ION BEAM FORMING AND SHARPENING OF DIAMOND TOOLS HAVING A SMALL APEX ANGLE

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A new edge- and tip-forming or sharpening process combining ion beam machining with conventional mechanical lapping methods has been developed. Also a simulation method has been developed for predicting the profile changes of diamond tools which are uniformly swung or fixed during ion beam machining. The method can treat a three-dimensional object such as a diamond knife with a hemi-cylindrical tip in a two-dimensional manner. Diamond knives and styli having apex angles less than 60 degrees are machined with Ar ions of 1.0 keV using an ion beam machining apparatus with a kaufman-type ion source. By comparing the profile changes obtained by computer simulation with those obtained by experiment, it is concluded that the method is useful for the prediction of profile changes of a hemi-cylindrical object having an apex angle of less than 60 degrees during ion beam machining with Ar ions of 1.0 keV.

1. Introduction

Diamond tools having a straight cutting edge and an apex angle of less than 60 degrees can be used as knives for ultramicrotomes and ophthalmic surgeon's instruments or probes for profile measuring instruments of diamond styli. Diamond styli with elliptical tips can be used for surface roughness measuring instruments. Usually, polishing of diamond tools is performed by an abrading process using harder diamond powder and a lap-plate of soft materials. In forming such diamond styli, remarkable accuracy is needed. However, it is very difficult to obtain styli having sharp tips with small apex angles by conventional mechanical lapping. For diamond knives, it is desirable to have an apex angle less than 50 degrees and an edge radius of less than 10 nm (nanometers). It is also very difficult to form such diamond knives by conventional mechanical polishing, whereas ion beam machining is suitable for ultra-fine machining of hard and brittle materials such as diamond\(^1\). However, when the ion energy is 1.0 keV, the apex angle of a diamond tool having a prefinished apex angle of less than 50 degrees is finished to 80 degrees, independently of the prefinished apex angle. In other words, a facet is generated on the top of the cutting edge of the tool. Moreover, when the ion energy is 20 keV, the diamond tool apex angle remains the same as the prefinished apex angle, if the prefinished apex angle is more than 40 degrees. In this case, an altered layer of diamond caused by ion bombardment becomes a problem. Hence, we have developed a new edge- or tip-forming process combining ion beam machining with conventional mechanical polishing. Namely, diamond tools prefinished by conventional mechanical polishing are formed or sharpened by ion beam machining under the conditions of the sample being swung or fixed.

2. Experimental apparatus and procedure

The experiments were conducted in an ion beam machining apparatus having an 8 cm Kaufman-type ion source generating argon ion 1.0 keV energy beams at an ion current density of about 0.5 mA/cm\(^2\). Inside the work-chamber, a motorized tilt stage was installed in order to swing the diamond specimen.

In these experiments, we used diamond specimens which were prefinished by conventional mechanical lapping as truncated right quadrangular pyramid shapes having a straight edge of 1 mm length and with tips several micrometers wide, because it is very difficult to make a diamond knife

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with a cylindrical tip. Moreover, diamond styli with hemi-spherical tips were used because they could be easily obtained, and their profile could be very easily observed with SEM.

The surface topography and two-dimensional profiles of the diamond specimens before and after ion beam machining were examined and measured by a scanning electron microscope (SEM) with two secondary electron detectors (Profile SEM)\(^{2,3}\). This can provide an image which is sensitive to the microtopography of the surface and the two-dimensional profile of the cutting edge of the diamond tools.

3. Simulation method for profile changes of hemi-cylindrical objects during ion beam machining

In order to simulate the profile change of the diamond knives during ion beam machining, the following assumptions were made:

1) The specimens have a hemi-cylinder as a diamond knife with a truncated right quadrangular pyramid tip or sphere as a diamond stylus with conical tip.

2) The tangential planes to the curved surface of the specimen move parallel to themselves during ion beam machining.

3) The angular dependence of the ion beam machining rate \( V_n(\theta) \) of diamond is given experimentally. \( V_n \) is the velocity of surface recession, \( \theta \) the angle of ion incidence with respect to surface normal.

4) The specimen is swinging at high speed about the \( z \)-axis, therefore there is little change in the shape/profile of the specimen during one swing.

5) Secondary effects such as re-deposition of sputtered atoms from the work-table and other surfaces to the surface of the specimen may be ignored.

Ions impinge on the surface along the direction parallel to the vector \( I \) as shown in Fig. 2,

\[
I = r \sin \alpha i + r \cos \alpha j
\]

where, \( i \) and \( j \) are the unit vectors in the \( x \) and \( y \) directions, respectively, and \( r \) is the radius.

The normal vector \( n \) at the point \( P \) on the surface is also given as follows;

\[
n = r (\sin \phi i + \cos \phi j). \tag{2}
\]

Then, the effective ion incidence angle \( \theta_e \) at a point on a hemi-cylindrical surface becomes:

\[
\cos \theta_e = \frac{I \cdot n}{|I| |n|} = \sin \phi \sin \alpha + \cos \phi \cos \alpha = \cos (\phi - \alpha). \tag{3}
\]

From Eq. (3), we can obtain the following relationship,

\[
\theta_e = \phi - \alpha. \tag{4}
\]

Assuming a parallel beam, the average ion beam machining rate \( V_n(\phi) \) of the point \( P \) on the profile
of the object during one swing of tilt angle from \( +\alpha_0 \) to \(-\alpha_0 \) is given by Eq. (5).

\[
V_s(\phi) = \frac{1}{2\alpha_0} \int_{-\alpha_0}^{+\alpha_0} V_s(\theta \phi) d\alpha
\]  

(5)

Using the rate \( V_s(\phi) \), we can simulate the profile changes of the object during ion beam machining. There are semi-analytical methods\(^5,6\) to simulate profile changes of objects during ion beam machining. However, we use an iteration method which is very close to a line segments method\(^6\).

4. Results and discussion

Figure 3 shows the average ion beam machining rates, \( V_s \), of diamond specimens as a function of \( \phi \) at various swing angles. As mentioned above, by using these data we can simulate the profile changes of both hemi-cylindrical objects and hemispherical objects in a two-dimensional manner.

Figure 4 shows profiles records of a hemispherical diamond stylus (nominal tip radius of 5 \( \mu \)m and an apex angle of 60 degrees) which was machined with Ar ions of 1.0 keV at an ion current density of 0.5 mA/cm\(^2\) under conditions of uniform swing (tilt angle being from \(-150 \) deg. to +150 deg.). The profile records were obtained by this profile simulation method.

Figure 5 shows SEM photos of a diamond tool (nominal tip radius of 5 \( \mu \)m and apex angle of 60 degrees) machined with Ar ions of 1.0 keV under the conditions of a fixed tilt angle of the worktable \( \alpha = +130 \) and \(-130 \) degrees (two directions). Figure 6 also shows the profile records obtained by this profile simulation method. The diamond stylus machined for 4.5 h has a nearly sharpened part at the top and that for 6.5 h has a sharpened part at the top without a facet formation. Therefore, we
can sharpen the diamond stylus having the apex angle of 60 degrees with Ar ions of 1.0 keV under the conditions of tilt angles of +130 deg. and −130 deg.

Diamond knives whose cutting edges were nearly sharpened by mechanical lapping and an apex angle is of 60 degrees machined with Ar ions of 1.0 keV at the normal ion incidence angle for 3 min. During this machining, the edge radius of the diamond knife may be decreased by several tens nm as shown in Fig. 7.

5. Summary

From the results obtained by the profile simulation method and experiments, the results are summarized as follows:

(1) Diamond knives and styli having apex angles of 60 degrees can be sharpened with Ar ions of 1.0 keV at fixed tilt angles of +130 and −130 degrees.

(2) Diamond knives (apex angle of 60 degrees) machined with Ar ions of 1.0 keV at uniformly changing tilt angles from +150 deg. to −150 deg. have sharpened tips at the top.

(3) A newly developed simulation method can be used to predict the profile changes of hemi-

cylindrical objects such as diamond knives and hemi-spherical objects such as diamond styli.

REFERENCES

5) J. P. Cucumun, M. Cantagrel, and M. Marchal, ibid. 9, 725 (1974).