Micromachining of polycrystalline CVD diamond-coated cutting tool with femtosecond laser

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Abstract
To enhance the cutting performance of chemical vapor deposit (CVD) diamond-coated tool, a short pulse laser grinding technique is applied. However, the thermal impact of a nanosecond laser damages the diamond crystallinity of the processed surface. To reduce this thermal impact, a femtosecond laser is innovatively used in this study to conduct the pulse laser grinding (PLG) of a CVD diamond-coated cutting tool, to achieve a sharpened tool edge with high quality. Furthermore, the CVD diamond tool edges processed by femtosecond and nanosecond lasers are compared based on sharpness, smoothness, and microstructure changes. The results show that a sufficient laser fluence higher than the threshold and a reduction in the pulse overlapping rate of the laser fluence of the femtosecond laser PLG could ensure a better tool edge shaping. A laser power of 7 W, processing angle of 20°, and scanning speed of 60 mm/s with roughness reduced to approximately half, are the suitable processing conditions of the femtosecond laser. From the observation of a scanning electron microscope, the tool edge processed by femtosecond laser PLG has a relatively sharp edge, with a radius of curvature around 1 μm, similar to that of a nanosecond laser. The further magnified images reveal a distinct processed surface characteristic. The nanosecond laser-processed surface has obvious longitudinal machining marks while that of the femtosecond laser has ablated debris. Moreover, the surface microstructure change of CVD diamond by femtosecond and nanosecond laser PLG are compared using Raman spectroscopy, further confirming that femtosecond laser could successfully suppress unfavorable structural effects in CVD diamond. Based on the results, femtosecond laser has a great potential for processing higher-quality CVD diamond tool edges.

Keywords: CVD diamond coated tool, Pulse laser grinding, Femtosecond laser, Tool edge sharpening, Surface microstructure change

1. Introduction

Chemical vapor deposit (CVD) diamond has received significant attention in the field of machining due to its excellent properties, including high hardness, thermal conductivity, Young’s modulus, as well as its low cost as a synthetic diamond. CVD diamond can be grown as a large free-standing substrate (Trava-Airoldi et al., 1997) or coated onto other mechanical components such as cutting tools. Owing to its excellent machinability, CVD diamond has a sharper cutting edge than a polycrystalline diamond. It exhibits similar or even better performance compared with single-crystalline diamonds in some respects because it is isotropic and free of cleavage (Jiao and Cheng, 2014). CVD diamond coating can achieve a series of high-precision, low-cost, and grinding-less machining. For example, a cemented carbide die can be directly carved by a cutting process. However, the surface of the CVD diamond contains many amorphous structures (Ballutaud et al., 2008) that result in decreased coating hardness. The high thickness of the coating improves its wear resistance. However, this leads to high tool edge roundness, which causes delamination of the rake face and increases the edge recession speed during the cutting process (Sahashi et al., 2017). Hence, CVD diamond-coated cutting tools require further processing; however, it is difficult to mechanically process CVD diamond due to its extreme hardness. Innovative processing techniques such as laser ablation, a non-contact processing method with high removal rate, high flexibility, and high accuracy, have shown high potential for processing synthetic diamond. Everson et al. (Everson and Molian,
2009) processed polycrystalline diamond micro-tools by Nd:YAG laser cutting with a high removal rate (approximately 0.002 mm²/min). However, the severe heat-affected zone on the surface requires further processing. Brecher et al. (Brecher et al., 2013) and Yang et al. (Yang et al., 2018) conducted a two-step diamond processing with nanosecond laser ablation to induce the graphitized surface and follow-up mechanical grinding, thereby obtaining the smallest cutting edge radius of 1.957 μm. However, these machining processes are expensive and inefficient. Recently, a new laser processing method, pulse laser grinding (PLG), was developed by our group using tool edge formation process, as shown in Fig. 1. In the method, CVD diamond is repeatedly scanned with a nanosecond laser at a small processing angle to create a sharp edge with high precision and efficiency, without the need for complicated multi-axis control and follow-up processing (Suzuki et al., 2013; Mabuchi et al., 2015). Based on the experimental results, the PLG-processed CVD diamond tool has a significantly reduced cutting force and effectively suppresses coating delamination. However, the current problem of the PLG processing of CVD diamond is that the thermal impact damages the diamond crystallization to a certain extent. Hence, femtosecond, regarded for its high precision ‘cold’ material processing, has been introduced to the PLG process. Meanwhile, some novel phenomena have been discovered for the femtosecond laser, such as silicon, diamond-like carbon (DLC), and graphite, which could increase the diamond crystallization after irradiation (Zhan et al., 2018; Nistor et al., 1994; Wang and Liu., 2017; Narayan et al., 2019). These phenomena have been confirmed for CVD diamond by Itoigawa et al. (Itoigawa et al., 2017), thereby providing a new possibility for the femtosecond laser processing of CVD diamond while simultaneously improving its hardness.

In this study, we aim to implement a higher-quality cutting tool edge of a CVD diamond tool with PLG processing, using a femtosecond laser. Here, high quality means a sharp tool edge from the geometry perspective that suppresses thermally negative microstructure changes. First, to confirm the feasibility, femtosecond laser PLG of CVD diamond is performed under different processing conditions to investigate the proper experimental parameters. Then, the CVD diamond-coated tool edge processed with a femtosecond laser under the optimal condition is compared with a diamond-coated tool edge processed with a nanosecond laser, based on tool edge formation and surface microstructure changes.

2. Experimental details

Figure 2 depicts the schematic of PLG processing. First, an ultra-short pulse laser beam is focused with a long focal distance lens to create a cylindrical and longitudinal focused laser processing area with a sufficient Rayleigh length (indicated by the blue part). Then, the focused beam repeatedly scans the work edge at a small processing angle (grinding wheel scanning) and the diamond coating is gradually ground. After a certain number of repeated scans, the laser beam is horizontally fed one step towards the laser beam and subjected to another round of scanning. After repeating the above-mentioned scanning and feeding processes several times, PLG processing is achieved by moving the tool only in the x-y direction. Using the same method to process the other sides of the edge, the CVD diamond tool edge can be shaped.

Commercial cutting tools used in this study are cemented carbide coated with CVD diamond with a thickness of approximately 20 μm, and below is short as the CVD tool. An ultra-short pulse fiber-based femtosecond laser was used to innovatively conduct the PLG processing. The focused laser beam spot diameter was approximately 50 μm. The lens has a focal length of 100 mm and a depth of focus of approximately 1.25 mm. The number of scans was 30 (reciprocating). The feed step was 2 μm, and the number of feeds was 5. To investigate the suitable laser processing parameters of the
femtosecond laser PLG and compare it with that of nanosecond laser, the CVD diamond tools were subjected to five different conditions (shown by Nos. 1–5 in Table 1), based on the limitations of the current laser processing machine and the previous results of nanosecond laser PLG. The laser power and processing angle were selected to represent the laser energy fluence and scanning speed for the laser processing kinematics, respectively. A power of 7 W and a speed of 60 mm/s were the upper limits of the current laser, whereas a processing angle of 10° and a power of 3 W were the lower limits of the machining implementation. Meanwhile, for comparison, conventional PLG processing with a Nd:YAG nanosecond laser was also performed on the CVD diamond tool edge under conditions in which a smooth surface similar to that of Suzuki et al. (Suzuki et al., 2013) can be obtained. The spot diameter of the nanosecond laser was approximately 25 μm, with the other laser processing conditions summarized in Table 1. After applying PLG processing to the rake and flank faces, we selected tool edge formation and surface microstructure change as the evaluation criteria for PLG processing. A scanning electron microscope (TM4000Plus, HITACHI, Japan) was used to evaluate the edge sharpness and straightness. Moreover, a Raman spectrooscope (LV-D0001, LambdaVision, Japan) was used to identify the microstructural changes in the processed surface at an exciting wavelength of 532 nm. The processed angle $\theta$ (defined as a small angle between the processed surface and the as-deposited coating surface) and roughness $R_a$ of the PLG-processed surface and CVD diamond coating were measured with laser microscopy (LEXT OLS4100, OLYMPUS, Japan), as shown in Fig. 3. Additionally, optical microscopy (VHX-6000, KEYENCE, Japan) was employed in this study to observe the processed surface.

![Fig. 2 Schematic of PLG processing at a small processing angle](image1)

![Fig. 3 Measurement of processed angle $\theta$ on CVD diamond surface with a laser microscope](image2)
3. Results and discussion

3.1 PLG processing with femtosecond laser under different conditions

Since a femtosecond laser was initially used to perform PLG processing on a CVD diamond tool, the processing results under various experimental conditions, such as changed laser power, scanning speed, and processing angle, were investigated to confirm its feasibility. Surface roughness after processing directly determines the friction during the cutting process and influences the sharpness and straightness of the tool edge. Furthermore, a negative change in the surface microstructure, such as graphitization, causes decreased mechanical properties, which significantly affects the cutting tool. Therefore, different processing conditions were evaluated based on the roughness and microstructure change of the PLG-processed surface.

The optical microscope images of the processed tool edges are shown in Fig. 4 under different conditions. Although the processed area (top of the images) became dark compared with the bright as-deposited area, the processed area generally appears to become smoother after laser grinding, except for specimen No. 5. Meanwhile, some ripple-like processing marks parallel to the edge were observed, especially in Fig. 4(1) and (2), corresponding to the gradual removal processing with the feed step in the PLG processing. Using a laser microscope, the roughness $Ra$ and processed angle $\theta$ are quantitatively summarized in Fig. 5, with as-deposited roughness shown as a reference on the right. Similar to the results from the optical microscope, the surface roughness $Ra$ at a processing angle of 10° is much higher than that under a processing angle of 20°, with the laser-processed surface of specimen No. 5 rougher than the as-deposited surface. The partially-processed uneven surface with bumps and hollows is considered to be caused by the relatively low fluence as the processing angle decreased to 10°, leading to the further scatter of the laser energy on the longitudinal processed area by each pulse. Meanwhile, the roughness of the processed surface at 20° could be reduced by approximately half compared to that of the as-deposited surface. Among the three specimens, specimen No. 2 under a laser power of 3 W is barely satisfactory compared to the other specimens, with a fine granular-like surface in Fig. 4(2), which is likely due to the relatively low central fluence of the laser. The specimens under 7 W (Nos. 1 and 3) exhibit a smooth processed surface, although they show different appearances in the optical microscope image. Finally, for the processed angle $\theta$ shown in the line chart of Fig. 5, a processing angle of 20° can achieve a processing removal of approximately 10°. In other words, after repeated laser grinding, the processing stops when the processing angle reaches around 10°.

Meanwhile, a lower angle will result in a fluence that is below the laser ablation threshold, which explains why specimen Nos. 4 and 5 could hardly be processed. Hence, tool edge formation removal processing could be effectively obtained with higher laser fluence (by increasing the power and processing angle).

![Fig. 4 Optical microscope images of femtosecond laser PLG-processed CVDD tool edges under different conditions](image-url)
The Raman spectra of the femtosecond laser PLG-processed surfaces under different conditions are shown in Fig. 6. For the as-deposited CVD diamond coating, a sharp peak around 1330 cm\(^{-1}\), and broad D and G bands around 1340 cm\(^{-1}\) and 1560 cm\(^{-1}\), respectively. The G band is attributed to the sp\(^2\) bond stretching mode, which is related to the presence of all sp\(^2\) structures, including olefinic chains and aromatic rings, while the D band is attributed to the collective breathing mode of aromatic rings (Ferrari and Robertson, 2000). Generally, the processed feature follows the as-deposited surface. However, some minor differences suggest small microstructural changes after femtosecond PLG processing. Based on the aforementioned roughness and surface structure results in Fig. 5, a higher fluence of the femtosecond laser is favorable for shaping the tool edge and processing a smoother surface, such as specimen Nos. 1 and 3. However, compared to specimen No. 1, the processing of specimen No. 3 at a lower scanning speed shows a slight tendency of growth of amorphous composition with an increase in the G band, probably due to the unnecessarily low scanning speed that causes accumulated energy. Meanwhile, the almost unchanged spectrum of specimen No. 1, which increases the scanning speed (decreases the laser pulses), could effectively avoid this impact. Overall, from the perspective of formability, smoothness, and microstructure of tool edge processing, higher laser fluence and lower overlap rate between the pulses could facilitate the edge formation processing of CVD diamond tools with femtosecond lasers. In the current experiment, a power of 7 W, scanning speed of 60 mm/s, and processing angle of 20° is the most suitable condition for femtosecond laser PLG processing. Hence, the PLG tool edge processing on both the rake and flank faces will be conducted under this condition and also compared with the results of nanosecond laser PLG processing. On the other hand, the peaks of the spectra under lower fluence seem to be more satisfactory than those under high fluence. More interestingly, for specimen No. 5 which had the lowest laser fluence, an obvious increase in the peak intensity could be observed, implying that a new possibility for the femtosecond laser to improve the crystallinity.

3.2 Comparison of PLG with femtosecond laser and nanosecond lasers

After applying the femtosecond and nanosecond laser PLG processing to the rake and flank faces of the CVDD tool, we used a scanning electron microscope to evaluate the tool edge formation and Raman spectroscopy to detect the microstructural changes.
3.2.1 Tool edge formation with femtosecond and nanosecond laser PLG

The CVDD tool edges processed by femtosecond and nanosecond lasers are shown in the SEM images in Fig. 7, where the surface quality and cutting-edge sharpness could be compared. From Fig. 7(a) and (b), the femtosecond and nanosecond lasers achieved a relatively sharp tool edge, thereby reducing the tool edge roundness from 20 μm to approximately 1 μm. The PLG processing of the CVDD diamond tool with femtosecond laser shows a better sharpness than the nanosecond laser, thereby confirming the feasibility of our technique. When the SEM images in Fig. 7(a) and (b) were further magnified (Fig. 7(c) and (d), respectively), different characteristics were observed in the laser-processed surfaces. Although the nanosecond laser-processed CVDD tool seems to have better edge straightness, longitudinal machining marks were obvious. On the other hand, the femtosecond laser-processed surface was slightly curved and had some debris, thus appearing to be rougher than that of the nanosecond laser. It should be noted that the debris cannot be removed by an ultrasonic acetone bath. The roughness measured by the laser microscope further confirms this, with \( Ra \) of the nanosecond laser-processed surface at 0.024 μm, which is lower than the value of 0.045 μm obtained by the femtosecond laser. Thus, for the evaluation of tool edge formation, although both processes could achieve a relatively sharp tool edge, the nanosecond laser PLG outperforms the femtosecond laser due to its smoother processed surface. Although this is somewhat different from our original expectation, it is difficult to conclude that the relatively rougher surface is completely caused by the pulse width because the other parameters, including wavelength, are also different.

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Fig. 6 Raman spectra of processed CVD diamond surfaces under different laser conditions

![Raman spectra](image)

![Fig. 6](image)

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Fig. 7 SEM images of CVDD tool edge sharpened by nanosecond and femtosecond PLG processing

![SEM images](image)
3.2.2 Microstructure change of processed surface after PLG

The results of the Raman spectroscope after the femtosecond and nanosecond PLG-processed surfaces are shown in blue and red in Fig. 8, with optical microscope images shown on the right side. The distinct Raman spectra and the change in brightness of the processed surfaces indicate the different surface modification effects of the two kinds of lasers in this study. The tool edge surface processed by nanosecond laser is brighter under an optical microscope compared with the surfaces darkened by femtosecond laser processing in Fig. 4 and the as-deposited CVD diamond surface. For the Raman spectra in the case of the nanosecond laser, a relative increase in the G peak could be observed, and a weak double-peak spectrum appeared with a tendency of graphitization. The spectrum obtained using a femtosecond laser is similar to that of the as-deposited surface. Meanwhile, nanosecond laser processing has an obvious effect of broadening the full width at half maximum (FWHM) of the diamond peak, which is commonly used as a measure of the diamond crystal quality, illustrating the deteriorated crystallinity. For the femtosecond laser, the diamond peak of the spectra after processing shows almost no negative change, as shown in Fig 4. This surface modification difference may be explained by the fact that the femtosecond laser can process materials much faster than the thermal energy exchange between photoexcited electrons and lattice ions (Fabisiak et al., 2006).

![Raman spectra of the PLG-processed CVD diamond surfaces with femtosecond and nanosecond lasers](image)

Fig. 8 Raman spectra of the PLG-processed CVD diamond surfaces with femtosecond and nanosecond lasers

3.3 Discussion

From the above results, a femtosecond laser could achieve tool edge formation with an extremely sharp edge as a nanosecond laser. More importantly, femtosecond laser PLG could reduce the thermal damage by suppressing the negative surface microstructural effects. Although there are different parameters for nanosecond and femtosecond lasers in this study, the basic geometric removal mechanism of PLG processing is consistent. In PLG processing, ablation occurs in an oblique direction, and slender and shallow crater processing are repeatedly implemented on the tool edge until the processed surface becomes smooth due to random irradiation in the laser scanning process. Thus, the length, depth, and width of the crater by each laser pulse, and the overlap between craters by the pulses directly affect the tool edge formation. In Section 3.1, which states the optimal processing conditions to obtain a smooth tool edge surface, we found that femtosecond laser PLG requires higher power, processing angle, and scanning speed compared with nanosecond laser.

For the total input energy fluence, the pulse fluence of the two kinds of laser was first compared: 40.8 J/cm² for nanosecond laser and 3.6 J/cm² for femtosecond laser, indicating that for each pulse, the fluence of the femtosecond laser is much lower. The laser pulse number \( N_{\text{eff}} \) was also calculated with the spot diameter, repetition rate, and scanning speed (Bizi-Bandoki et al., 2011), and the result was 12.5 pulses for nanosecond laser and 83.3 pulses for femtosecond laser. Based on this, the input energy fluence for each one-way scan is 509.6 J/cm² for nanosecond laser and 297.2 J/cm² for femtosecond laser. If the processing angle is considered, the theoretical total energy for the femtosecond laser at 20° is approximately 2.5 times that of the nanosecond laser at 4.5°. Meanwhile, the femtosecond laser at 10° (condition 4) is 1.3 times, which indicates that, to process the CVD diamond, the femtosecond laser requires higher input energy compared with nanosecond laser. The reasons why the nanosecond laser possesses higher ablation rate for polycrystalline
CVD diamond than femtosecond laser are as follows: Firstly, the wavelength of the nanosecond laser is in the ultraviolet range, while that of the femtosecond laser in this study is in the infrared range, which makes the adsorption rate of nanosecond laser much higher for the micromachining of CVD diamond (Konov, 2012). Meanwhile, it has also been reported that for CVD diamond, the ablation threshold decreases with pulse duration, since the diamond graphitization caused by the thermal stimulated process significantly influences the laser ablation (Kononenko et al., 2005). This difference in ablation rate (different crater sizes by each laser pulse) may also explain why femtosecond laser PLG produces no longitudinal machining marks compared to the nanosecond laser PLG.

On the other hand, laser processing kinematics should be considered, since the horizontal scanning speed for a femtosecond laser is twice that of the nanosecond laser, although slowing down the scanning could theoretically increase the input energy for one scan and increase the removal intensity. Therefore, from the perspective of the pulse overlap degree, the horizontal interval was characterized not only by the scanning speed but also by the repetition frequency of the laser considered. The horizontal interval of the pulse-to-pulse for the nanosecond laser is 2 μm, while that of the femtosecond laser is 0.6 μm. In other words, the high repetition rate (100 kHz) of the current femtosecond laser makes the scanning process more intensive. The debris in Fig. 7(c) may be due to continuous and intensive laser irradiation, leading to insufficient dissipation of the high-temperature plasma and resulting in the re-deposition of the ablated debris. To solve this problem, it is suggested to use the steaming shielding gas to assist the laser processing. It has been reported that the gas stream does not only remove the ablated particles but also quenches the surroundings, indicating that a more precise processed surface with no thermal effect can be expected (Park et al., 2000).

In view of the above, a femtosecond laser has great potential for higher-quality tool edge formation for CVD diamond tools. Considering both the processing efficiency and smooth surface with less damage or debris as well as a short laser wavelength with a higher adsorption rate for CVD diamond, such as in the ultraviolet range, a femtosecond laser with a decreased repetition rate might be a better option for CVD diamond tool edge processing. Meanwhile, the mechanism of PLG processing has not been clarified yet; thus, it is suggested that the effects of laser parameters such as wavelength or repetition rate should be systematically investigated and the PLG processing conditions should be further optimized. In addition, based on our previous results (Itoigawa et al., 2017), after proper irradiation with a low-fluence femtosecond laser, part of the amorphous structure of CVD diamond begins to crystallize, as proven by Raman, XRD, and XAS results. It has also been reported that the femtosecond laser-modified CVD diamond-coated tool could show higher wear resistance than a CVD diamond-coated tool processed only by nanosecond laser PLG in the turning experiments (Natsume et al., 2019). Although the mechanism of this interesting phenomenon has not yet been clarified, the Raman results shown in Fig. 6(5), reproducing this with a significant growth of diamond, shows that femtosecond laser PLG processing has greater possibilities. This implies that femtosecond laser PLG processing on CVD diamond not only achieves a sharp tool edge and suppress the negative thermal impact but also simultaneously achieves positive surface modification, such as improved crystallinity with higher hardness. For instance, after the normal PLG acts as a removal process, a new PLG step with a suitably low fluence of femtosecond laser is applied to complete the processing and achieve surface modification. However, applying the surface modification effect of femtosecond laser to PLG processing is subject to further study.

4. Conclusion

In this study, we performed PLG processing of a CVD diamond-coated cutting tool with a femtosecond laser to obtain a high-quality sharp cutting tool edge. Under the optimal laser processing conditions investigated in this study, the femtosecond laser could sharpen the tool edge from 20 μm to approximately 1 μm and reduce the edge surface roughness Ra by half to 0.45 μm. More importantly, unfavorable microstructure changes to the tool due to thermal damage by nanosecond laser PLG processing could be effectively avoided. To further improve the PLG processing efficiency as well as tool edge straightness and smoothness, it is suggested that a femtosecond laser in the ultraviolet range with a lower repetition rate should be used in the next step.

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