Ultrafine ductile-mode dicing technology for SiC substrate with metal film using PCD blade

Takashi FUJITA*, Yasuo IZUMI ** and Junji WATANABE ***

* Tokyo Seimitsu Co., Ltd.

2968-2 Ishikawa-machi Hachioji, Tokyo 192-8515, Japan

E-mail: fujitata@accretech.jp

** Shin-Nihon Tech, Inc.

2-2-81 Hama, Tsurumi ward, Osaka, 538-0035, Japan

*** Kumamoto University, Osaka Office

1-4-1 Aramotokita, Higashiosaka, Osaka, 577-0011, Japan

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Abstract

For cutting a SiC substrate coated with a metal film stably, a novel ductile-mode dicing process was developed using a blade made of a single body of poly-crystalline diamond (PCD) with only 50 μm in thickness. It is difficult for a conventional diamond blade with metal binder to cut the SiC substrate in a straight line accurately due to insufficient buckling strength. In addition, self-sharpening effect of the cutting edge is suppressed by adhesion of metal film to blade surface. In this study, a rake face and a flank face of the cutting edge were formed by irradiating pulsed laser light tangentially to the cutting edge. Under the high speed rotation condition of 30,000 rpm (500 s^{-1}), the developed PCD blade acts on the workpiece with the continuous cutting edge in a stable posture due to the inertial force of the rotation, and the depth of cut per a cutting edge is about 5 nm. Under these conditions, the ultrafine cutting tip of the metal film also becomes on the order of nanometers. 4H-SiC substrate 350 μm in thickness with Au / Ni / Ti film was cut using the developed PCD blade. Under the half cut condition, there was no chipping or crack on the surface, and the bottom of the groove was finished in a mirror state. Under the full cut condition with a width of 50 μm , the SiC substrate and the metal film were cut at once, and any crack did not occur at the interface between SiC and the metal film. As the result, it was demonstrated that ductile mode machining was realized and the metal film did not adhere to the cutting edge.

Keywords : Poly-crystalline diamond, Dicing blade, Cutting edges by laser beam, SiC substrate, Metal film, Ductile-mode machining

1. Introduction

In recent years, SiC substrates have emerged as next generation substrates for high reliability power devices, and are finding increasing use (Senzaki, et al. 2018; Tsuchida, et al. 2018). In particular, as a SiC device with a metal film, a minority carrier type of bipolar device such as an IGBT (Insulated Gate Bipolar Transistor) is mainly used for the purpose of switching resistance reduction accompanying a high breakdown voltage. Other uses are also widely used in various places as high temperature transducer elements or high temperature electronics elements (Goel, 2014). One of the technical barriers preventing their further spread is the difficulty involved in machining them (Huang, et al. 2015). The SiC substrate is very hard and stiff, with high Young's modulus, and is chemically stable (Agawal, et al. 2010; Ding, et al. 2014). Therefore, machining difficulties have been reported in various processes, such as grinding and polishing (Kasuga, et al. 2009; Kido, et al. 2014; Nagae, et al. 2015).

In the case of conventional dicing blades, in which the abrasive grains are hardened with binder, the strength of the blade depends on the rigidity of the binder (Zhang et al. 2011). Since the SiC substrate is extremely strong, significant

Table 1 Mechanical properties

	PCD	4H-SiC (single crystal)	Nickel (binder)
Hardness GPa (Micro Vickers)	100	24	0.64
Young's modulus GPa	1041	448	200
Poisson's ratio	0.07	0.16	0.31
Specific gravity	3.52	3.21	8.9
Thermal conductivity W/mK	2100	140	92

Fig. 1 Indentation test results for PCD, SiC, and electro-plated nickel metal under a 500-mN load

buckling deformation may easily occur when the blade is manufactured with a normal binder.

Since the SiC substrate is also very hard, the binder plastically deforms at the point where the diamond in the blade comes into contact with the workpiece. Therefore, even if there are abrasive diamond grains on the blade edge, since the grains recede into the binder at the moment of contact with the SiC surface, the diamond cutting edges may not cut effectively.

In addition, in many cases, SiC substrate is coated with soft metal as an electrode film. When cutting such coated SiC substrates using a conventional electroforming blade, chips from the metal film adhere to the blade surface and accumulate on the diamond cutting edges of the blade edge. The self-sharpening effect of the blade is thereby further inhibited, and the diamond cutting edges gradually become covered with metal film chips, which may finally render ineffective the cutting of the substrate.

As part of this research, we have already reported machining with a PCD blade as a rigid blade enabling ductile mode processing of SiC substrate (Izumi, et al. 2016). The PCD blade consists of polycrystalline diamond grains sintered under high pressure without binder. It has a diamond content of over 85%, and its strength and hardness are comparable to single crystal diamond. As PCD is extremely hard and rigid compared to SiC substrate, even a thin blade made of PCD material can cut SiC substrate in a straight line with almost no buckling deformation. In addition, the blade edge is configured with equal cutting edge intervals by the grain boundaries. Therefore, it is possible to perform ductile mode processing which in principle does not cause cracks (Fujita, et al., 2017).

In this study, in addition to achieving feasible ductile mode machining to SiC substrate with exploiting the high rigidity of PCD, an extremely fine metal-film chips were yielded by a blade edge with equally spaced cutting edges rotating at high speed, so that metal-film adhesion to the blade surface was suppressed. As a result, stable machining performance was achieved under stable cutting edge conditions. In order to achieve such stable machining performance, equally spaced cutting edges, each with a rake and flank face, were formed on the edge of the PCD blade, using a pulsed laser. The resulting blade enables ductile mode processing without cracks on SiC substrate, making it possible to cut a metal thin film as very fine chips. (Fujita, et al., 2018).

In this way, ductile mode machining of SiC substrate was achieved without crack generation, and it was

demonstrated that no metal film adhered to the surface of the blade during machining.

2. Problems and solution directions regarding machining SiC substrate with metal film

Table 1 shows the mechanical properties of SiC as a substrate, nickel metal as the binder of a conventional blade and PCD. The hardness and Young's modulus of the nickel metal used as a blade binder are much less than those of the SiC substrate. Therefore, it is extremely difficult to cut SiC substrate with a thin blade using nickel metal as a binder, because the nickel binder cannot provide sufficient rigidity.

In contrast, PCD is a diamond aggregate sintered at high pressure with abrasive grain content of over 85%. The hardness and stiffness of PCD are extremely high, comparable to single crystal diamond. It is much harder than SiC, and has high rigidity. Therefore, it is expected that the substrate can be cut in a straight line with almost no buckling deformation, even with a thin blade.

Figure 1 shows the indentation results for PCD, SiC, and electro-plated nickel metal. Fisher scope HM 500 manufactured by Fisher Corp. was used as the nano-indenting device. SiC is a very hard material, with deformation of only 1 μm with 500 mN downforce; whereas the deformation of nickel as a conventional binder is extremely high, at 10 μm with 500 mN downforce. This means that in a conventional nickel electroformed blade, even though the abrasive diamond grains are hard, the nickel that binds the diamond grains is locally highly deformed in absorbing the impact of the diamond abrasives. Therefore, the blade does not make a precision cut in the SiC substrate.

In contrast, PCD has a deformation of only 0.6 μm with 500 mN downforce, which is extremely small compared to SiC. In addition, there is almost no deformation hysteresis. Since almost no plastic deformation occurs, extremely large stress can be applied to the SiC substrate without local deformation of the blade edge. This results in precision cutting.

Furthermore, when the blade edge cuts into the workpiece, there is no plastic deformation in the thickness direction of the blade due to the Poisson's ratio, so that the contact force between the workpiece and the blade is reduced. Therefore, with the PCD blade, high-precision processing of the SiC substrate is possible even with a thin blade. When the cutting edge of the PCD blade cuts into the workpiece, the plastic deformation in the blade thickness direction based on the Poisson's ratio due to the reaction force from the workpiece is also negligibly small. The frictional resistance between the flat side of the blade and the workpiece is greatly reduced. On the other hand, SiC substrate typically has a thin metal film on the surface as an electrode material. When dicing such thin-film SiC substrate, metal film chips adhere to the diamond abrasives, which results in the cutting edges being covered by metal film. In this case, the sharpness of the blade rapidly deteriorates, and it is more difficult to stably cut the SiC substrate for a prolonged period of time. Figure 2 shows a diamond blade with a thick deposit of metal film completely covering the surface. In this state, the self-sharpening effect is hardly functional. In order to promote the self-sharpening effect, soft and fragile binder materials have been employed. However, use of such materials sacrifices the hardness and rigidity of the blade. As a result, it is extremely difficult to precision cut thin-film SiC substrate. To investigate the mechanism of adhesion of the metal film to the blade, copper plate (as a soft metal) was cut with a conventional diamond blade, and the resulting surface state of the copper plate was observed. Figure 3 shows the surface state after cutting a groove in a copper plate using a conventional blade. The formation of very minute needle-like burrs is observed in the raised

Fig. 2 Edge of conventional blade covered with metal film

Fig. 3 A surface state in a copper plate after cutting grooves using a conventional blade with metal binder (Blade thickness, 0.13 mm; abrasive #800)

Fig. 4 Typical initial cut chip of copper film on the blade surface

portion of the groove edge. These burrs are in the sub-micron-order in thickness and micron-order in length. In order to gauge the formation of such needle-like burrs, the state of the blade edge was observed at the initial stage after grooving the plate.

Figure 4 shows chips of copper film adhering to the edge of the blade in the initial stage of grooving the plate. Since the chips are on the order of a few micrometers, their size is consistent with that of the needle-like burrs. It is considered that such chips adhere to and gradually accumulate on the periphery of the blade. In light of this, it is desirable to minimize their number and size.

Figure 5 shows the cutting edge configuration in the conventional blade and in an ideal blade, respectively. In the conventional blade, the abrasive diamond grains that form the cutting edges are sparsely distributed in the binder material. The density distribution of the abrasive grains is more or less varied in the each area of the blade. Therefore, it is inevitable that a long interval part between abrasive grains exists in the blade with a certain probability. The long interval part between abrasive grains sometimes causes a fatal crack in the brittle material and contributes to the formation of needle-like burrs and the formation of large cutting chips in the metal material.

These large chips are somewhat softened by the heat caused by the plastic deformation involved in cutting the groove, and adhere to the blade surface away from the workpiece surface.

Therefore, in order to suppress the adhesion of such chips to the blade surface, it is necessary to generate only ultrafine (nanometer-order) chips on the circumference of the blade, which can then be washed away with water. For that purpose, the controlled cutting edge interval is essential to make fine cutting chips.

It has been shown that PCD blades are optimal for achieving ductile-mode dicing processing of SiC substrates, with respect to the critical cutting depth and the elimination of cracks (Izumi, et al. 2016). Likewise, such blades are optimal for cutting thin-film SiC substrate, with respect to the formation of ultrafine metal chips. Figure 6 shows the principle involved in cutting the workpiece using a blade with cutting edges at regular intervals. Utilizing fine cutting

Fig. 5 Schematic view of distribution of cutting edge intervals

Fig. 6 Principle of ductile-mode machining using equal-interval cutting edges

Fig. 7 Appearance and specifications of the developed PCD blade

edges at small regular intervals means that the cutting depth per cutting edge is less than the critical depth of transition from the plastic deformation range of the workpiece to brittle fracture (Fujita, et al. 2014). This makes it possible to achieve ductile mode processing that does not cause cracks in the workpiece. The depth of cut per cutting edge ‘g’ for ductile mode machining is given by the following equation:

$$g = 2\sigma \frac{v_w}{v_t} \sqrt{\frac{t}{D}} \quad (1)$$

where v_w is the workpiece feeding speed, v_t is the outer circumferential speed of the blade, D is the blade diameter, t is the depth of cut, and σ is cutting edge interval.

With a workpiece feed rate of 10 mm/s at a rotation of 30,000 rpm (500 s^{-1}), the cutting edge interval of $200\mu\text{m}$, the cutting depth per cutting edge is approximately 5.1nm. The critical depth of cut ‘g’ on SiC is reported to be 60 nm (Bhattacharya, et al., 2006) or 70 nm at 6H-SiC (Jacob, et al. 2005). They are generally less than 100 nm. Therefore, using the above cutting edge interval, it is possible to cut SiC substrate in ductile mode without causing fatal cracks. Likewise, with this cutting edge interval, it is possible to produce only ultrafine metal-film chips of nanometer-order in breadth (Pen, et al., 2011), thereby suppressing adhesion of the metal film to the blade.

3. Developed PCD blade cutting edge formation and process evaluation

Figure 7 shows specifications of the developed PCD blade. The PCD blade is made of a single round body of PCD on the base plate of the cemented carbide. The PCD portion was thinned to a thickness of $50 \mu\text{m}$.

Fig. 8 Schematic diagram of manufacturing process of the PCD blade

Fig. 9 Laser-machined cutting edges on the outer circumference of the developed blade

Table 2 Laser irradiation conditions

Laser source	R-200, Raydiance Inc.	Pulse width fs	800
Laser wavelength nm	1552	Max pulse energy μJ	80
Frequency kHz	60	Blade diameter mm	54.85
Output W	10	Cutting edge pitch μm	100

Figure 8 shows a schematic diagram of manufacturing process of the PCD blade. The blade is made of a circular cemented carbide plate with a single PCD layer. The peripheral portion of the cemented carbide is removed by grinding and the central hole is removed by wire electric discharge machining. Then, the PCD of the cutting edge portion is thinned by a special electric discharge machining process, and the final finish is given by ultraviolet light polishing treatment through the quartz glass plate (Touge, et al., 2014).

The process serves to prevent breakage of the cutting edge due to cracks on the PCD blade surface. As a result, it is possible to manufacture a precise, thin and strong blade. In order to improve the blade's performance in machining thin-film SiC substrate, the cutting edges were formed by machining the outer circumference of the blade with a fiber laser (Fig. 9). Table 2 shows laser irradiation conditions. The laser beam was incident perpendicular to the blade edge, and the cutting edges were formed at regular intervals while rotating the blade. Semicircular cutting edges, 30 μm in diameter and 100 μm in pitch, were formed at equal intervals. Given this configuration, even if (to take an example) a blade of 50 mm in diameter is rotated at 30,000 rpm (500 s^{-1}), and a workpiece is fed at 10 mm/s with a blade cutting depth of 500 μm , the maximum cutting depth per cutting edge is approximately 5.1 nm, which is less than 0.01 μm . The depth of cut is small enough to avoid causing cracks in the workpiece, and theoretically ductile mode machining can be achieved to the SiC substrate (Goel et al., 2011). In addition, the coated metal film is cut to be nanometer-order small chips. SPDT (Single-point diamond turning) is an effective method to evaluate the performance of ductile-mode machining (Blackley, et al. 1991; Scattergood, et al. 1990; Patten, et al. 2008). They play an important role in determining the experimental conditions of machining workpiece. Based on the knowledge, it is necessary to make a device configuration that ensures a stable depth of cut without causing minute vibration and intermittent friction such as stick slip in order to carry out an actual efficient machining. Also, a diamond tip as a cutting tool is exposed to the thermal environment machining workpiece for a long period. Since diamond tends to be thermally worn out, it is necessary to make a device configuration that supposes thermal wear.

Figure 10 shows the experimental device, the machining operation and PCD blade appearance. The experimental device was a commercially available dicing device of type AD20T in Tokyo Seimitsu, Co., Ltd. and the developed

Fig.10 Experimental device and machining operation

Fig. 11 Machining results for the blade, with and without laser-processed cutting edges

blade can be also attached to the dicing device. The machine has an air spindle rotation mechanism. The blade is fully aligned and hardly vibrates under 30000rpm (500 s^{-1}) rotation. The runout of the blade was adjusted to be less than $1 \mu\text{m}$. The relative posture of each cutting edge and the workpiece is constantly kept stable by the inertial force of the blade rotating at high speed with respect to the flat chucked workpiece. Since the PCD blade is a disk-shaped blade made of a body of PCD material, the thermal conductivity is extremely high.

Therefore, it tends to be a uniform temperature distribution within the blade surface. While the cutting edge does not contact the workpiece, each cutting edge is immediately cooled. Even if a small amount of heat remains in the blade, since the thermal distribution expands radially, thermal deformation due to shear stress based on the Poisson's ratio does not occur. Therefore, the circumferential part of the PCD blade is on the same plane and the cutting edges are on an accurate straight line in principle even under continuous cutting conditions.

Figure 11 shows the results of machining using the blade with the laser-processed cutting edges. Table 3 shows the

Table 3 Experimental conditions

Apparatus	AD20T dicing system (Tokyo Seimitsu Co., Ltd.)	Blade diameter	50.8 mm
Wafer	4H-SiC 340 μm	Cutting direction	Down cut
Blade rotation	500 s^{-1}	Cooling DIW Cutting DIW	0.3 L / min 0.5 L / min
Cutting depth	Half cut : 250 μm	Blade	PCD material with laser-processed cutting edge Diamond cont. : approx. 90 vol% Thickness: 50 μm
Work feed speed	1 mm / s		

Fig. 12 Change in the face of the blade edge after cutting a roughly 3 m long groove

Fig. 13 Mechanism of wear at the cutting edge

experimental conditions. The ductile-mode machining with the former PCD blade has been performed using the grain boundary as cutting edges. This study confirmed that the developed blade can achieve ductile-mode machining without chipping or cracking even with evenly spaced cutting edges formed by laser beam. However, the presence of numerous cracks around the cut lines was confirmed shortly after this process. To investigate the cause, the blade edge was compared before and after machining.

Figure 12 shows the blade edge before and after machining a roughly 3 m long cut. Observation of the state of the blade edge after machining revealed obvious glazing in the area between the cutting edges due to wear.

Figure 13 shows the mechanism behind edge wear at the cutting edges. The surface between the cutting edges becomes glazed because, though there is a rake surface on the cutting edges, there is insufficient flank face clearance. Therefore, the flank surface is in constant contact with the surface of the workpiece. Given this, once the cutting edge becomes even slightly worn, the cutting chips become lodged on and adhere to the flank face. Thus, the insufficient flank clearance leads to the large negative rake angle at the local point of view of the tip of the cutting edge (Akbari, et al. 2016). The insufficient flank clearance at the foot of the cutting edges renders the cutting process inefficient.

Furthermore, even at the outer circumference of the blade, laser irradiation results in a slightly different hole diameter between the incident and outgoing side. Therefore, the cutting edges are not symmetrical. When the cutting edges are formed by laser irradiation perpendicular to the blade edge, there is no clearance on the flank surface of the cutting edges, and the size of the cutting edges differs between the left and right sides of the blade. Thus, the cutting edge formation is not optimal. Therefore, in order to properly form the rake and flank faces of the cutting edges on the outer circumference of the blade, the laser beam was directed tangentially to the blade surface.

Figure 14 shows the laser irradiation method. Table 4 shows the laser irradiation conditions. As the blade rotates, equally spaced cutting edges are formed on the outer circumference of the blade.

Figure 15 shows pictures of the laser-processed cutting edge formation. Laser processing, to form cutting edges at constant intervals, was performed using periodic pulses as the blade was rotated. The laser irradiation was tangentially incident at 60 degrees from the blade center, so as to form rake and flank faces on the outer circumference of the blade.

Figure 16a shows a side view of the periphery of the blade, with the cutting edges formed by laser irradiation. The

Fig. 14 Laser irradiation method used to form rake and flank faces on the blade cutting edges

Fig. 15 Laser-processed cutting edge formation method

Table 4 Laser irradiation conditions

Laser wavelength nm	660-670	Incident angle deg	60
Blade diameter mm	54.85	Pulse width μs	300
Blade rotation s^{-1}	0.058	Shot number	1892
Frequency kHz	30	Focus point mm	+1
Output W	6		

rake and flank surfaces are formed at the edge of the blade.

Figure 16b is a magnified top view of part of the blade edge. It was confirmed that sharp edges were formed up to the tips of the cutting edges on the periphery of the blade. The tool nose radius is one of important factors that greatly influence the ductile to brittle transition (Goel, et al. 2013).

In the PCD blade, the protruding concavo-convex configuration formed by the laser acts as a cutting edge. Therefore, regular cutting edge intervals can be formed based on the periodicity of the laser pulse, and this helps to achieve ductile mode machining. The blade, with its regular cutting edge intervals, is essentially different from conventional blades that self-sharpen through binder wear. Periodic cutting edge formation by laser processing makes it possible to perform sustainable ductile mode machining.

Fig. 16 Side view and top view of part of the laser-processed blade edge

Fig. 17 The state of top surface and bottom surface after half-cutting the SiC wafer

Fig. 18 Surface views of the cut substrate

4. Evaluation of thin-film SiC substrate cutting

First, in order to confirm the ductile-mode machining performance, the SiC substrate was half-cut to evaluate the groove condition.

Figure 17 shows the state of the surface and the groove bottom of the post half-cut SiC substrate by the PCD blade, as compared with the machining result by the conventional electroformed metal blade. As the conventional blade, the blade hardened with nickel binder of 110 μm in thickness was used. Table 4 shows the experimental conditions. In the conventional blade, the surface has chipping and the groove bottom is rough. Black spots indicate cracks inside the substrate. This is partly because the abrasives dropped from the nickel binder caused chipping of SiC substrate. In addition, this is also because the excessive abrasive protrusion before abrasive's drop promoted fatal crack generation inside SiC substrate as the nickel binder receded due to wear.

On the other hand, the PCD blade is in a mirror state without chipping or cracking. In the PCD blade, it can be seen that it is mirror-finished with no cracks and is ductile-mode machining. This is partly because each cutting edge supported by rigid PCD fulfills effective cutting function without abrasives dropped from the blade. Moreover, this is also because each cutting edge keeps regular interval and cut SiC substrate and metal film by extremely small depth of cut under high rotation speed. In addition, even in the erosion evaluation using a high concentration KOH solution, it was confirmed that there was no crack in the machined surface because there was no excessive erosion (Izumi, et al. 2016). Next, SiC substrate with a metal film on its back surface was used for cutting evaluation. The metal film

Table 5 Experimental conditions

Apparatus	AD20T dicing system (Tokyo Seimitsu Co., Ltd.)	Cutting depth	Half cut : 250 μm (Fig. 17) Full cut : 420 μm (Fig. 18, 19)
Wafer	4H-SiC: 380 μm /Ti: 0.2 μm , Ni: 0.5 μm , Au: 0.2 μm	Cooling DIW Cutting DIW	0.3 L / min 0.5 L / min
Cutting direction	Down cut	Blade rotation	500 s^{-1}
Work feed speed	3 mm / s	Blade diameter	55 mm
Blade1	(1)PCD material with laser cutting edge	Blade2 (Fig.17)	(2)Diamond blade with nickel binder
Developed type	Diamond content :90 vol % Thickness 50 μm	Conventional type	Abrasive content. 20% Thickness 110 μm

Fig. 19 Cross-sectional views of the cut substrate

contained a gold film which is one of soft metal. The gold of the metal film is likely to adhere to the blade surface, making continuous processing difficult.

Figure 18 shows the surface views of the cut substrate with metal film using the developed blade. Table 5 shows the experimental conditions again. There is no burring or chipping, even at the intersection of the grooves. Also, even in the magnified view, the SiC substrate has been cut without chipping or cracks.

Figure 19 shows cross-sectional views of the cut substrate. Even a SiC substrate 370 μm thick can be machined with one cut, and the metal film is cut without burring. Furthermore, there is no chipping of the SiC at the intersection with the metal film. PCD has extremely high hardness and stiffness, comparable to those of single crystal diamond. Therefore, even if the blade is thin, it can be machined in a straight line with almost no buckling deformation. In addition, it is possible to cut cleanly to the boundary between the SiC and the metal film without generating burrs on the metal film.

Figure 20 shows a magnified view of the blade edge before and after use. No metal film adheres to the cutting edges of the blade after machining. Thus, no metal-film deposit formed on the cutting edges during machining. Moreover, the chips were too small to be collected. With conventional blades, the long cutting edge intervals that inevitably exist yield large chips of the submicron order, which here accumulated on the blade edge and finally covered the surface. However, it was confirmed that when the cutting edge interval was properly specified, to the size of ultrafine cutting chips, metal film did not accumulate on the blade surface.

It was confirmed that the developed PCD blade has high rigidity with respect to SiC substrate with metal film, thus enabling ductile mode machining to be linearly performed. In addition, it was confirmed that machining performance is stable, without the deposition of metal film on the blade cutting edges.

If cutting edge formation by laser irradiation were similarly applied to a conventional blade with abrasive grains hardened with a binder, it would not create the same equally spaced cutting edges. This is because when a binder is melted with a laser, sharp cutting edges do not immediately appear on a conventional blade. The cutting edge spacing depends on the distribution of diamond abrasives inside the binder, irrespective of the laser pulse parameters.

Also, with excessive laser irradiation, not only the metal of the binder but also the diamond abrasive grains are melted by the heat of the laser. Therefore, it is impossible to form evenly spaced cutting edges simply through laser irradiation.

Using the novel method here described, the portion where the diamond wears is removed by laser irradiation, and the

Fig. 20 State of the blade edge after making 3-m long cut in SiC substrate with metal film (top view)

protruding concavo-convex cutting edge configuration immediately acts as a blade edge.

Therefore, the basic cutting edge interval does not change, and the periphery of the blade acts as a cutting edge with regular intervals. As a result, ductile-mode machining can be stably performed.

In this way, it was demonstrated that laser-processed cutting edge formation on a PCD blade makes it possible to achieve sustainable ductile mode machining of SiC substrate with metal film.

5. Conclusion

(1) Dicing blades for SiC substrate with metal film are required to perform ductile-mode machining without causing buckling deformation even with a thin blade thickness of 50 μm . It is difficult for conventional blades to cut the SiC substrate in a straight line with almost no buckling deformation with blade thickness of 50 μm , and cutting performance deterioration due to adhesion of a metal film to the blade has also been a major problem. In this research, we newly developed and manufactured a new dicing blade made of a single body of PCD of 50 μm in thickness for dicing process of SiC substrate with metal film.

(2) By rotating the developed PCD blade at high speed, the continuous cutting edges due to its inertial force act in a stable posture to the workpiece and serve ductile-mode machining without causing cracks. Laser beam was irradiated to the tangential direction of the PCD blade edge, and the rake face and the flank face were formed equally as the cutting edges. Under the high speed rotation of 30000 rpm (500 s^{-1}), the depth of cut per one cutting edge is around 5 nm, which condition contributes to ductile-mode machining for SiC substrate. Under these conditions, the ultrafine cutting tip of the metal film also became nanometer order, and the adhesion of the metal film to the blade was suppressed.

(3) 4H - SiC substrate of 350 μm in thickness with Au / Ni / Ti film was cut using the PCD blade with cutting edges formed by laser irradiation. It was confirmed that the chipping and cracks were not present on the surface and the groove bottom also was in the mirror state under the half-cut condition. In addition, the SiC substrate and the metal film were cut at once and there was no crack at the interface between the SiC and the metal film under the full cut condition with the line width of 50 μm . In addition, though it was impossible to collect the ultrafine cut chips after machining, it was confirmed that there was no adhesion or deposition of metal film on the edge of the blade.

References

- Agawal, S., Rao, P.V., Grinding characteristics, material removal and damage formation mechanisms in high removal rate grinding of silicon carbide, *International Journal of Machine Tool and Manufacture* Vol. 50 (2010) pp.1077-1087
- Akbari, M., Buhl, S., Leinenbach, C. and Wegener, K., A new value for Johnson Cook damage limit criterion in machining with large negative rake angle for understanding of grinding, *Journal of Material Processing Technology*, Vol. 234 (2016) pp.58-71
- Bhattacharya, B., Patten, J. A. and Jacob, J., Single Point Diamond Turning of CVD Coated Silicon Carbide, *Proceedings of ASME 2006 International Conference on Manufacturing Science and Engineering, Part A and B* (ASME 2006) pp.1153-1158
- Blackley, W. S. and Scattergood, R. O., Ductile-regime machining model for diamond turning of brittle materials, *Precision Engineering* Vol. 13 (1991) pp.95-103
- Ding, K., Fu, Y., Su, H., Gong, X. and Wu, K., Wear of diamond grinding wheel in ultrasonic vibration-assisted grinding of silicon carbide, *International Journal of Advanced Manufacturing Technology*, Vol. 71 (2014) pp.1929-1938
- Fujita, T., Izumi, Y., and Watanabe, J., Dicing blade, Pat. US. 9,701,043 (2017)
- Fujita, T., Izumi, Y., and Watanabe, J., Dicing blade, Pat. JP. 6,282,613 (2018)
- Fujita, T., Izumi, Y., and Watanabe, J., Development on ultra-precision dicing technology by PCD blade, *Proceedings of Japan Society of Precision Engineering* (2014 Autumn) 999-1000 (in Japanese)
- Goel, S., Luo, X., Reuben R. L. and Rashid, W. B., Atomistic Aspects of Ductile Responses of Cubic Carbide during Nano-metric cutting, *Nanoscale Research Letters* (2011) Letter 6, pp.1-9.
- Goel, S., Luo, X., Comley, P., Reuben, R. L. and Cox, A., Brittle- Ductile transition during diamond turning of single crystal silicon carbide, *International journal of Machine Tools & Manufacture* Vol. 65 (2013) pp.15-21
- Goel, S., The current understanding on the diamond machining of silicon carbide, *Journal of Physics D, Applied Physics*, Vol. 47 (2014) 243001
- Huang, H., Zhang, Y. and Xu, X., Experimental investigation on the machining characteristics of single crystal SiC sawing with the fixed diamond wire, *International Journal of Advanced Manufacturing Technology*, Vol. 81 (2015) pp.955-965.
- Izumi, Y., Fujita, T., Minami, H., Watanabe, J. and Touge, M., Development on PCD Dicing Blade for SiC Semiconductor Substrate (in Japanese), *Journal of the Japan Society for Abrasive Technology*, Vol.60, No.11, (2016) pp597- 602
- Jacob, J., Patten, J. A., Bhattacharya, B., Couey, J. A. and Marsh, E. R., Determination of the Ductile to Brittle Transition and Critical Depth of Cut in 6H- Silicon Carbide through fly cutting, *ASPE* (2005) pp.1748-1751.
- Kasuga, H., Mishima, T., Ohmori, H., Lin, W., Watanabe, Y. and Doi, T., Efficient and smooth grinding characteristics of monocrystalline 4H-SiC wafer, *J. Vac. Sci. Technol. B*, Vol. 27, No. 3 (2009) pp. 1578-1582
- Kido, T., Nagaya, M., Kawata, K. and Kato, T., A novel grinding technique for 4H-SiC single-crystal wafers using tribo-catalytic abrasives, *Material Science Forum*, Vol. 778/780 (2014) pp. 754-758
- Nagae, S., Kubota A. and Touge, M., Development of the local polishing technique for single-crystal SiC wafer, *Key Engineering Materials*, Vol. 656-657, (2015) pp. 204-207
- Patten, J. A. and Jacob, J., Comparison between numerical simulations and experiments for single-point diamond turning of single-crystal silicon carbide, *Journal of manufacturing processes*, Vol. 10 (2008) pp.28-33.
- Pen, H. M., Liang, Y. C., Luo, X. C., Bai, Q. S., Goel, S. and Ritchie, J. M., Multiscale Simulation of Nanometric Cutting of Single Crystal Copper and its Experimental Validation, *Computational Materials Science* Vol. 50 (2011) pp.3431-3441
- Scattergood, R. O. and Blake, P. N., Ductile-regime machining of germanium and silicon, *Journal of American Ceramic Society*, Vol. 73 (1990) pp.949-957
- Senzaki, J., Hayashi, S., Yonezawa, Y., and Okumura, H., Challenges to realize highly reliable SiC power devices: From the current status and issues of SiC wafers, *IEEE Conference Proceedings*, (2018) p. 3B 3-1
- Touge, M., Nagano, T., Tagawa, T., Sakamoto, T., Yokoi, Y., Iwamoto, T. and Watanabe, J., Study on Polishing

Mechanism of Single Crystal Substrate by UV-Excitation, Journal of the Japan Society for Precision Engineering, Vol.80, No.1, (2014) pp.112-116. (in Japanese)

Tsuchida, H., Kamata, I., Miyazawa, T., Ito, M., Zhang, X. and Nagano, M., Recent advances in 4H-SiC epitaxy for high-voltage power devices, Materials Science in Semiconductor Processing, Vol. 78, (2018) pp. 2-12

Zhang, B., Ding, W.F., Xu, J. H., Pan, Q. and Shi, Y. J., Self -sharpening abrasive composite bulks with pcbn grains, Key Engineering Materials, Vol. 487 (2011) pp.220-224