Improvement in Sintered Tungsten Carbide Tool Surface Integrity Using Femtosecond Pulse Laser

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Abstract

In this paper, we propose a surface integrity technique referred to as pulse laser grinding (PLG). This method is a combination of laser ablation and averaging processes, such as grinding, and has two characteristic features. The first feature is that the irradiation area consists of a long-focus lens and a pulse laser with a Gaussian profile, and this method has a laser irradiation area equivalent to that of the grinding wheel. However, owing to the difference in the removal process of PLG and that of conventional grinding, the surface roughness after processing is expected to be different. The second feature is that the workpiece is placed at an approximately parallel angle between the laser axis and the work surface to undergo laser ablation on the surface. The characteristic piece placement restrains laser-specific problems such as debris and redeposition. This study targets sintered tungsten carbide (WC-Co), for which it is particularly difficult to form low-roughness surfaces. Binder removal followed by WC grain detachment caused by conventional grinding contributes to the increase in roughness and deterioration of corner sharpness. The experimental results of PLG with a sufficiently averaged surface of a WC-Co tool confirmed that the parallel roughness reached an arithmetical mean roughness (R_a) of $0.025\text{ }\mu\text{m}$, and the perpendicular roughness reached R_a below $0.006\text{ }\mu\text{m}$, in agreement with the aforementioned considerations.

1. Introduction

Various finishing techniques have been evaluated and their characteristics have been classified because the material finishing processes influence the product performance [1]. Surface roughness, which reflects geometrical accuracy, is a basic criterion for evaluating these processes. It is important to determine the tribological properties and sharpness of the cutting tool edge comprising the two surfaces. Sharpness improves the cutting performance of the tool and reduces damage to the workpiece [2]. However, high-hardness tool materials such as WC, cBN, and diamond are difficult to finish with low roughness owing to the hardness or toughness of the materials. Grinding methods using grindstones or abrasive grains for these materials have been studied. Hegeman et al. reported that, when diamond-grinding wheels were used to grind WC-Co, the arithmetical mean roughness (R_a) was $0.77\text{--}0.28\text{ }\mu\text{m}$ [3]. A higher wear resistance of WC-Co was observed with high loads and coarse abrasives of a few hundred micrometers [4, 5], and binder removal followed by WC grain detachment also contributes to the deterioration of corner sharpness [6]. Mogilnikov et al. reported that the main methods to obtain smoother surfaces involved polishing with diamond powders or electrochemical grinding [7]. However, in both techniques, the polishing time and cost of the abrasives posed inherent limitations.

Pulsed laser ablation can be applied as a new alternative technique to grinding to fabricate surfaces with greater integrity. We proposed pulse laser grinding (PLG), a combination of characteristic laser ablation and averaging processes, such as grinding. The sharpening of the tool edge enhances the cutting performance [8–12]. However, these reports only mention the effects of smoothing and cutting performance on certain tools. In this paper, we clarified the roughness factors that should be considered for PLGs to process various materials. The WC-Co tool roughness obtained by PLG using a femtosecond

laser was experimentally evaluated, parallel and perpendicular to the infeed direction, which demonstrated the advantage of PLG. Based on the experimental results, we identified the factors that determine the finished surface roughness.

2. Theoretical Plg Mechanism

2.1 Motivation for pulse laser processing

A pulse laser with high energy facilitates the processing of materials [13–15]. Ultrashort pulse lasers with an instantaneous application of a high laser fluence enable ablation without a heat-affected zone on the surface [16]. Low-surface-roughness fabrication and application to hard and difficult-to-process materials with pulse lasers have been investigated. Dumitru et al. confirmed the ablation threshold of ultra-hard metals and reported the fundamentals of laser ablation [17, 18]. Eberle and Wegener used WC-Co and polycrystalline diamond (PCD) to demonstrate that Ra obtained using ultrashort pulses was significantly lower than that obtained using nanosecond pulses [19]. However, Fang et al. observed that femtosecond multi-pulse irradiation caused repetitive melting and redeposition of cemented tungsten carbides [20]. Denkena et al. reported the formation of B_2O_3 at a higher laser fluence using picosecond and femtosecond lasers on a polycrystalline cubic boron nitride (PcBN) surface, distinguishing it from thermal effects such as melting using a nanosecond laser [21]. Therefore, a low fluence is recommended, and the number of pulses, pulse energy, and laser spot size should be controlled. Dumitru et al. demonstrated in a study pertaining to the laser processing of holes or grooves that the discharge performance of debris decreased and the roughness was not improved [22]. Reflection at the side wall fabricated by laser processing was used to investigate the variations in hole shapes [23], effect of laser drill welding [24], and keyhole welding model [25], which inhibits the fabrication of flat surfaces. Hence, the control of debris and shape during processing is important for perpendicular laser irradiation.

2.2 PLG mechanism

PLG is a laser processing method that has a laser irradiation area equivalent to that of the grinding wheel. However, its features differ from that of conventional laser processing methods such as drilling, cutting, and laser polishing, which are perpendicular laser irradiation methods. The first feature is that the irradiation area consists of a long-focus lens and a pulse laser with a Gaussian profile. Therefore, it is necessary to construct a three-dimensional fluence distribution. The Gaussian fluence $F(r)$ is expressed as follows [26]:

$$F(r) = \frac{2E_p}{\pi w^2} \exp\left(-\frac{2r^2}{w^2}\right), \quad (1)$$

where E_p denotes the single-pulse energy, r denotes the spatial coordinate with the peak intensity as the origin, and w denotes the radius, referred to as beam waist, defined by the beam intensity decreased to

$1/e^2$ (13.5%) of its peak. When the laser is focused with the lens, the beam radius, $w(z)$, at the propagation distance from the focusing point, z , is expressed as follows:

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}, \quad (2)$$

where λ denotes the wavelength, and w_0 denotes the beam waist at the focus point determined by the laser spot diameter and focal length. The spatial distribution of the laser intensity, $I(r, z)$, is obtained by assigning $w = w(z)$ in Eq. (1). Therefore, the laser power density can be calculated from the squared laser intensity. The contour profile of the calculated power density is shown in Fig. 1.

There is a long, narrow power-density area. This power density has a cylindrical distribution in the three-dimensional PLG area. The length along the z -axis is determined by the focal length of the lens, pulse energy, and laser spot size. Therefore, by determining the laser fluence such that the inside of the PLG area is equal to or above the processing threshold of the material, only the material overlapping with the PLG area can be removed. The second feature is that the workpiece is placed at an approximately parallel angle between the laser axis and the work surface to undergo laser ablation on the surface (Fig. 2). This piece placement restrains the residual debris because the discharge of the ablation particle is perpendicular to the surface. Processing owing to the reflection laser on the wall surface formed by the previous processing is avoided. However, the angle of incidence based on the irradiated surface is often larger than Brewster's angle, and the reflectance is larger than that of perpendicular irradiation. Therefore, high-energy and P-polarized pulses are required.

The PLG area is multi-scanned in the ridge of the cutting tool edge. The processing volume is larger near the cutting tool edge, where the laser fluence is higher. However, the processed surface gradually deviates from the center of the Gaussian beam at each scan. All positions on the surface are finished with the same fluence, which is slightly higher than the processing threshold. Furthermore, as most laser pulses after finishing pass through the finished surface after finishing the surface, it is possible to prevent melting or redeposition. This implies that it is not necessary to strictly determine the number of irradiations as long as the number of irradiations is substantial. For example, even if the operator decides that the process is complete by the end of the plasma emission, the same quality is always obtained.

The finished PLG roughness is decreased using the same averaging method as that of plunge grinding. However, the function of the PLG area differs from that of the grindstone. Finished surfaces obtained by plunge grinding have been reported [3, 27–31]. The surface profile parallel to the infeed direction is formed by different rotation trajectories consisting of abrasive grains with irregular heights (Figs. 3(a) and (b)). Multi-scanning averages these trajectories and the vibration of the scanning movement. The elastic deflection by the vertical load is completely removed in the finishing stage, which is referred to as spark-out [29, 32, 33]. However, the shapes of the tall abrasive grains remain on the finished surface owing to abrasive grain wear before averaging is completed [34, 35]. In addition, the linear and angular motion errors attributed to the guideway accuracy are not averaged. However, there is no averaging effect

in the perpendicular direction. The abrasive grain profile directly determines the perpendicular surface roughness (Fig. 3(c)). Therefore, the perpendicular surface roughness is higher than the parallel surface roughness, which shows that the profile of the grindstone and effect of wear have a strong influence on the roughness.

The finished PLG roughness is defined as the variance of the laser ablation depth in the surface direction. The ablation depth has been reported as a function of the laser fluence, pulse width, and ablation threshold [16, 36]. The variances of the laser fluence and pulse width are averaged by multi-scanning (Fig. 4(a)). Unlike abrasive grain wear, these averages do not shift. The ablation threshold depends on the material used. Its variance depends on the defect variance that affects the absorption coefficient. In addition, the ablation threshold for an ultrashort pulse laser decreases owing to accumulation defects, referred to as incubation effects [37–40]. Structural defects, crystal lattices, and thermal effects have been reported as incubation factors [38, 39, 41]. The variance in these effects is unclear. However, if the low and averaged laser fluence do not affect the variance of the ablation threshold, the parallel surface roughness is determined only by the material-specific defect variance and motion error (Fig. 4(b)). Furthermore, the laser fluence profile in the perpendicular surface direction without the averaging effect and motion error is the fluence trajectory of one pulse; there is no laser fluence variance in this direction (Fig. 4(c)). Therefore, the perpendicular surface roughness depends only on the material defect variance and is smaller than the parallel surface roughness; a result that is opposite to that of plunge grinding, even though the infeed directions are the same.

3. Experimental Setup

We considered the roughness convergence irrespective of the position and difference depending on the direction and conducted experiments to confirm the surface formation with overlapping PLG areas. The overlap depth was determined by the radius of the PLG area and the distance between the surface and the laser axis. The adjustment of the spot size with optical components, such as a lens, was challenging because of the complexity of the system. A simple method was to increase the pulse energy. However, the increase in the PLG radius was not proportional to the pulse energy. When the beam waist, w_0 , matches the PLG radius, the threshold fluence is obtained using Eq. (1).

$$F_{th} = \frac{2E_p}{\pi w_0^2} \exp(-2) \quad (3)$$
 If the PLG radius at a times the pulse energy E_p is r_a , the fluence of that circumference also has the same threshold fluence,

$$F_{th} = \frac{2E_p}{\pi w_0^2} \exp(-2). \quad (3)$$

If the PLG radius at α times the pulse energy E_p is r_α , the fluence of that circumference also has the same threshold fluence,

$$F_{th} = \frac{2\alpha E_p}{\pi w_0^2} \exp\left(-\frac{2r_\alpha^2}{w_0^2}\right). \quad (4)$$

The PLG radius is

$$r_\alpha = w_0 \sqrt{1 + \frac{\log \alpha}{2}}. \quad (5)$$

For example, when the beam waist $w_0 = 5 \mu\text{m}$ and the pulse energy factor is 5, the radius expansion is only $0.81 \mu\text{m}$. Therefore, it is easier to adjust the overlap width based on the machining depth. The PLG surface roughness with different pulse energies and machining depths was confirmed in this study.

A WC-Co cutting tool of grade “G10E” with an average grain size of $2.5 \mu\text{m}$, 6-wt% Co, and edge line with right-angle corners (Sumitomo Electric Hardmetal Corp.) was selected. The flank surface was completed by grinding only in the horizontal direction. Based on the measurements using a laser microscope, $Ra = 0.087$ and 0.137 in the horizontal and vertical directions, respectively. Because Ra differs according to the grinding direction, we defined the initial surface roughness and compared it with that of a pulse laser ground surface.

A schematic of the PLG system is presented in Fig. 5. A Yb:KGW chirped pulse amplification system (PH2-10 W, Light Conversion) with a nonlinear optical unit at a wavelength of 257 nm (PH1F4, Light Conversion) with a pulse frequency of 25 kHz was used. The scanning stage (L-731, PI) had a scanning speed and pulse-to-pulse distance of 2.5 mm/s and $0.1 \mu\text{m}$, respectively. The laser shutter opening was controlled at an arbitrary position by the laser control module connected to the laser and scanning stage. When a mirror is inserted in front of the focus lens, the focus position is adjusted by the Z-stage and CCD camera. In this experiment, the deviation between the camera focus and laser focus was verified in advance and corrected. All focal points were adjusted to the tool edge line.

An ultrashort pulse was focused using a plano-convex lens with $f = 100 \text{ mm}$. The calculated beam waist diameter was $12.6 \mu\text{m}$, whereas the processing hole diameter with $8 \mu\text{J/pulse}$ was $10.5 \mu\text{m}$, as previously verified. The flank surface was tilted at a processing angle of 8° using a p -polarized pulse laser. In this system, the tool surface and laser axis were maintained at an appropriate distance to prevent laser ablation. Subsequently, the tool approached the laser axis gradually by $5 \mu\text{m}$ such that the PLG start position was smaller than the spot size from the tool edge line (Fig. 6). We defined the first pass for which

plasma with laser ablation was visually observed. Pulse energies of 4, 6, 8, 10, and 26 μJ were used to demonstrate the relationship with the pulse energy. The samples were processed using the first-pass method. The depth of the machining from the first to the second pass was 10 μm . Furthermore, to confirm that the finished PLG surface affected the defect generation during PLG processing, the depths of machining from the first to the second pass were 1, 2, 5, and 10 μm with a pulse energy of 4 μJ . The number of scans per pass was set to 50 for all passes. This implied that a larger machining depth corresponded to higher-fluence processes.

Table 1
Parameters of the PLG system

Wavelength nm	Pulse frequency kHz	Scanning velocity mm/s	Pulse energy $\mu\text{J}/\text{pulse}$	Machining depth μm
257	25	10	4, 6, 8, 10, 26	10
			4	1, 2, 5, 10

4. Results And Discussion

Scanning electron microscopy (SEM) was used to observe the finished surfaces. Using a laser microscope, roughness was evaluated with R_a along two axes: one parallel to both the infeed direction and the finished surface and another perpendicular to the infeed direction and parallel to the surface. The measurement positions of the parallel roughness were 20 and 40 μm from the tool edge line.

The finished PLG surfaces and profiles with different pulse energies observed using SEM and a laser microscope with an inclination of 45° are shown in Fig. 7. The R_a of the PLG-processed surface was measured, as shown in Fig. 8. The perpendicular surface roughness, R_a , did not vary with the pulse energy and was in the range of 0.011–0.012 μm . This implied that the surface was processed by a uniform laser profile, irrespective of the pulse energy. The finished surface roughness was formed depending only on the variance defects of the WC-Co tools. The parallel surface roughness had no correlation with the pulse energy and was in the range of 0.041–0.054 μm . The roughness at the position of 40 μm was lower than that at 20 μm , except for the result at 8 μJ . The effect on the intensity and gradient of the profile near the circumference of the beam waist was assumed to be small, even if the pulse energy was increased. Moreover, because the parallel surface has more variance factors than the perpendicular surface, sufficient irradiation pulses are required to average these factors. Therefore, the finished surface under each condition had a small difference in the removal depth. The finished surface was treated with the same fluence. The variation in roughness occurred because of the variability owing to incomplete PLG with the lack of averaging and removal.

The SEM images and profiles with different machining depths are presented in Fig. 9. The measured roughness values are shown in Fig. 10. The perpendicular surface roughness, R_a , was in the range of 0.006–0.011 μm . The roughness depending on the material defect variance was formed irrespective of

the irradiation conditions, as in the previous experiment. The parallel surface roughness decreased as the depth of machining decreased and was in the range of 0.025–0.038 μm , with a minimum roughness of 0.025 μm and a machining depth of 1 μm . This experiment had the same machining depth of 10 μm and pulse energy as that in the previous experiment at 4 $\mu\text{J}/\text{pulse}$. However, the parallel surface roughness was smaller than that in the previous experiment, and there was a low variation depending on the measurement position, probably because the overlap in this experiment was lower than that in the previous experiment because the first pass was defined with a gradual approach of 5 μm . Moreover, a smaller machining depth corresponded to a smaller parallel surface roughness. A smaller removal volume corresponded to a lower and more converged surface roughness by a sufficient averaging process. In addition, the parallel convergence roughness was larger than the perpendicular surface roughness. This indicated that the parallel surface had non-averaging effects, such as motion errors, in addition to the defect variance. This implied that PLG could produce low-roughness surfaces without a laser profile shift during processing, such as grindstone wear.

5. Conclusions

In this study, the PLG method and WC-Co surface obtained by PLG using an ultraviolet femtosecond laser were evaluated. The results of this study can be summarized as follows.

☐ The PLG system included an approximately parallel irradiation and averaging process based on conventional grinding. This irradiation angle restrained laser-specific problems such as debris and redeposition. A low surface roughness was realized by averaging the vibration of the processing system and the variance of the laser pulses. In addition, the PLG with a uniform and non-shifted laser profile during processing was explained to achieve a lower roughness than that of conventional grinding with grindstone wear.

☐ The experimental investigation with WC-Co also showed a lower roughness than that of conventional grinding. The perpendicular surface had a minimum roughness, R_a , of 0.006 μm , whereas the parallel surface had a minimum roughness, R_a , of 0.025 μm .

However, sufficient averaging by multi-scanning with a low fluence was required. The fluence and number of irradiation pulses differed depending on the material.

☐ The variance of material-specific defects and motion error was not considered to restrain even if the averaging process was sufficient. The parallel surface roughness was higher than the perpendicular surface roughness owing to the motion error. This is important when parallel surface roughness is required owing to irradiation direction restrictions (e.g., tool cutting edges).

Declarations

a. Funding

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b. Conflicts of interest/Competing interests

The authors declare no competing interests

c. Availability of data and material

Not applicable

d. Code availability

Not applicable

e. Ethics approval

Not applicable

f. Consent to participate

Not applicable

g. Consent for publication

Not applicable

h. Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Osamu Konda and Xiaoxu Liu. The first draft of the manuscript was written by Osamu Konda and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

Spatial power density of the focused Gaussian beam

Figure 2

PLG mechanism

Figure 3

(a) Schematic of plunge grinding. (b) Parallel and (c) perpendicular directions

Figure 4

(a) Schematic of the PLG. (b) Parallel and (c) perpendicular directions

Figure 5

Schematic of the PLG system

Figure 6

PLG depth of machining

Figure 7

PLG with different pulse energies and non-PLG surface

Figure 8

Parallel and perpendicular roughnesses with different pulse energies

Figure 9

PLG with different depths of machining

Figure 10

Parallel and perpendicular roughnesses with different depths of machining