few tenths of the theoretical strength but decreases remarkably with increasing crack size. Although the microcracks induced by polishing reduce the fracture strength on a larger scale, the microstrength is almost independent of surface conditions. Diamond microstrength shows close correlation with the infrared absorption spectra and electron spin resonance, which reflect some forms of crystalline defects in diamond. The relations give the possibility of nondestructive testing of the microstrength.

Diamond specimens subjected to temperatures higher than 800 K deteriorate in strength by the effect of crack elongation due to oxidation. Specimens heated at temperatures lower than 600 K show some improvement in strength due to the crack-healing effect. These are the other significant properties for understanding the reliability of diamond tools from the thermochemical point of view.

Acknowledgements. The authors express their sincere thanks to Osaka Diamond Industrial Co., Ltd. for their support of this work.

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