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Analytical Model for the Assessment of Vertical Elliptic Vibration Assisted Grinding of Brittle Material

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Keywords： Elliptic vibration-assisted grinding, Material removal mechanism, Equivalent shear plane, Brittle material, Stress condition.

ABSTRACT

In the past, researches mainly focused on the feasibility of the vibration assisted grinding in machining some brittle materials and the mechanism study is still absent. In this paper, an analytical model is presented to interpret the material removal mechanism of vibration assisted grinding brittle material. The model investigates the cutting kinematics of single grinding grain and the stress condition alone the equivalent shear plane within the chip formation zone. The theoretical analysis combined with the experimental result show that the proposed analytical model can be used to explain the material removal mechanism of vibration assistance grinding of brittle material.

INTRODUCTION

Commercial Vibration-assisted machining (VAM) has been researched widely during the past decades and was thought to be a potential high-efficiency and high-quality technique in machining brittle materials (Moriwaki, 1995; Shamoto, 1999, 2005; Negishi, 2003; Suzuki, 2004; Brehl, 2006, 2008). It is characterized by some distinct advantages, such as tool life extension, surface integrity improvement, machining force reduction and burr suppression.

Two dimensional (2D) vibrations were also introduced into the grinding process (Mult, 1996; Suzuki, 2000; Denkena, 2003; Yan, 2009; Ding, 2011). It was found that the 2D vertical vibration-assisted grinding (vertical VAG) can achieve much larger material removal rate than the 2D in-plane VAG. Suzuki proposed a 2D VAG technique utilizing 2D ultrasonic vibration grinding wheel, of which one vibration is vertical to the work-surface, and the other is parallel to the grinding speed direction. It was found that material removal rate increased and normal grinding force decreased but surface roughness has few change (Suzuki, 2000). Ding performed similar 2D vertical VAG experiment of nano-Zro2 and found the surface quality was superior to that of conventional grinding (Ding, 2011). Wu proposed a different elliptic VAG technique (Wu, 2005; Nomura, 2005), of which the workpiece vibrates both vertical to the work-surface and parallel to the grinding wheel axis simultaneously. This vertical EVAG could achieve the high efficiency machining of brittle materials, such as sapphire (Liang, 2009) and monocrystal silicon (Liang, 2009). The vertical elliptical ultrasonic vibration-assisted grinding of polysilicon even showed that the grinding force and surface roughness were reduced by 30% and 20% respectively when compared to those in conventional grinding (Peng, 2011). Wu (2010) and Liang (2012) also found that the diamond wear was decreased with the assistance of 2D vibration. Peng (2012) conducted the 2D vertical VAG experiment of polysilicon and examined the chip integrity. The result revealed that vibration assistance can be beneficial to the ductile removal of the chip.

Till now, most of the previous research works about vertical VAG technology were mainly limited to the feasibility in machining of some brittle materials. However, the related machining mechanism investigation is still absent. In this paper, an analytical model was presented to assess the vertical elliptic VAG technique which aimed to reveal the removal mechanism of brittle materials. Firstly,

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an analytical model of vertical EVAG was developed. Secondly the equivalent shear plane of individual single grain was established. Thirdly, the stress condition was investigated. Finally, the material removal mechanism of vertical EVAG in grinding of brittle materials was studied combined with the experimental results.

DEVELOPMENT OF ANALYTICAL MODEL

Modeling of grinding process

The vertical elliptical vibration-assisted grinding is schematically illustrated in Figure 1. The grinding wheel is fixed and rotates with an angle frequency. The workpiece is fed with a feed rate respectively. The vertical elliptic vibration with frequency is applied on the workpiece. Therefore the grains' position relative to the workpiece can be obtained with following equation

$$\begin{cases} y = y_0 - ft + (R+g_0)\sin(\varphi_0 - \omega_1 t) \\ +A\cos\theta\cos(\omega_2 t) - B\sin\theta\sin(\omega_2 t) \\ z = R - d - (R+g_0)\cos(\varphi_0 - \omega_1 t) \\ +A\sin\theta\cos(\omega_2 t) + B\cos\theta\sin(\omega_2 t) \end{cases}, \tag{1}$$

where y_0 is the original distance between two coordinates o and o', g_0 is the height of single grain compared to the equivalent diameter R of grinding wheel surface, φ_0 is the initial included angle of single grain, A and B are semi-axis length respectively, θ is the elliptic vibration angle.

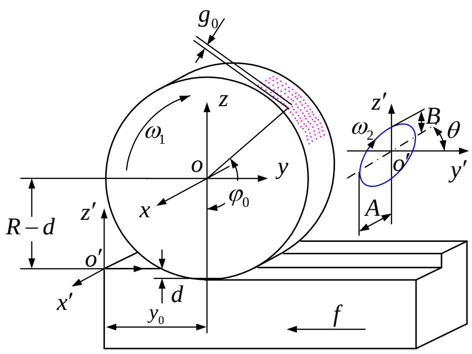


Fig. 1. Schematic view of the surface grinding process with vibration assistance

The material removal in grinding is realized by the consecutive cutting action of single grits on the grinding wheel. Hence, a consistent physical modeling of the grinding process must begin from the basic physics of the process given by the interaction of individual grinding grains with the workpiece (Hecker, 2007). Then, it must be expanded to the behavior of the whole grinding wheel. The single grit-workpiece interaction can be characterized by the undeformed chip thickness and the amount of plowing produced, which has a direct influence on the modeling of process variables such as grinding force and stress condition.

In order to explore the cutting action of single grits, it is important that the grit is properly modeled in a simplified way. As shown in Figure 2, the grit is approximated as a tip with round spherical top. The equivalent spherical diameter d_g of the diamond grain is given as (Hwang, 1999)

$$d_g = 15.2M^{-1}, \tag{2}$$

where M is the mesh size used in the grading sieve.

During the grinding procedure, some of the grits are not engaged in the cutting action. Using a simple geometric spherical relationship, the number of active grits per unit area derived is as follows (Gopal, 2004)

$$C = \frac{4\zeta}{d_g^2 (4\pi/3\xi)^{2/3}}, \tag{3}$$

where ξ is the volume fraction of diamond in the grinding wheel and ζ is the fraction of diamond particles that actively cut in grinding. To obtain an estimated C, it is usually assumed that only one half of the diamond particles on the wheel surface are actively engaged in cutting (Hwang, 1999), or $\zeta = 0.5$.

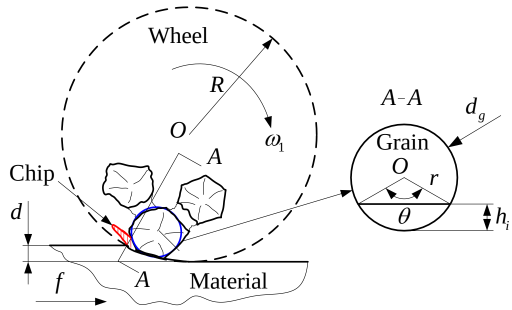


Fig. 2. Schematic of grain engaged in cutting action

Modeling of grinding process

The rake angel of individual grinding grains is generally in a big negative value, which is thought to benefit the ductile material removal during grinding process (Syoji, 2007). Hence, it is important to examine the effect of elliptic vibration on the instantaneous rake angle of grits. In precision grinding machining, the undeformed chip thickness is generally less than the cutting edge radius of the activately grits and hence a negative rake angle prevails in the machining which is highly negative compared with nominal rake angle. As shown in

Figure 3, the instantaneous undeformed chip thickness h_i is assumed to be less than the value of $r(1-\sin\gamma_i)$, which is always that condition in grinding, then the instantaneous rake angle of grinding grain in vertical EVAG can be written as

$$\gamma_i = -\frac{\pi}{2} + \cos^{-1}\left(\frac{r-h_i}{r}\right). \tag{4}$$

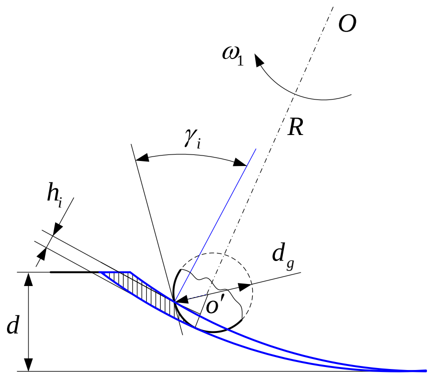


Fig. 3. Instantaneous rake angle of single grain

It is generally known that the diamond wheel radius is far greater than the chip thickness. Then the actual chip thickness can be approximated as

$$h_i = r\left[1-\sin\left(\gamma_i\right)\right]. \tag{5}$$

During grinding, the nominal undeformed chip thickness of individual grit varies repeatedly from zero to maximum and then to zero, which results in the corresponding variation of the instantaneous rake angle. Therefore, the analysis of the stress condition and material removal model are very complicated and a reduced model should be presented to simplify the analysis procedure. It is generally thought that there is a definite shear plane in chip formation zone, on which the cutting forces acting along and normal to the shear plane play an important role in the material removal.

In this paper, the average equivalent undeformed chip thickness is taken to simply analyze the whole undeformed chip thickness of individual grit. The instantaneous effective rake angle also changes with the undeformed chip thickness during the grinding process. Then, an equivalent shear angle can be determined based on average effective rake angle. The average effective rake angle is defined as the angle made with vertical by a line that connects intersection of the unmachined surface on rake face or cutting edge and last point of tool, workpiece contact before machined surface is cleared by the tool. As shown in Figure 4, the average effective rake angle of single grit may be defined as

$$\gamma_e = -\frac{\pi}{2} + \cos^{-1}\left(\frac{r-\bar{h}}{r}\right), \tag{6}$$

where $\bar{h}$ is the average of undeformed chip thickness.

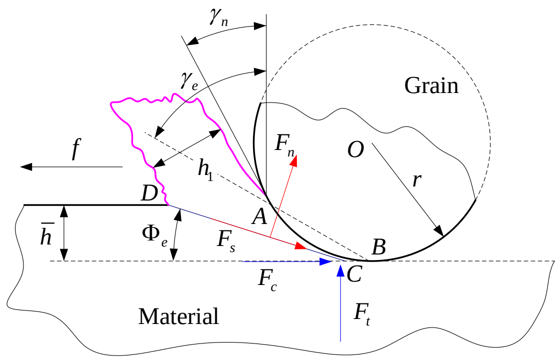


Fig. 4. Mechanics of ductile-mode machining

The corresponding equivalent shear angle is given by

$$\Phi_e = \tan^{-1}\left(\frac{r_c\cos\gamma_e}{1+r_c\sin\gamma_e}\right), \tag{7}$$

where r_c is the chip ratio of single grain removing the material and is defined as the rate of average effective undeformed chip thickness $\bar{h}$ to the chip thickness h_1.

Modeling of grinding process

The undeformed chip thickness of a single grain starts from zero and approaches towards the maximum value during grinding process as the grain-workpiece contact further increases. It is ductile mode machining at the beginning of individual grit grinding for very small range of undeformed chip thickness because the cutting forces within this range are not sufficiently high to cause brittle fracture. In order to examine the material removal type, the grinding force on individual grit applied by the workpiece and chip should be modeled firstly.

In analysis of milling force, Zhou and Wang (1983) showed that the tangential cutting force is equal to the area of the chip-section multiplied by specific tangential cutting pressure constant, and the radial force is equal to the tangential force multiplied by a cutting force ratio. Similarly, the tangential force in grinding can be proportional to the total uncut chip area (Tlusty, 1975). Hence,

$$F_c = K_s S_T, \tag{8}$$

where K_s is a constant of proportionality called specific cutting pressure. Traditionally, the calibration of the cutting force model is performed by running tests at different combinations of cutting conditions. $S_T = N\Delta S$ is the total chip-section area, which equals the grits number N actively engaged in cutting action multiplied with the contact area ΔS of single grit intersected with the material the material during grinding process, which can be formulated according to Fig. 2 as

$$N = Cbt_0, \tag{9}$$

$$\Delta S = \frac{\theta_i r^2}{2} - \sqrt{r^2 - (r - h_i)^2}\,(r - h_i), \tag{10}$$

where b is the width of the grinding wheel, t_0 is the actual nominal cut depth of wheel, h_i is the instantaneous cut depth of single grain, and $\theta_i = \cos^{-1}\frac{r - h_i}{r}$ is the included angle shown in Fig. 2.

Then the thrust force can be written as proportional to the cutting force (Zhou, 1983)

$$F_t = K_r F_c, \tag{11}$$

where K_r is force ratio determined empirically.

Modeling of the stress in chip formation zone

From theory of cutting mechanics, the force normal and parallel to shear plane can be written as

$$F_n = F_t \cos\Phi_e + F_c \sin\Phi_e, \tag{12}$$

$$F_s = F_t \sin\Phi_e - F_c \cos\Phi_e, \tag{13}$$

where F_n is the cutting force acting normally on shear plane, S_s is cross-section area of shear plane equal to width of the cut times the length of shear plan.

Then the stress normal and parallel to equivalent shear plan can be written as

$$\sigma_n = \frac{F_n}{Cbt_0}\frac{\sin\Phi_e}{\bar{h}}, \tag{14}$$

$$\tau_s = \frac{F_s}{Cbt_0}\frac{\sin\Phi_e}{\bar{h}}, \tag{15}$$

$$\frac{\sigma_n}{\tau_s} = \frac{F_c \sin\Phi_e + F_t \cos\Phi_e}{F_c \cos\Phi_e - F_t \sin\Phi_e} = \frac{1 + {F_c}/{F_t}\tan\Phi_e}{{F_c}/{F_t} - \tan\Phi_e}. \tag{16}$$

Evaluation of the material removal model

Then potential material removal model is discussed according to the flow chart shown in Figure 5. The processing parameters of grinding are firstly analyzed and the equivalent shear plane is modeled. Then the average stress condition along the shear plane is calculated and investigated, based on which the potential material removal model can be discussed. Furthermore, the energy/specific cutting force requirements of the material removal can be obtained and the size effect of machining is explored.

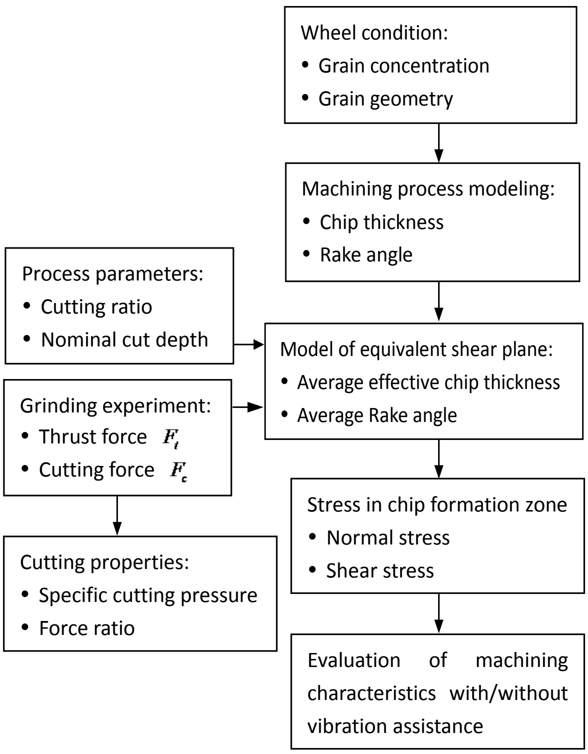


Fig. 5. Procedure for the assessment of machining characteristics

EXPERIMENTAL VERIFICATION AND DISCUSSION

Then potential material removal model is discussed according to the flow chart shown in Fig. 5. The processing parameters of grinding are firstly analyzed and the equivalent shear plane is modeled. Then the average stress condition along the shear plane is calculated and investigated, based on which the potential material removal model can be discussed. Furthermore, the energy/specific cutting force requirements of the material removal can be obtained and the size effect of machining is explored.

Stress analysis along equivalent shear plane

The type of the used resin bonded surface diamond wheel is SDC400N75BG: 180D-3X-15T-31.75H, which has a concentration/ volume fraction $\xi = 0.25$. All the grinding experiments have been conducted under the dry condition. Based on the experimental results of grinding forces (Peng, 2011), the stress condition along the equivalent shear plane with/without vibration was calculated and shown in Figures 6-8.

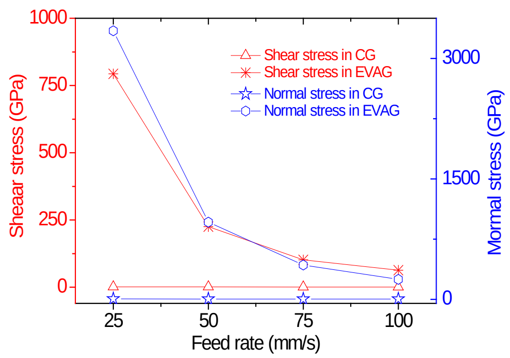


Fig. 6. Stress along the average shear plane

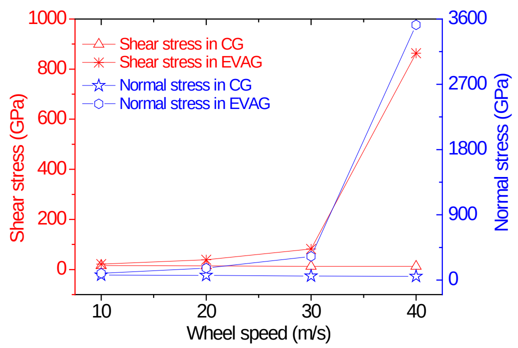


Fig. 7. Stress along the average shear plane

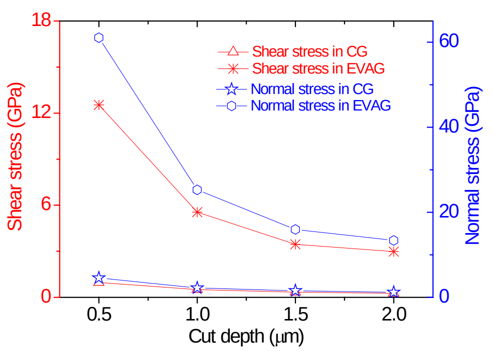


Fig. 8. Stress along the average shear plane

Examining the curves shown above, it can be found that the common feature is that the normal/shear stress along the equivalent shear plane with vibration are both generally larger than those without vibration, which are totally contrary to the trend of grinding forces. This result means that the vibration assistance can help generate much larger normal/shear stress in chip formation zone than these in conventional grinding cases though it may result in much less grinding forces. Furthermore, both normal/shear stress along the average shear plane decreases with the increase of feed rate and cut depth, while it increases with wheel speed.

The calculated specific cutting pressure and force ratio are shown in Figures 9-11. It is shown that specific cutting pressure and force ratio with vibration assistance are almost both much larger than these in conventional grinding. This means that it needs much more energy to remove the unit volume brittle material because of the modulation of vibration assistance.

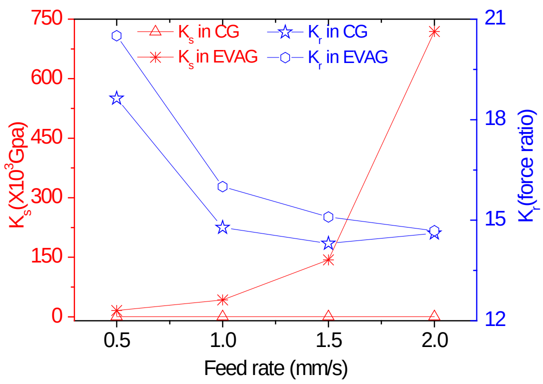


Fig. 9. Specific cutting pressure vs feed rate

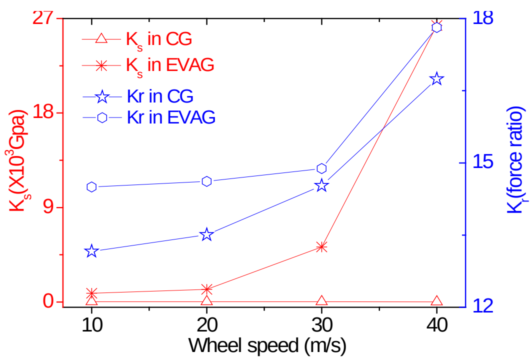


Fig. 10. Specific cutting pressure vs wheel speed

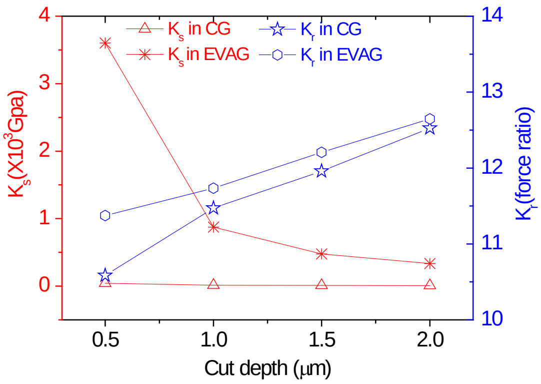


Fig. 11. Specific cutting pressure vs cut depth

The calculated nominal chip thickness and stress ratio are shown in Figures 12-14. With the assistance of vibration, the nominal chip thickness of individual grain can be greatly decreased when compared to that of conventional grinding. However, the calculated stress ratios along the shear plane with the assistance of vibration are mainly less than these without vibration.

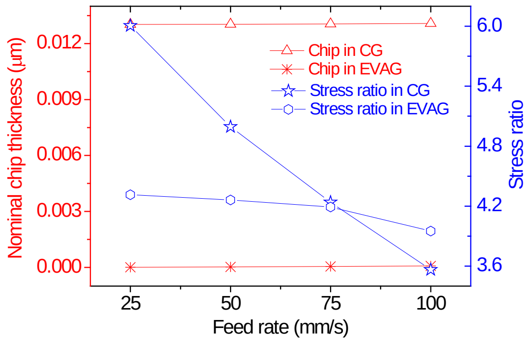


Fig. 12. Nominal chip thickness vs stress ratio

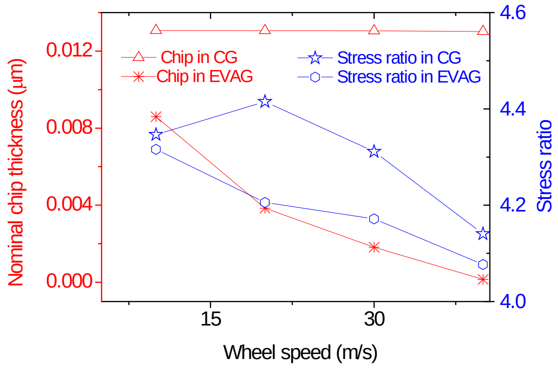


Fig. 13. Nominal chip thickness vs stress ratio

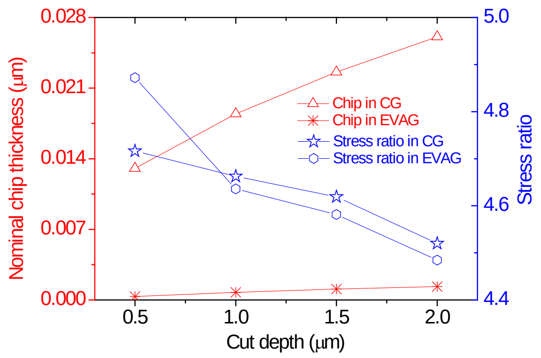


Fig. 14. Nominal chip thickness vs stress ratio

Discussion about the stress analysis result

From the curves shown above, the main features are that the cutting specific pressure and force ratio with vibration are all larger than those without vibration because of the modulation of the vibration assistance. The same trends are also visible in the variation of normal and shear stress along the equivalent shear plane. The reason may be the size effect of the material removal process, of which the vibration assistance helps largely decrease the nominal chip thickness of individual grains as shown in Figs. 12-14 and the cutting specific pressure and force ratio with vibration are large with vibration assistance. From the energy view, the size effect will result in the increasing of the specific energy to remove the tiny amount of materials in the chip formation zone, while the total removal force increases because of the miniature volume of material to be removed. Then the brittle material will become energetically favorable to be removed plastically rather than to fail by crack propagation and ultimately fracture as the scale of deformation decreases based on the theory of Blake and Scattergood (1990).

The decrease of nominal chip thickness may also make the actual cut depth of individual grain become less than the critical chip thickness, which may help the material to be removed in ductile model according to the research by Bifano (1991). The critical chip thickness is shown in Figure 15 and is formulated as

$$d_c = b\left[\frac{K_c}{H}\right]^2\left[\frac{E}{H}\right], \tag{17}$$

where K_c is the fracture toughness, H is the hardness, E is the elastic modulus, and b is a constant which depends on the grain geometry.

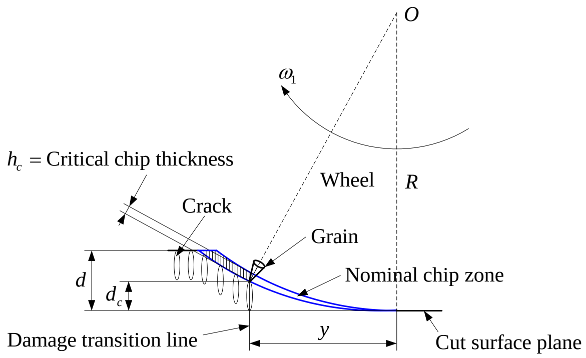


Fig. 15. Illustration of nominal chip thickness

Moreover, both the nominal chip thickness and the processing characteristics are beneficial for the brittle material removal. As has been known, the cracks presenting in brittle material are sources of stress concentration and hence would assume critical importance since the cracks propagate under the influence of stress ultimately cause the material to fail by fracture. The stress intensify factor K_I and its relation to the fracture toughness K_c are very important when considering the fracture of brittle materials (Venkatachalam, 2007). The stress intensify factor around the crack sharp vicinity of a plate with cracks of length $2a$ subjected to a tensile stress σ at the boundary is (Liu, 2007)

$$K_I = \Upsilon\sigma\sqrt{\pi a}\left[1+\frac{\pi^2 a^2}{3W^2}+\frac{2\pi^4 a^4}{15W^4}\right]^{\frac{1}{2}}\sin^2\omega, \tag{18}$$

where Υ is the geometric factor, $f\left(\frac{a}{W}\right)$ is a function of the crack size and distribution, W is width of the finite plate with an internal crack. It can be seen that stress intensify factor can be decreased with the vibration assistance. Therefore, the stress condition around the grain tip zone is in a much bigger compressive value rather tensile because of the calculated negative rankle angle of cutting grains. Hence, it can be further ensured that the stress intensify factor should be much less than the fracture toughness (K_c). On the other hand, the shear stress along the equivalent shear plane is greatly enhanced under the modulation of vibration assistance, which may result that the resolved shear stress (τ_c) is greater than a critical value (a material property τ_{slip}). Once the above conditions are met, which are

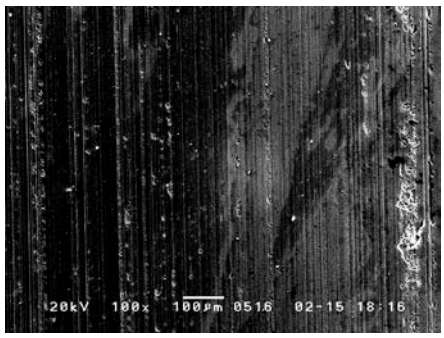
$$\begin{cases} K_I = K_c \\ \tau_{slip} = \tau_c \end{cases}, \tag{19}$$

the situation is conducive for plastic deformation to take place in the localized region of the grain-workpiece interface (Liu, 2007). Furthermore, the big normal stress on the shear plane with vibration can firmly ensure the shielding of crack propagation along the tool-workpiece interface.

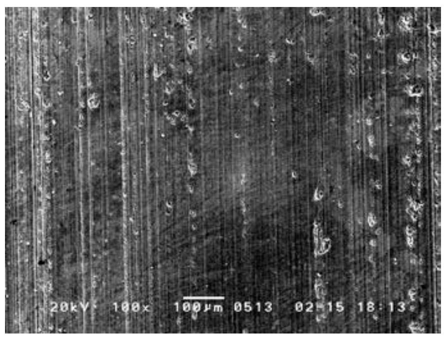
The analysis results also show that the variation trend of force ratio is basically contrary to that of stress ratio along the equivalent shear plane with/without vibration assistance. The reason may be that the modulation of vibration helps to decrease the grinding force and force ratio, which means that the interfacial friction between the grains and the workpiece can be weakened. This in turn can decrease the wear of grinding grains, which has been shown in the works by Liang (2012). As far as the decreasing of stress ratio along the equivalent shear plane with vibration is concerned, it can be explained that the increasing amplitude of the shear stress with vibration is greater than that of conventional grinding, which means the brittle material can be easier to be both plowed/chipped because of the tiny chip thickness as has been shown in (Peng, 2012). The features mentioned above with vibration can be thought to be beneficial the ductile machining of brittle material. But the detail mechanism still needs the further investigation.

Evaluation of the material removal model

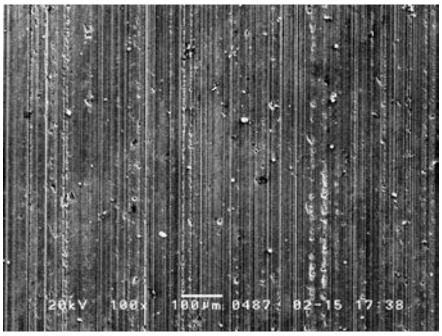
To further verify the analysis, the ground surfaces of polysilicon were examined. Figures 16-19 show the SEM pictures with different cut depth with/without vibration assistance.



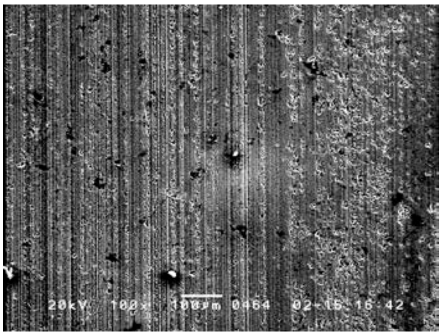
(a) With vibration



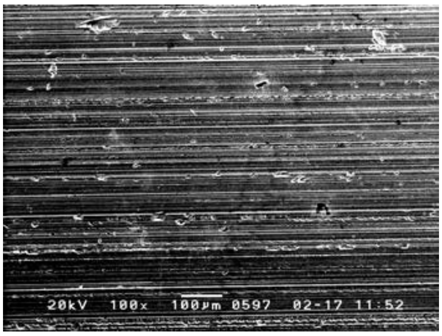
(b) Without vibration
Fig. 16. SEM picture (cut depth: 0.5 μm)



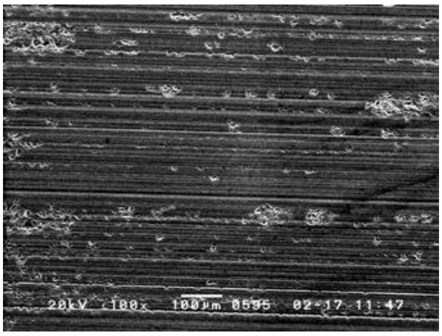
(a) With vibration



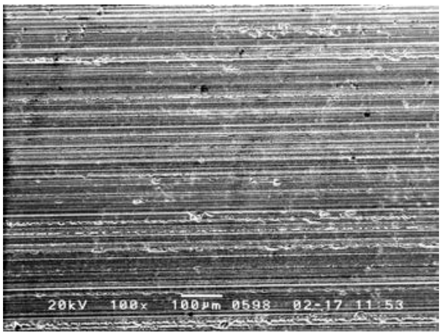
(b) Without vibration
Fig. 17. SEM picture (cut depth: 1μm)



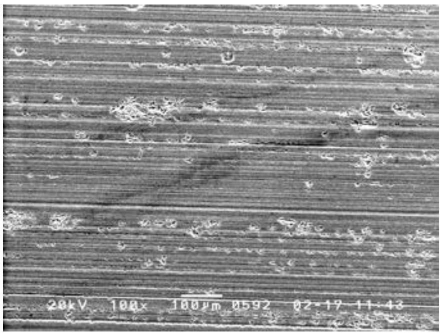
(a) With vibration



(b) Without vibration
Fig. 18. SEM picture (cut depth: 1.5μm)



(a) With vibration



(b) Without vibration
Fig. 19. SEM picture (cut depth: 2 μm)

Closely examining the figures, it is shown that these pictures do have their own features. One is that the grinding trails of individual grains with vibration are much more obvious than those without vibration. This may be that the actual cut depth of grains was further deepened with the assistance of vertical vibration. The other is that the ground surfaces without vibration have much bigger crack spots than those with vibration, which means that the vibration assisted grinding may be a good technique to increase the ductile removal percentage of brittle material. In additional, the ground surface with vibration is also much smoother than that of conventional grinding, which has been illustrated in comparison of the SEM images shown in Ref. (Liang, 2009), (Peng, 2011) and (Wu, 2010). Moreover, the surface roughness in EVAG is also better than that in CG, which further proves that vibration assistance can be much helpful for the high-quality grinding of the brittle material.

CONCLUSIONS

An analytical model was presented to assess the mechanism of the vibration assisted grinding technique. Based on that model, the stress condition along the equivalent shear plane was investigated. It reveals that the average nominal chip thickness of individual grain decreases with the vibration assistance and results in the size effect of material removal process. The shear/normal stress along the equivalent shear plane can be greatly improved with the assistance of vibration. Most importantly, the calculated specific pressure and force ratio with vibration are much bigger than those in conventional grinding. These features are thought to facilitate the ductile machining of brittle material and can used to explain the material removal mechanism of vibration assisted grinding. The examination of the grinding surface verified the analysis conclusion.

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REFERENCES

Bifano, T. G., Dow, T. A., and Scattergood, R. O., "Ductile-regime grinding: a new technology for machining brittle materials,"; Journal of Engineering for Industry, Vol. 113, No. 2, pp. 184-189(1991).

Blake, P. N., and Scattergood, R. O., "Ductile-regime machining of germanium and silicon,"; Journal of the American Ceramic Society, Vol. 73, No. 4, pp. 949-957(1990).

Brehl, D., "Microstructure fabrication using elliptical vibration-assisted machining,"; Proc ASPE, Vol. 39, pp. 511-514(2006).

Brehl, D. E., and Dow, T. A., "Review of vibration-assisted machining,"; Precision engineering, Vol. 32, No. 3, pp. 153-172(2008).

Denkena, B., Friemuth, T., Reichstein, M., and Tönshoff, H. K., "Potentials of different process kinematics in micro grinding,"; CIRP Annals-Manufacturing Technology, Vol. 52, No. 1, pp. 463-466(2003).

Ding, A., Wu, Y., and Liu, Y., "Surface topography of fine-grained ZrO2 ceramic by two-dimensional ultrasonic vibration grinding,"; Journal of Wuhan University of Technology-Mater. Sci. Ed., Vol. 26, No. 6, pp. 1162-1165(2011).

Gopal, A. V., and Rao, P. V., "A new chip-thickness model for performance assessment of silicon carbide grinding,"; The International Journal of Advanced Manufacturing Technology, Vol. 24, No. 11, pp. 816-820(2004).

Hecker, R. L., Liang, S. Y., Wu, X. J., Xia, P., and Jin, D. G. W., "Grinding force and power modeling based on chip thickness analysis,"; The International Journal of Advanced Manufacturing Technology, Vol. 33, No. 5, pp. 449-459(2007).

Hwang, T. W., and Malkin, S., "Upper bound analysis for specific energy in grinding of ceramics,"; Wear, Vol. 231, No. 2, pp. 161-171(1999).

Liang, Z., Wu, Y. B., Wang, X. B., Peng, Y., Xu, W., and Zhao, W. X., "A two-dimensional ultrasonically assisted grinding technique for high efficiency machining of sapphire substrate,"; Materials Science Forum, Vol. 626, pp. 35-40(2009).

Liang, Z., Wu, Y., Wang, X., Zhao, W., Sato, T., and Lin, W., "Two-dimensional ultrasonically assisted grinding of monocrystal silicon," Proc., of the 5th LEM21, The Japan Society of Mechanical Engineers, Osaka. (2009).

Liang, Z., Wang, X., Wu, Y., Xie, L., Liu, Z., and Zhao, W., "An investigation on wear mechanism of resin-bonded diamond wheel in Elliptical Ultrasonic Assisted Grinding (EUAG) of monocrystal sapphire,"; Journal of Materials Processing Technology, Vol. 212, No. 4, pp. 868-876(2012).

Liu, K., Li, X. P., and Liang, S. Y., "The mechanism of ductile chip formation in cutting of brittle materials,"; The International Journal of Advanced Manufacturing Technology, Vol. 33, No. 9, pp. 875-884(2007).

Moriwaki, T., and Shamoto, E., "Ultrasonic elliptical vibration cutting,"; CIRP Annals-Manufacturing Technology, Vol. 44, No. 1, pp. 31-34(1995).

Mult, H. C., Spur, G., and Holl, S. E., "Ultrasonic assisted grinding of ceramics,"; Journal of Materials Processing Technology, Vol. 62, No. 4, pp. 287-293(1996).

Negishi, N., "Elliptical vibration-assisted machining with single crystal diamond tools,"; M. S. thesis, North Carolina State University, America(2003).

Nomura, M., Wu, Y., Kato, M., Tachibana, T., and Kuriyagawa, T., "Investigation of ultrasonic grinding: effects of ultrasonic vibration in truing of small CBN grinding wheel,"; JSME Annu Meet, Vol. 4, pp. 69-70(2005).

Peng, Y., Wu, Y. B., Liang, Z. Q., Guo, Y. B., and Lin, X., "An experimental study of ultrasonic vibration-assisted grinding of polysilicon using two-dimensional vertical workpiece vibration,"; The International Journal of Advanced Manufacturing Technology, Vol. 54, No. 9, pp. 941-947(2011).

Peng, Y., Liang, Z., Wu, Y., Guo, Y., and Wang, C., "Characteristics of chip generation by vertical elliptic ultrasonic vibration-assisted grinding of brittle materials,"; The International Journal of Advanced Manufacturing Technology, Vol. 62, No. 5, pp. 563-568(2012).

Shamoto, E., and Moriwaki, T., "Ultaprecision diamond cutting of hardened steel by applying elliptical vibration cutting,"; CIRP Annals-Manufacturing Technology, Vol. 48, No. 1, pp. 441-444(1999).

Shamoto, E., Suzuki, N., Tsuchiya, E., Hori, Y., Inagaki, H., and Yoshino, K., "Development of 3 DOF ultrasonic vibration tool for elliptical vibration cutting of sculptured surfaces,"; CIRP Annals-Manufacturing Technology, Vol. 54, No. 1, pp. 321-324(2005).

Suzuki, N., Masuda, S., Haritani, M., and Shamoto, E, "Ultraprecision micromachining of brittle materials by applying ultrasonic elliptical vibration cutting," Proc., of the 2004 International Symposium on (pp. 133-138). IEEE.

Suzuki, K., Uematsu, T., Makizaki, T., and Iwai, M., "Ultrasonic grinding utilizing a stator of an ultrasonic motor,"; Proceedings of JSME Conference Manufacturing and Machine Tool, Vol. 2, pp. 183-184(2000).

Syoji Katsuo, Grinding Technology, Mechanical Press (Translation in Chinese), 2007.

Tlusty, J., "Dynamics of cutting forces in end milling,"; CIRP Annals - Manufacturing Technology, Vol. 24, pp. 21-25(1975).

Venkatachalam, S., and Liang, S. Y., "Effects of ploughing forces and friction coefficient in microscale machining,"; Journal of Manufacturing Science and Engineering, Vol. 129, No. 2, pp. 274-280(2007).

Wu, Y., Kondo, T., and Kato, M., "A new centerless grinding technique using a surface grinder,"; Journal of Materials Processing Technology, Vol. 162, pp. 709-717(2005).

Wu, Y. B., Liang, Z. Q., Wang, X. B., and Lin, W. M., "Elliptical ultrasonic assisted grinding (EUAG) of monocrystal sapphire-wear behaviors of resin bond diamond wheel,"; Advanced Materials Research, Vol. 126, pp. 573-578(2010).

Yan, Y., Bo, Z., and Liu, J., "Ultraprecision surface finishing of nano-ZrO2 ceramics using two-dimensional ultrasonic assisted grinding,"; International Journal of Advanced Manufacturing Technology, Vol. 43, No. 5, pp. 462-467(2009).

Zhou, R., Wang, K. K., and Merchant, E., "Modelling of cutting force pulsation in face-milling,"; CIRP Annals - Manufacturing Technology, Vol. 32, No. 1, pp. 21-26(1983)

脆性材料垂直橢圓振動輔助磨削分析模型

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摘 要

以往的研究主要集中于振動輔助磨削某些脆性材料的可行性上，對振動輔助磨削機理的研究尚不多見。本文建立了振動輔助磨削脆性材料時材料去除機理的解析模型。該模型研究了單個磨粒的切削運動學和切屑形成區內等效剪切面的應力條件。理論分析和實驗結果表明，該分析模型可用於解釋脆性材料振動輔助磨削的材料去除機理。