Abstract

Optimized microscopic cutting edge designs could bring a significant improvement to high performance cutting. This article presents the application of newly developed cutting edge preparation technology to sharpen cutting edges of poly-crystalline diamond (PCD) tools with sub-micro meter radii. This new polishing method is called ultraviolet-rays irradiation assisted polishing. Materials would be removed by a mechano-chemical removal process combined with the photochemical reaction of ultraviolet-rays. After preparation of the sharp edge, the cutting edge radius became smaller than diamond grain size. Several cutting tests showed burr reduction in the cutting of non-ferrous metals and carbon fiber reinforced plastics (CFRP) owing to the decrease of normal cutting force by using the sharpened PCD cutting tool.

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1. Introduction

The cutting edge design is one of the most important factors which can affect cut surface integrity and the resultant quality of products. For reasonable tool costs, the microscopic design of the cutting edge has a great significance. While the formation of an optimized cutting edge configuration is still challenging, many researchers have undertaken the endeavor [1-6]. Processes for cutting edge preparation such as abrasive water jet, magnet-abrasive and laser machining were applied [1, 3, 5]. These methods could provide an increase in the radius of the cutting edge. Some researchers have reported that severely rounded cutting edges can achieve a longer tool life than unprocessed tools because of the suppression of chippings and improvement of peeling resistance of the coating layers. Large cutting edge radii, on the other hand, can cause damage to the material, for example an increase of affected layer depth on the newly formed work material surface due to the size effect [7, 8]. The size effect depends on the ratio between the cutting edge radius and the uncut chip thickness. When the undeformed chip thickness is thinner than a certain amount, the effect would be prominent [7]. In other words, the damage on the workpiece would appear visually as burrs in the case of a finishing turning cut and a milling cut accompanied by continuous change of uncut chip thickness.

In the drilling process, the burrs on the entrance and exit of a hole are a critical problem for manufactures regardless of the variety of materials [9]. In the production of automobiles and aircraft where the reduction of weight and the control of product quality are significant affairs, it has been reported that helical drilling using an endmill can reduce the axial feed force and prevent burr formations on products [10, 11]. Although helical milling could perform high precision cutting without burrs, it requires a long process time due to extended spiral tool trajectory.

Consequently, with regard to burr suppression in cutting operations, we should investigate the possibility of alternative solutions instead of blunted cutting edges and extended tool path. The present research prefers to minimize the cutting edge radius (CER) by the ultra-
precision process using ultraviolet-ray irradiation assisted polishing. This polishing method has been recently developed in our laboratory [13]. We have a distinct objective to reveal the effects of ultra-sharp cutting edges on burr suppression in three kinds of workpieces; aluminum casting alloys for engine cylinder head covers, high tension magnesium alloys [14] and carbon fiber reinforced plastics (CFRP).

2. Ultraviolet-rays irradiation assisted polishing (UV-assisted polishing)

2.1. Principle of UV-assisted polishing method

UV-assisted polishing has been developed to achieve the ultra-precision polishing of next generation power devices for semiconductors such as silicon carbide (SiC) and single crystal diamond [13]. The planarization of diamond and SiC substrates without any damage at the atomic scale can be achieved by UV-assisted polishing. Polycrystalline diamond (PCD), which has been increasingly applied to die materials, could also be polished by this novel polishing technology [15, 16].

Figure 1 shows the removal principle of this method schematically. The photochemical reaction induced by the ultraviolet-ray irradiation would be overlapped by the action of the mechano-chemical removal mechanism. When carbon atoms on the diamond surface are excited by the ultraviolet-ray irradiation, electrons and holes are newly generated. Electrons and holes react immediately with the surrounding oxygen and water molecules in the air, and a hydroxyl radical as well as reactive oxygen species are generated. Despite the fact that these reactive oxygen species have a very short life, they have an intense oxidation effect. They could oxidize the carbon atoms on most of the area of the diamond substrate and finally excrete them as CO$_2$ or CO gas. Hence, the ultraviolet-rays should be irradiated directly onto the polishing zone with elevated temperature induced by high speed and high contact pressure. The quartz disk was applied as the polishing plate because of its high penetration rate for ultraviolet-rays. This mechano-chemical polishing mechanism combined with the photochemical reaction can promote the polishing of diamond substrates.

2.2. Cutting edge sharpening of PCD tool

A PCD cutting edge is difficult to be sharpened into a smaller radius by the conventional polishing technologies due to its high hardness. The UV-assisted polishing has been reported to remove diamond at an atomic level. Using UV-assisted polishing, a PCD endmill cutting edge was sharpened. The margin on the flank face of the endmill was polished to a width of 20 $\mu$m. The cutting edge sharpness is defined in this paper as the radius of the ridge between the rake face and the flank face.

Figure 2 shows the used edge sharpening unit in our laboratory consisted of the air spindle to rotate the quartz polishing plate, pillars, the endmill fixing jig, the driving unit, and ultraviolet-ray generator. The cutting edge radii were estimated using results from laser microscope measurements. The measurements were conducted at the 6 points across the cutting edge. The variation of the polished cutting edge against polishing time is shown in Figure 3. The radii clearly decreased in the early period of polishing, gradually reduced in the middle, and finally obtained a relatively homogeneous sharp cutting edge.
with a radius of 0.5 μm. Despite the heterogeneous cutting edge radii before polishing, the edge was uniformly polished with increased polishing time. Finally, sharp edges were obtained without dispersion of edge radii.

**Figure 3**: Edge sharpening process with respect to cutting edge radius

![Figure 3](image)

**Figure 4**: SEM images of cutting edge: (a) As-received, (b) Sharpened

![Figure 4](image)

Figure 4 shows the scanning electron microscope (SEM) images of as-received and sharpened PCD cutting edge by UV-assisted polishing. There are multiple chippings on the ridge in the as-received image with an approximately size of 10 μm. In the sharpened image, the ridge between the rake face and the flattened margin face is distinctly defined without chippings by polishing the flank face side of the cutting edge.

3. **Effect of sharpened edges on the suppression of burr formation**

3.1. **Aluminum casting alloy**

In the production of automobile engine cylinder head covers made of the aluminum casting alloy JIS ADC12, there are pre-opened holes created by near net shape casting techniques. These holes created by the casting are administered a finishing cut with end-milling tools. PCD substrates have been frequently applied to the cutting tool material because of their low frictional coefficient and good surface roughness, which can prevent the adhesion of work material to the tool. The effects of cutting edge sharpening on the burr suppression in the hole finishing process were examined by using the PCD cutting tool. In the experiment, there were pre-bored holes with a diameter of 9.5 mm instead of pre-opened holes from the casting. A workpiece of ADC12 with a thickness of 5 mm was used. An endmill of 8 mm in diameter moved continuously along the tool path circle with a 1 mm radius. The finished hole diameter was 10 mm. The experimental conditions are shown in Table 1. The cutting parameters were set to cutting speeds of 30–206 m/min and feed speeds of 1000 mm/min. The cutting edge radii were assorted into sharpened 0.5 μm, as-received 1.4 μm and worn 4.8 μm to investigate the effectiveness of the edge sharpening by the UV-assisted polishing. The height of the burrs under the cutting speed of 206 m/min and the feed speed of 1000 mm/min was measured for a maximum of 31.59 μm with the worn cutting tool and for a minimum of 8.06 μm with the sharpened cutting tool, as shown in Figure 5. There is a remarkable difference between the worn cutting edge and the sharpened cutting edge. This result indicates the distinct decrease of surface damage. Figure 6 shows the height of burrs under the experimental conditions in Table 1. This indicates the decrease of burr formation by the sharpened cutting edge among all experimental conditions. The effect of sharpening the cutting edge on burr suppression was confirmed in these experiments.

**Table 1**: Experimental conditions of die cast aluminum alloy cutting

| Tool                  | PCD end mill | Diameter | 8 mm |
|-----------------------|--------------|----------|------|
| Work                  | Aluminum die cast | JIS ADC12 |
| Thickness             | 5 mm         |
| Diameter of prebored hole | 9.5 mm |
| Cutting parameter     | Cutting speed | 30, 80, 120, 206 m/min |
|                       | Feed         | 1000 mm/min |

![Table 1](image)

**Figure 5**: 3D images of burr measured by laser microscope: (a) CER = 4.8 μm, (b) CER=0.5 μm, cutting speed was 206 m/min, feed speed was 1000 mm/min

(a) ![Image](image) (b) ![Image](image)
3.2. High tension magnesium alloy

Like aluminum alloys, magnesium alloys have the useful benefit of having a reduced product weight due to its high strength-to-weight ratio and low specific gravity. Recently, the high tension magnesium alloy, which has a dramatically improved high temperature strength compared with conventional magnesium alloys, was developed [14]. This alloy has a tensile strength above 600MPa, and may be applied to parts under high load. As this innovative magnesium alloy has less data on cutting performance and machinability, the effects of the sharpened PCD cutting edge were examined. The experiment was carried out by means of circular milling under similar conditions to the aluminum alloy as shown in Table 1 except the workpiece thickness (7 mm).

Figure 7 shows the results of measured burr height. Although the burr height was larger than that of the aluminum alloys, the burr height was also reduced by using the sharpened cutting tool under any experimental condition. Hence, the cutting edge radius has an intense effect on the cutting performance for high tension magnesium alloy and the edge radius is an important parameter in the design of cutting tools for this newly developed alloy. By using an as-received tool, on the other hand, the results have an unpredictable tendency unlike using the sharpened tool or the worn tool. Namely the high burr formation appearing under low cutting speed makes the prediction of burr height difficult. A similar phenomenon also appeared on the burr data of the aluminum alloys in Figure 6. This may be caused by the random edge radius due to large-scale chippings on the ridge of the tool as shown in SEM image of Figure 5 (a).

4. Sharp cut of carbon fiber

The validity of a sharp cutting edge to reduce the damage and delamination in carbon fiber reinforced plastic (CFRP) cutting was shown in a previous paper [8]. In this paper, the CFRP trimming experiment was conducted to examine the effect of the sharpened PCD cutting edge. The cutting conditions as shown in Table 2 were selected at a comparative low cutting speed where is difficult to realize the high precision cutting. The cutting forces acting on the workpiece was measured by dynamometer (KISTLER 9257B) during the experiment. Figure 8 shows SEM images of the cut surface of CFRP where carbon fibers are perpendicular to the paper.

Table 2: Experimental conditions of CFRP cutting

| Tool     | PCD end mill | Diameter | 8 mm |
|----------|--------------|----------|------|
| Work     | CFRP         | Cutting edge radius | 0.5, 4.8 μm |
|          |              | Thickness | 7 mm |
| Cutting parameter | Cutting speed | 30 m/min |
|          | Feed         | 1000 mm/min |
|          | Depth of cut | 0.1 mm |

Figure 8: SEM images of cut carbon fiber in CFRP: (a) CER = 4.8 μm, (b) CER = 0.5 μm
Figure 9 : Measured waveform of cutting force for one tooth: (a) CER = 4.8 μm, (b) CER = 0.5 μm

In the image (a) CER = 4.8 μm, the epoxy resin is severely injured and the carbon fibers are submerged into the epoxy resin. Additionally the carbon fibers, which are only slightly seen, are collapsed. On the other hand, in the image (b) CER = 0.5 μm, there is less damage on the matrix resin, and the definite cut surface of carbon fiber could be observed. Moreover the height of the cut fiber surface is nearly the same as the cut resin surface.

Figure 9 shows the cutting forces by one tooth of the endmill over time. The tangential cutting force shows the same value in Figures 9(a) and 9(b), whereas the normal cutting force decreased in Figure 9(b) CER = 0.5 μm compared to Figure 9(a) CER = 4.8 μm. This difference in the normal cutting force, which compresses the work material, led to the difference in the morphology of the carbon fibers, as confirmed in Figure 8. Therefore the sharpened cutting edge by the UV-assisted polishing realized the reduction of the cutting force which collapses the material, as a result, it is revealed that the damage on the cut surface could be decreased by a sharpened tool.

5. Conclusion

This paper revealed that the newly developed polishing technology which is called ultraviolet-ray irradiation assisted polishing (UV-assisted polishing) achieves a sub-micro meter radii of the cutting edge by applying to the method a PCD endmill. In the circular hole finishing cut experiment of the aluminum casting alloy and high tension magnesium alloy, it was shown that the burr formation on the work material could be decreased by using the PCD tool sharpened by UV-assisted polishing. Regarding the CFRP cutting, the reduction of cutting force, which compresses the newly formed surface, was realized.

As explained above, The UV-assisted polishing achieves the smaller radius of cutting edge than the grain size of PCD; this technology enables the designs of cutting edges in sub-micro meter scale.

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References

[1] Biermann D, Terwey I. Cutting edge preparation to improve drilling tools for HPC processes, CIRP Journal of Manufacturing Science and Technology 2008, Vol.1, Issue 2, pp.76-80
[2] Denkenea B, Lucas A, Bassett E. Effects of the cutting edge microgeometry on tool wear and its thermo-mechanical load, CIRP Annals – Manufacturing Technology 2011, Vol.60, pp.73-76
[3] Franke V. Drilling of long fiber reinforced thermoplastics – Influence of the cutting edge on the machining results, CIRP Annals – Manufacturing Technology 2011, Vol.60, pp.65-68
[4] Faraz A, Biermann D, Weinert K. Cutting edge rounding: An innovative tool wear criterion in drilling CFRP composite laminates, International Journal of Machine Tools & Manufacture 2009, Vol.49, pp.1185-1196
[5] Aurich J C, Zimmermann M, Leitz L. Preparation of cutting edges using a marking laser, Production Engineering Research and Development 2011, Vol.5, pp.17-24
[6] Fang N, Wu Q. The effects of chamfered and honed tool edge geometry in machining of three aluminum alloys, International Journal of Machine Tools & Manufacture 2005, Vol.45, pp.1178-1187
[7] Aramcharoen A, Mativaga P T. Size effect and tool geometry in micromilling of tool steel, Precision Engineering 2009, Vol.33, pp.402-407
[8] Kaneeda T. CFRP cutting mechanism (3rd report) –Effects of tool edge roundness and relief angle on cutting phenomena-, Journal of Japan Society for Precision Engineering 1991, Vol.57, pp.93-98
[9] Aurich J C, Dornfeld D, Arrazola P J, Frake V, Leitz L, Min S. Burrs – Analysis, control and removal, CIRP Annals – Manufacturing Technology 2009, Vol.58, pp.519-542
[10] Denkena B, Boehnke D, Dege J H. Helical milling of CFRP – titanium layer compounds, CIRP Journal of Manufacturing Science and Technology 2008, Vol.1, pp.64-69
[11] Brinksmeier E, Fangmann S, Rentsch R. Drilling of composites and resulting surface integrity, CIRP Annals – Manufacturing Technology 2008, Vol.60, pp.57-60
[12] Sakamoto S, Higashinicho K, Matsutori T. High precision drilling of CFRP plates by method of helical cutting, Proceedings of the Japan Society of Mechanical Engineer 2008, Vol.1, 263-264
[13] Watanabe J, Hong S H, Yamaguchi K, Touge M, Kuroda N. Effect of TiO2 and CeO2 particles on SiC semiconductor surfaces polished under ultraviolet-ray irradiation, Journal of The Japan society for Abrasive Technology 2008, 52(8), pp.459-463
[14] Kawamura Y, Hayashi K, Inoue A, Masumoto T. Rapidly solidified powder metallurgy Mg97Zn1Y2 alloys with excellent tensile yield strength above 600 MPa, Materials Transactions 2001, Vol.42, pp.1172-1176
[15] Touge M, Nakano T, Yamaguchi K, Kubota A, Watanabe J. Study on precision finishing of PCD by contact-pressure grinding and UV-polishing , Key Engineering Materials 2009, 355, pp.407-408
[16] Nakano T, Miyoshi A, Touge M, Watanabe J. Ultra-precision machining of PCD by UV-assisted polishing, Journal of The Japan society for Abrasive Technology 2009, 53(4), pp.242-247