Ion Beam Sharpening of a Diamond Knife without Facet and Ripple Formation by Swinging It†

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Diamond is considered a promising candidate for the source material of various small scale mechanical tools and electro-mechanical and optical devices. Usually, the diamond tools are fabricated by conventional mechanical lapping method using fine diamond powder, and a lap-plate of soft material. But, these processes can cause micro-chipping in the cutting edges and hence they are not recommendable. FIB (focused ion beam) machining is found more effective for ultra-fine machining of diamond tools but in this process formation of ripples, high damage layer, slow processing and high running cost are some major drawbacks. In order to overcome these limitations, we applied low energy ion beam machining (IBM) using broad ion beam for the sharpening of diamond knife at normal ion incidence and fixed tilt angles. However, formation of facet and/or ripples becomes problematic in this case and the possible machining conditions such as ion beam energy and tilt angle of the tools are very limited. In order to broaden the possible machining conditions as well as get facet and ripple free sharp diamond knife, we proposed swinging of the sample during ion beam sputtering process. To understand the swinging effects on diamond knife, we at first conducted experiment on flat diamond substrates by sequential sharpening process with varying angle of ion incidence. We also developed a simulation method for predicting the profile changes of diamond tools due to IBM at different swing angles. From our experiment and simulation we found, we can get very smooth and sharp diamond knife at the swing angle of ±30°. [DOI: 10.1380/ejssnt.2012.210]

Keywords: Diamond knife; Ion beam machining; Facet, and ripple and swinging

I. INTRODUCTION

Diamond has many attractive and superior qualities over other materials such as ultra-high hardness, ultra-high tensile strength, very-low friction coefficient, high thermal conduction and so on [1–7]. Therefore, diamond is considered a promising candidate for source material of various small scale mechanical tools and electro-mechanical and optical devices e.g., diamond blade, stylus, knife, indenter and optical window for artificial satellites and optics for X-ray free electron laser (X-FEL) [8–10]. Diamond tips are used as probes and styli for profile measurement tools such as scanning probe microscope (SPM) and atomic force microscope (AFM) [11, 12]. Diamond knives are used for ultramicromotombing, and as ophthalmic surgeons instruments. Generally, these diamond tools are mechanically polished using fine grade diamond powder on lap plates of soft materials. However, this type of mechanical process can cause micro-chipping in the cutting edges and tips of the diamond tools, hence they are not recommendable. On the other hand, dry processes such as PE (plasma etching) [13], RIE (reactive ion etching) [14, 15], IBM (ion beam machining) [16–18], RBM (reactive ion beam machining) [18], IBAE (ion beam assisted etching) [19], and FIB (focused ion beam) machining [20, 21] have been found to be more effective for ultra-fine machining of diamond tools. RIE, which is commonly used for surface micro-machining of CVD diamond MEMS, cannot be applied for the forming and sharpening of diamond styli or for diamond probes, because in these methods the incident angle of the ions cannot be changed as required. FIB machining method can be employed for the sharpening of diamond probe [22], and for forming of diamond micro-tools [23, 24]. However, in this case, formation of ripples on the probe's surface, high damage layer, slow rate production due to one by one processing and high running cost, are some major shortcomings. In order to overcome these limitations of FIB machining, we have applied low energy IBM (using broad ion beam) for the sharpening of diamond tools at normal ion incidence and fixed tilt angles [25–27]. A drawback with IBM of diamond tools is the formation of facet on the top of the diamond tools that occurs due to the dependence of the etching rate on the ion incidence angle. Since the shape of the diamond tips is mostly hemispherical, facet is formed on the cutting edge where the etching rate is maximum. Another drawback with IBM is the formation of ripples on the surface of diamond tools. In some cases, facets and ripples are formed simultaneously on the diamond tools. Moreover, in this method the possible machining conditions are very limited such as tilt angle of the tools and ion energy. Therefore, we have introduced a new technique addressing all the problems of IBM. In our new method, we proposed swinging the diamond knife in a prescribed angle and orientation during IBM by 1 keV Ar⁺ ion beam. In order to realize the effect of swing on the surface of the diamond knife, we at first applied sequential sputtering process on a flat diamond surface with varying ion incidence angle and observed the morphology of the sputtered surface. Then we also developed a simulation method to predict the profile changes of diamond knife due to IBM at different swing angles. In order to justify the simulation result, we extended our research and performed IBM of the diamond knives at different swing angles. Result shows that the change of profile of diamond knife obtained

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by simulation is the same as that obtained from experiment.

II. EXPERIMENTAL APPARATUS

In the experiment, the sequential sputtering process was applied on two pieces of flat diamond surface of $R = 0.134$ nm rms and $R = 0.074$ nm rms. The surface morphology of the flat diamond surface was observed by AFM before and after the sequential sputtering. Two natural single crystal diamond knives with the apex angle of 90° and nominal tip radius of 5 µm were used as specimen for the ion beam sharpening under swing condition. IBM was done by an ion beam processing apparatus with an electron cyclotron resonance (ECR) type ion source (ELIONIX Inc. EIS-200ER) which can generate broad ion beam of diameter 30 mm with the beam energy in a range of 0.2–3.0 keV. We used 1 keV Ar$^+$ ion beam for our experiment and the ion current density was 0.9 mA/cm$^2$. A vertical type step motor was attached to the ion beam apparatus for swinging the specimen. The step motor was connected to a PC via a cable for controlling the speed and angle of the swing. The maximum speed of the swing motor was ±45°/s. During the IBM, the pressure of the plasma generation chamber was kept at 1 × 10$^{-4}$ Pa. The profiles of the diamond knives were observed by a scanning electron microscope (SEM) before and after the IBM. The simulation program was developed using Matlab software.

III. EFFECT OF SEQUENTIAL SPUTTERING ON FLAT DIAMOND SURFACE

The sequential sputtering process was conducted on the flat diamond surface in two steps. In the first step, sputtering was done in sequences on the same sample varying the ion incidence angle in increasing order i.e. 0°, 20°, 40°, 60° and 80° while each time the duration of sputtering was 2 minutes. In the second stage, sequential sputtering was done in the same manner but varying the ion incidence angle in the reverse order (80°–0°). Figure 1(a1) shows the AFM image of an unprocessed diamond chip with the surface roughness of $R = 0.134$ nm rms (sample-1). Figures 1(a2)–(a4) show the AFM images of the sputtered surface with ion incidence angle, $\theta = 0°$, $\theta = 0°+20^°+40^°+60^°$ and $\theta = 0°+20^°+40^°+60^°+80^°$ respectively. As shown in the Fig. 1(a2), the surface roughness was increased a little ($R = 0.137$ nm rms) due to 1 keV Ar$^+$ ion beam sputtering at normal incidence. From the Fig. 1(a3), we find that ripples appear and the roughness increases from 0.137 nm rms to 1.2 nm rms when the surface was further processed at 20°, 40° and 60° ion incidence angles. The direction of the ripples changes and roughness increases up to 3.7 nm rms when the processed surface was again sputtered at the ion incidence angle of 80° as shown in Fig. 1(a4).

Figure 1(b1) shows the AFM image of the unprocessed flat diamond chip (sample-2) with the surface roughness, $R = 0.074$ nm rms. The surface was sputtered by 1 keV Ar$^+$ beam sequentially varying the incidence angles in the reverse order (80°–0°). As shown in Fig. 1(b2), dot patterns were appeared on the surface and the surface roughness was increased to $R = 0.39$ nm rms when the diamond substrate was sputtered at ion incidence angle of 80°. From Fig. 1(b3), it is found that the dot pattern changes to ripples and roughness increases to $R = 0.5$ nm rms when the dotted pattern was sputtered at ion incidence angle of 60°. However, the ripples disappeared when the rippled sample was further sputtered at 40°, 20° and 0° ion incidence angles in sequences, therefore, the surface becomes smooth again with $R = 0.17$ nm rms which is shown in Fig. 1(b4). From these observations, we can conclude that ripples are formed during sequential sputtering of 0° to 80° and eliminated by reverse order sequential sputtering (i.e. 80° to 0°). Moreover, we can assume that if the sequential sputtering is limited within lower incidence angles (i.e 0°–60°), the smoothing mech-
anisms may dominate over the roughening mechanisms and therefore, the surface will be smoothened and ripple free.

IV. SIMULATION OF THE PROFILE CHANGES OF A CONICAL TYPE DIAMOND STYLUS

The simulation of profile changes of the diamond knife (apex angle 90°) due to IBM under swing condition was based on the following postulates:

1. The object was symmetrical around its axis of swing.
2. The tip of the knife is half-circular as shown in Fig. 2(b).
3. The knife was swung around the x-axis as shown in Figs. 2(a) and (b).
4. The secondary effects such as re-deposition of sputtered atoms from the work piece or other sources on diamond stylus were ignored.

When a diamond knife is swung during IBM, the ion incident angle on each point of the stylus and hence the etching rate will vary in each swing cycle. Let us consider, the surface of the knife is divided into “i” number of segments and the swing half-cycle is divided into “n” number of time slots. As shown in Fig. 2, a point \( P(x, y, z) \) at a vertical angle, \( \phi \) on the surface of the diamond knife will move around x-axis when it is swung around the x-axis by an angle \( \alpha \) (\(-\alpha\) to \(+\alpha\)). Therefore, the effective ion incidence angle, \( \theta_e \) at point \( P \) in the y-z plane would be

\[
\theta_e = \phi \pm \alpha
\]

When \( i = 0 \), \( P \) may be regarded as \( P_0 \) at a vertical angle \( \phi_0 \). At the beginning of the swing (\( t = t_0 \)), \( \theta_e = \phi_0 - \alpha_1 \) at point \( P_0 \). After the completion of the first time slot of the swing (\( n = 1, t = t_1 \)), the knife is inclined at an angle \( \alpha_1 \), therefore, \( \theta_e = \phi_0 - \alpha_1 \) at point \( P_0 \). In this manner, after the completion of the \( n^{th} \) time slot of the swing (\( t = t_n \)), the knife is inclined at the maximum angle of swing (\( \alpha_n = \alpha \)), therefore, the effective ion incidence angle at point \( P_0 \) would be \( \theta_e = \phi_0 - \alpha_n \). Similarly, when \( i = 1 \), \( P \) may be regarded as \( P_1 \) at a vertical angle \( \phi_1 \) and the effective ion incidence angle at point \( P_1 \) would be \( \theta_e = \phi_1 - \alpha_n \) at \( t = t_n \).
the swing, the etching rate will differ. Hence, the total etching depth, $\vec{R}(\phi_i)$, attained after completion of the $i^{th}$ time slot of the swing for the $i^{th}$ number of segment can be expressed by Eq. (2). The vector of the etching depth, $\vec{R}$ is expressed by Eq. (3), where $\vec{V}$ and $\vec{t}$ represent the vector of average etching rate and time duration associated with each swing cycle respectively.

$$
\vec{R}(\phi_0) = \vec{V}(\phi_0 - \alpha_0) \cdot t_0 + \vec{V}(\phi_0 - \alpha_1) \cdot t_1 + \vec{V}(\phi_0 - \alpha_2) \cdot t_2 + ... + \vec{V}(\phi_0 - \alpha_n) \cdot t_n,
$$

$$
\vec{R}(\phi_1) = \vec{V}(\phi_1 - \alpha_0) \cdot t_0 + \vec{V}(\phi_1 - \alpha_1) \cdot t_1 + \vec{V}(\phi_1 - \alpha_2) \cdot t_2 + ... + \vec{V}(\phi_1 - \alpha_n) \cdot t_n,
$$

$$
\vec{R}(\phi_i) = \vec{V}(\phi_i - \alpha_0) \cdot t_0 + \vec{V}(\phi_i - \alpha_1) \cdot t_1 + \vec{V}(\phi_i - \alpha_2) \cdot t_2 + ... + \vec{V}(\phi_i - \alpha_n) \cdot t_n,
$$

$$
\vec{R} = \vec{V} \cdot t,
$$

The value of the etching rate corresponding to the effective ion incidence angle, $\theta_i$, can be obtained by using the experimental data of Kiyohara et al. [28], and then the average etching rate $V$ is derived for each cycle. Figure 3 shows the plots of the average etching rate against the vertical angle $\phi$ for the swing angle ±30°, ±60°, ±90° and ±120°. The corresponding polynomials were drawn from the fifth, fourth, third, and fifth order approximation of the discrete $V$ (average etching rate) data respectively. In order to observe the profile changes of the diamond knife under the swing angle of ±30°, ±60°, ±90° and ±120°, respectively, as obtained by the simulation method. In our simulation, we considered $i = 11$, $n = 13$ (for $\alpha = \pm 30^\circ$), 25 (for $\alpha = \pm 60^\circ$), 37 (for $\alpha = \pm 90^\circ$) and 49 (for $\alpha = \pm 120^\circ$). Simulation was done for $t = 1$ h, 2 h and 4 h. As shown in Fig. 5(a),

![FIG. 6: SEM images of the diamond knife in the y-z plane before and after the IBM at $\alpha = \pm 30^\circ$ (a) un-processed knife, (b) processed knife at $t = 2$ h, (c) processed knife at $t = 4$ h, (d) processed knife at $t = 7$ h.](http://www.sssj.org/ejsnt (J-Stage: http://www.jstage.jst.go.jp/browse/ejsnt/))

![FIG. 7: SEM images of the diamond knife in the y-z plane before and after the IBM at $\alpha = \pm 60^\circ$ (a) un-processed knife, (b) processed knife at $t = 2$ h, (c) processed knife at $t = 4$ h, (d) processed knife at $t = 7$ h.](http://www.sssj.org/ejsnt (J-Stage: http://www.jstage.jst.go.jp/browse/ejsnt/))

$$
x = x_0 - \left\{ \frac{dV(\phi)}{d\phi} \cos \phi + V(\phi) \sin \phi \right\} \cdot t,
$$

$$
y = y_0 - \left\{ \frac{dV(\phi)}{d\phi} \sin \phi + V(\phi) \sin \phi \right\} \cdot t,
$$

where $\frac{dV(\phi)}{d\phi}$ can be obtained from the slopes of the polynomials of Fig. 3.
initially \((t = 0)\) the knife is blunt. Due to IBM under the swing angle of \(\pm 30^\circ\), the profile of the knife gets sharper with increasing process time. At \(t = 4\) h, the profile of the diamond knife becomes very sharp. In the case of \(\pm 60^\circ\) swing angle, the profile becomes flat at \(t = 4\) h instead of getting sharp as shown in Fig. 5(b). Therefore, as found from the simulation, a knife cannot be swung at the swing angle of \(\pm 60^\circ\) for its sharpening. As shown in Fig. 5(c), the profile of the knife does not become sharp with increasing process time at the swing angle of \(\pm 90^\circ\). Therefore, swinging at \(\pm 90^\circ\) is also not recommended for the sharpening of the diamond knife. In case of swinging at \(\pm 120^\circ\), as represented in Fig. 5(d), the knife becomes sharp at \(t = 4\) h compared to the unprocessed one \((t = 0\) h). However, the sharpness is not very significant at the swing angle of \(\pm 120^\circ\) compared to that at \(\pm 30^\circ\).

V. EXPERIMENTAL OBSERVATION

In order to investigate the accuracy of prediction of the profile changes from simulation, we conducted experiment by IBM on the diamond stylus varying the swing angle. The experimental results were observed by a SEM at different time interval. The change of the shape profile was observed in the \(y-z\) plane while the surface pattern for smoothness was observed in the \(x-z\) plane. Figure 6 shows the SEM images of the unprocessed and processed diamond knife that was swung at the swing angle of \(\pm 30^\circ\). Figure 6(a) represents the SEM image of an unprocessed diamond knife which has a nominal tip radius of \(5\) \(\mu m\) and an apex angle of \(90^\circ\). As shown in the figure, initially the head of the knife was blunt. The changes in shape profile due to machining by 1 keV \(Ar^+\) beam under the swing angle of \(\pm 30^\circ\) at \(t = 2\) h, \(t = 4\) h and \(t = 7\) h are represented in Figs. 6(b), (c) and (d) respectively. It is found that the sharpness of the knife increases with increasing process time and after 4 hours of machining the knife became significantly sharp. The sharpness continued to increase until \(t = 7\) h.

Figure 7(a) shows the SEM image of another unprocessed knife that was machined under the swing angle of \(\pm 60^\circ\). The profile of the processed knife at \(t = 2\) h, \(t = 4\) h and \(t = 7\) h are shown in Figs. 7(b), (c) and (d), respectively. It is apparent form the figures that the tip of the knife becomes faceted instead of getting sharp due to machining at the swing angle of \(\pm 60^\circ\). Comparing the SEM images of the processed knives shown in Figs. 6 and 7 to that with the predicted profile obtained from simulation, it is found that they are in harmony. Therefore,
the required swing angle can be predetermined from the simulation for the sharpening of the diamond knife.

Figure 8 shows the surface morphology of the diamond knives before and after the processing at the swing angle of ±30° and ±60°. From the SEM image of the unprocessed knife as shown in Fig. 8(a1), it is found that initially the surface was rough and there were many scratches and engravings on the surface. The surface appeared smooth at t = 4 h due to IBM at the swing angle of ±30° and became further smooth at t = 7 h as shown in Figs. 8(a2) and (a3), respectively. In case of swinging at ±60°, the roughness of the surface was not significantly improved even after 4 hours of machining as shown in Fig. 8(b2) compared to the unprocessed one represented in Fig. 8(b1). However, the surface appeared smooth at t = 7 h as shown in Figs. 8(b3). From Fig. 8, it is apparent that the surface becomes smooth due to swinging the specimen while ion beam sputtering.

VI. CONCLUSION

We applied a new technique for the sharpening of a diamond knife by 1 keV Ar+ ion beam sputtering process. In our technique, the sample was swung during IBM. From our experimental observation and simulation results, we can draw the following conclusions:

a) We conducted experiment on the flat diamond surface by sequential sputtering process in order to realize the effect of swing during IBM. We found ripples appear on smooth surface as the ion incidence angle increases to 60° in case of sputtering at the incidence angles in the sequence of 0° ~ 80°. The ripples are eliminated when sequential sputtering is done at the ion incidence angles in the reverse order (80° ~ 0°). From this experiment, it is assumed that if IBM is done on the diamond knife under swinging condition, the formation of ripples as found in case of fixed tilt angles can be avoided.

b) We developed a simulation method for the prediction of the profile changes due to IBM at different swing angles. From the simulation we found that we can get a sharp knife at the swing angle of ±30° and ±120°. While the tip of the knife becomes flat in case of ±60° swing angle.

c) After the predictions from simulation, we conducted IBM on the diamond knives by 1 keV Ar+ beam at the swing angle of ±30° and ±60°. We obtained ripple free sharp and smooth knife at the swing angle of ±30°. The sharpness of the knife increases with increasing the process time and finally becomes saturated after 7 hours. The surface of the knife also becomes smooth due to swinging while IBM. While in case of swinging at ±60°, the knife becomes faceted at the tip.

d) The changes in shape due to ion beam sputtering under swing condition are in harmony with the simulation results.

[1] H. Sumiya and S. Satoh, Diamond and Related Mater. 5, 1359 (1996).
[2] Y. Mokuno, A. Chayahara, and H. Yamada, Diamond and Related Mater. 17, 415 (2007).
[3] Y. A. Mankelevich and P. W. May, Diamond and Related Mater. 17, 1021 (2007).
[4] M. Kamo, Y. Sata, S. Matsumoto, and N. Setaka, J. Crystal Growth 62, 642 (1983).
[5] R. Haubner and B. Lux, Diamond and Related Mater. 2, 1277 (1993).
[6] T. Irfune, A. Kurio, S. Sakamoto, T. Inoue, and H. Sumiya, Nature 421, 599 (2003).
[7] H. Sumiya, T. Irfune, A. Kurio, S. Sakamoto, and T. Inoue, J. Mater. Sci. 39, 445 (2004).
[8] H. Sumiy, Rev. Sci. Instrum. 76, 016112 (2005).
[9] G. F. Ding, H. P. Mao, Y. L. Cai, Y. H. Zhang, X. Yao, and X. Z. Zhao, Diamond and Related Mater. 14, 1543 (2005).
[10] R. Otterbach and U. Hilleringmann, Diamond and Related Mater. 11, 841 (2002).
[11] T. Nagase, J. Kawamura, S. A. Pahlovy, and I. Miyamoto, Microeect. Eng. 87, 1494 (2010).
[12] I. Miyamoto, T. Ezawa, and K. Itabashi, Nanotechnology 2, 52 (1991).
[13] D. T. Tran, T. A. Grotjohn, D. K. Reinhard, and J. Asmussen, Diamond and Relat. Mater. 7, 717 (2008).
[14] M. D. Stoikou, P. John, and J. I. B. Wilson, Diamond and Relat. Mater. 17, 1164 (2008).
[15] Y. Ando, Y. Nishibayashi, K. Kobashii, T. Hirao, and K. Oura, Diamond and Relat. Mater. 11, 824 (2002).
[16] I. Miyamoto, Prec. Eng. 9, 71 (1987).
[17] I. Miyamoto, J. Taniguchi, and S. Kiyohara, New Diamond and Frontier Carbon Technol. 10, 63 (2000).
[18] T. J. Whetten, A. A. Armstead, T. A. Gizykowski, and A. L. Ruoff, J. Vac. Sci. Technol. A 2, 477 (1984).
[19] N. N. Efremov, M. W. Geis, D. C. Flanders, G. A. Lincoln, and N. P. Economou, J. Vac. Sci. Technol. B 3, 416 (1985).
[20] Nan Yao (Ed.), Focused Ion Beam Systems (Cambridge Univ. Press, 2010).
[21] L. A. Giannuzzi and F. A. Stevie (Eds.), Introduction to Focused Ion Beams (Springer, 2005).
[22] A. Olbrich, B. Ebersberger, C. Bött, Ph. Niedermann, W. Hänni, J. Vac. Sci. Technol. B 17, 1570 (1999).
[23] D. P. Adams, M. J. Vasile, T. M. Mayer, and V. C. Hodges, J. Vac. Sci. Technol. B 21, 2334 (2003).
[24] Y. N. Picard, D. P. Adams, M. J. Vasile, and M. B. Ritchey, Prec. Eng. 27, 59 (2003).
[25] I. Miyamoto, T. Ezawa, and K. Nishimura, Nanotechnol. 1, 44 (1990).
[26] I. Miyamoto, K. Kawata, and M. Kimura, J. Mater. Sci. Lett. 7, 1175 (1988).
[27] T. Nagase, H. Kato, S. A. Pahlovy, I. Miyamoto, and Y. Nakamura, J. Vac. Sci. Technol. B 27, 2686 (2009).
[28] S. Kiyohara, I. Miyamoto, T. Masaki, and S. Honda, Nucl. Instrum. Methods Phys. Res. B 121, 191 (1997).
[29] J. P. Ducommun, M. Cantagrel, and M. Marchal, J. Mater. Sci. 9, 725 (1974).