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Abstract

The ploughing force can be assigned to supervisory control of the tool wearing and machining process on-line in micro milling, for the reason that the ploughing force is closely related with the processed surface quality and radius of cutting edge. A new theoretical model is established to determine the ploughing force in micro milling of crystals with soft-brittle characters in consideration of the cutting edge roundness, and it is verified by Finite Element Method. The ploughing force decreases quickly with an decrease of the cutting edge roundness, and it can be controlled to be less than the shearing force, which helps for obtaining a good machined surface quality, under the condition that the radius of cutting edge is less than 2.8 μm or the feed speed is larger than 5 $\mu\text{m}/\text{z}$ when the radius of cutting edge is larger than 4.2 μm . Meanwhile, a large feed speed would bring heavy tool traces on the processed surface of soft-brittle crystals, destroying the processed quality. The energy consumption is researched by investigating the specific cutting force, showing that the energy consumption has a sharp increase with a small feed speed. The energy consumption is mainly caused by the ploughing effect, especially for tools with blunt cutting edge. Therefore, both the micro mill with sharp tool edge or blunt tool edge (under the cutting condition that the feed speed almost have equal value to the radius of cutting edge) are highly recommended for micro end milling of soft-brittle crystals.

Keywords	Soft-brittle crystals; Micro end milling; Ploughing force; Radius of cutting edge; Specific cutting force; Finite element method
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List of Corrections

Dear editors and reviewers:

We would like to thank the editors and reviewers for their time and help. We have considered their comments carefully and carried out a revision of the manuscript according to their suggestions (the changes are marked in red within the marked-up copy of the revised manuscript, which is uploaded as a 'Manuscript'). The corresponding responses to the comments are listed below:

Responses to Reviewer #1:

1. In this paper, the runout of tool is neglected, which is great influential parameter for micro milling. How you can consider the effect of runout.

Reply: We appreciate reviewer's viewpoint that runout is a great influential parameter for micro milling. In order to reduce the effect of runout, the stability of CNC machining center is studied. After starting the machine, machine slides are moved several times with the speed rate changing from small to large by manual control, and spindle speed also increases from zero to 40,000 r/min gradually. After a long time research, we find that the stability of this machining center would achieve best possible optimizations when it starts after 40 minutes.

A conventional milling force model is used to generate Fig. R1, which gives the theoretical feed forces for 6 $\mu\text{m}/\text{z}$ feed speed without and with a tool-tip runout of 2 μm . It can be seen that tool-tip runout has great influence on the cutting force. As shown in Fig. R2, the cutting force under the cutting condition of feed speed of 5 $\mu\text{m}/\text{z}$, spindle speed of 30,000 r/min and cutting edge radius of 4.2 μm in our experiment is similar like the cutting force in Fig. R1a, so the tool-tip runout has little impact on cutting force in this paper.

a. simulation of the cross feed force without runout

b. simulation of the cross feed force with runout

Fig. R1 Simulation of the cross feed force using conventional milling force model for 6 $\mu\text{m}/\text{z}$ feed rate without runout and with 2 μm runout.

Fig. R2 The cross feed force under the cutting condition of feed speed of 5 $\mu\text{m}/\text{z}$, spindle speed of 30,000 r/min and cutting edge radius of 4.2 μm in our experiment.

2. General, the cutting edge radius of the micro-mill depends on the manufacturing process used to produce the tool and not on the application. The reviewer doubt about the measurement of the cutting edge radius shown in Fig. 5.

Reply: We agree on the reviewer's viewpoint that the cutting edge radius of the micro-mill depends on the manufacturing process used to produce the tool and not on the application. Several micro CBN end mills diameter of 500 μm have been bought in our lab. Then cutting edges are detected by an atomic force microscope (Nanosurf® CoreAFM) and radii of cutting edge are fitted by Matlab® (R2013), respectively. Four micro end mills with radii of 1.9, 2.8, 4.2 and 5.3 μm which are among the all brought micro end mills are selected. One of micro CBN end mills with the radius of cutting edge of 2.8 μm used in the experiments and cutting edge radius measurement (new added) are shown in Fig. 5.

Fig. 5 One of micro CBN end mills with the radius of cutting edge of 2.8 μm used in the experiments and cutting edge radius measurement, **a.** rake face, **b.** flank face, **c.** the fitting of the radius of cutting edge of 2.8 μm .

3. English need to go for proof reading throughout the paper, for example, in section 3.2, the depth of cut is set as a uniform value of 6 mm, this should be 6 μm .

Reply: We are very sorry for the poor English presentation of the paper. The grammatical problems and the typing errors have been corrected as far as we can, and another author has also made a careful check of the writing issues, we hope the revised manuscript will be readable and valuable.

4. In Eq.11, which direction does the cutting force refer to?

Reply: The cutting force in Eq. 11 is the abbreviation of Eq. 9 after the analysis, and represents Eq. 9. So, the direction of the cutting force in Eq.11 refers to three directions, namely x (feed), y (cross feed) and z (thrust) directions in coordinate system O_{xyz} in Fig. 1.

5. In the section 5, the author descript that a small feed speed would lead to high consumption of cutting energy and severe ploughing effect, while the heavy tool marks will be generated on the surface of work piece with the large feed speed which is in the end also leading to poor machined surface quality. Please specialize the surface quality, the surface quality means surface roughness, micro cracks or other?

Reply: We are very sorry for the confusion brought from the unclear definition of *machined surface quality*. In micro end milling of KDP crystal, the severe ploughing effect can increase the machined surface roughness. While micro cracks, tool marks and so on can also increase the machined surface roughness. The machined surface roughness can monitor the machined surface quality in micro end milling of KDP crystal. So, the machined surface quality mainly represents machined surface roughness in this paper.

According to the reviewer's kind suggestion, the meaning of *machined surface quality* is clarified at page 18 of Section 4 in the revised manuscript.

6. In the section of conclusion, the author should summarize the research from both theoretical significance and practical significance, and puts forward the research shortcoming and future research direction.

Reply: Thanks very much for your kind suggestions. The conclusion (Section 5) has been re-written, as following:

This study investigated the ploughing force in micro milling of soft-brittle crystals. A theoretical model is built to estimate the ploughing force. It can decompose the cutting force into shearing force and ploughing force components by following approach: A linear fitting for cutting forces at non-zero radii of cutting edge is carried out to get the cutting force at zero radius of cutting edge of tool, then the obtained truncate value is shearing force. The ploughing force has the same value to the total force subtracting above obtained truncate value. The ploughing force arises quickly with the growth of radius of cutting edge, and the shearing force is always larger than ploughing force helping to enhance the machined surface quality when radius of cutting edge is less than 2.8 μm . A micro mill having sharp edge roundness is beneficial for the machining process in the micro end milling of a soft-brittle crystal. The increased specific force is mainly caused by the ploughing effect, especially for the micro end mill with large radius of cutting edge. Above results could explain how ploughing effect influence the micro milling process theoretically. A small feed speed would lead to high consumption of cutting energy and severe ploughing effect, while the heavy tool marks will be generated on the surface of work piece with the large feed speed which is in the end also leading to poor machined surface quality. Therefore, a micro mill with small radius of cutting edge or a micro mill with large radius (under the condition that the feed speed is nearly equivalent to the radius) are both highly advised for micro milling of soft-brittle crystal. This result could be applied in micro milling of soft-brittle crystal. The theoretical model for estimation of ploughing force established in this paper has not including the brittle cutting mode. We have to eliminate the brittle cutting mode cases when we using this model. The theoretical model which can eliminate the brittle cutting mode automatically is highly encouraged in further studies.

Thanks very much for Reviewer 1's valuable comments. We have improved the manuscript very carefully according to your suggestions.

Responses to Reviewer #2:

1. I have no objections against publication in IJMS.
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Reply: Thanks very much for your detailed review and appreciation to this manuscript. We also have improved this manuscript very carefully.

Responses to Reviewer #3:

1. The main problem is on the analytical model validation based on the use of a numerical model (FEM). Is the FEM validated?

Reply: We are very sorry for the confusion brought from the unclear explanation.

In order to validate the theoretical model for estimation of ploughing force, the cutting forces under non-zero cutting edge radii and zero cutting edge radius should be obtained. Then the comparison between the cutting force at zero cutting edge obtained by an extrapolated fitting of other cutting forces under non-zero cutting edge radii and the directed obtained cutting force at zero cutting edge radius is carried out to validate the theoretical model. The zero cutting edge radius can be got by FEM simulation, but can't be got from experiments because the zero cutting edge radius is not existed in actual cutting. Moreover, the FEM simulation in this paper had been validated in our previous published paper [27]. So, we use the FEM simulation rather than experiments to validate the theoretical model. Furthermore, the experiments in Section 4 also validate the model indirectly.

The FEM simulation had been validated in our previous published paper (Chen N, Chen M, Wu C, Guo Y, Wang Y. The design and optimization of micro polycrystalline diamond ball end mill for repairing micro-defects on the surface of KDP crystal. *Precis Eng* 2016;43:345-355) [27]. The method is that the comparisons between the simulated and experimental milling force in cross feed, thrust and feed directions are studied under different spindle speed and depth of cut. Good agreements both in the magnitudes and trends are obtained from the comparisons between the predicted and the measured cross feed force and thrust force.

According to the reviewer's kind suggestion, the reasons for *Why validate the analytical model using FEM simulation* and *Is the FEM validated* are added at pages 9 and 10 of Section 2.2 in the revised manuscript.

2. In the paper, the Authors reject some points of Figure 6. In this manner, the agreement with the model is improved. But, the given justification is not convincing. The defects highlighted can be observed also under different cutting conditions.

Reply: The theoretical model for estimation of ploughing force in this paper is established under the assumption of micro machining ductile materials. The brittle cutting mode has not been considered in this theoretical model. In our previous published paper [8], the brittle cutting mode was appeared

in micro end milling of KDP crystal which is shown as many cracks and white areas on the machined surface when the ratio of feed per tooth to radius of cutting edge is beyond 3. In this paper, the ratio of feed per tooth to radius of cutting edge is beyond 3 under three cases, namely the feed speed is 7 and 9 $\mu\text{m/z}$ for a radius of cutting edge of 1.9 μm , and the feed speed is 9 $\mu\text{m/z}$ for a radius of 2.8 μm . The morphology of machined grooves with ductile cutting mode and one of above cases is studied and shown in Fig. 7 verifying the brittle cutting mode when the cutting conditions are under above three cases. So, the above three cases should be excluded when analyzing the ploughing force in this paper. The theoretical model for estimation of ploughing force which is including the brittle cutting mode are expected to be presented in the next paper of our group.

The defects highlighted in Fig. 7c and d can be mainly observed under brittle cutting mode in micro end milling of KDP crystal.

According to the reviewer's kind suggestion, the reasons for rejecting some points of Fig. 6 are added at pages 14 and 15 of Section 4 in the revised manuscript.

3. The analysis on the data must be improved.

Reply: Thanks very much for your kind suggestions. We've checked and improved the analysis on the data in Section 4. The detailed modification can be seen in revised manuscript.

Thanks very much for Reviewer 3's valuable comments. We have improved the manuscript very carefully according to your suggestions.

We would like to thank all reviewers for their valuable detailed comments.

We have very carefully tried to improve the paper. All of the related analysis process, experiment validation, Equations, Figures and Tables have been checked. The detailed content has also been improved corresponding to each Reviewer's comments.

1. A new mechanistic model is established to determine the ploughing force in micro end-milling of soft-brittle crystals.
2. The ploughing force can be controlled less than shearing force with the suitable cutting edge radius and feed rate.
3. The increased energy consumption is mainly caused by the ploughing effect, especially for the large cutting edge radius.
4. The small cutting edge radius or large cutting edge radius (under the condition that the feed per tooth is nearly equal to cutting edge radius) are recommended.

Research on the ploughing force in micro milling of soft-brittle crystals

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Abstract: The ploughing force can be assigned to supervisory control of the tool wearing and machining process on-line in micro milling, for the reason that the ploughing force is closely related with the processed surface quality and radius of cutting edge. A new theoretical model is established to determine the ploughing force in micro milling of crystals with soft-brittle characters in consideration of the cutting edge roundness, and it is verified by Finite Element Method. The ploughing force decreases quickly with an decrease of the cutting edge roundness, and it can be controlled to be less than the shearing force, which helps for obtaining a good machined surface quality, under the condition that the radius of cutting edge is less than 2.8 μm or the feed speed is larger than 5 $\mu\text{m}/\text{z}$ when the radius of cutting edge is larger than 4.2 μm . Meanwhile, a large feed speed would bring heavy tool traces on the processed surface of soft-brittle crystals, destroying the processed quality. The energy consumption is researched by investigating the specific cutting force, showing that the energy consumption has a sharp increase with a small feed speed. The energy consumption is mainly caused by the ploughing effect, especially for tools with blunt cutting edge. Therefore, both the micro mill with sharp tool edge or blunt tool edge (under the cutting condition that the feed speed almost have equal value to the radius of cutting edge) are highly recommended for micro end milling of soft-brittle crystals.

Keywords: Soft-brittle crystals; Micro end milling; Ploughing force; Radius of cutting edge; Specific cutting force; Finite element method

1. Introduction

Soft-brittle crystals like lithium fluoride (LiF) crystal, calcium fluoride (CaF_2) crystal and potassium dihydrogen phosphate crystal (KH_2PO_4 , KDP), are widespread applied in inertial confinement fusion (ICF) projects [1-3]. Before such crystals can be used in ICF, they have to be machined according to specification (often requiring micro-structures on the surface). However, these soft-brittle crystals are widely known as the difficult-to-cut materials because of their particular material properties (extremely fragile and soft) [4, 5]. Chen et al. [6] and Zhang et al. [7] pointed out that micro end milling had been applied to producing components with complex structures and unique material properties because of its processing flexibility. Therefore, micro end milling can be now envisaged to fabricate the micro-structures on soft-brittle crystals. The radius of cutting edge for cutting tool can't downscale with the tool diameter leading to that the undeformed chip thickness almost has same value with the radius of cutting edge in micro machining [8]. Ploughing effect emerges easily and heavily influences the processed surface quality because of the elastic recovery in the cutting zone of the work piece [9, 10]. This ploughing force is caused by the small undeformed chip thickness with relatively blunt cutting edge, and it is closely concerned with the processed surface quality because the ploughing effect would increase the extrusion effect in chip formation. In that sense, the ploughing force is a effective factor to monitor the wear of tool and cutting process [11, 12]. Therefore it is meaningful to research the ploughing force, and establish the relationship between ploughing force and radius of cutting edge.

Many experts researched the ploughing force in micro machining adopting experimental and theoretical approaches. The methods to measure the ploughing force can be mainly classified in direct and indirect methods. Stevenson [12] used feed-dwell approach, a direct method identifying the absolute values of the force components at the feed speed of zero, to get the ploughing force directly. This direct method has the disadvantage that it can't cut always with the undeformed chip

thickness of zero value because of a non-ideal rigidity of machine tool.

The indirect methods mainly include the extrapolation method of the cutting thickness with zero value and the method of comparing cutting forces at various wear positions of flank face. Albrecht [13] put out the extrapolation method which is plotting cutting forces with the variation of feed speed under invariable cutting speed and extrapolates these to the feed speed of zero value. The ploughing force is defined by this intercept value. Guo and Chou [14] used the extrapolation method to predict the ploughing force in metal cutting, and verified that this method is useful way to forecast the ploughing force. Wyen and Wegener [15] applied this method to acquire the ploughing force by taking account of the effect of radius of cutting edge, and thus obtained how the cutting speed influence the ploughing force. However, the extrapolation method was also questioned by many experts, such as Stevenson [12] and Arsecularatne [16], and the ploughing force calculated by the above indirect method has shown to be larger than the feed-dwell method.

The method of comparing cutting forces at various wear positions of flank face was first put forward by Zorev [17], and could be shown as: if the flank wear of tool increased with the constant of other cutting condition, the chip formation and cutting force above the rake face will not change. However, the ploughing force increases at the size effect area which is between the processed surface of work piece and the major flank face because of the increase of wear on flank face. Therefore, the increased force is mainly contributed by increased ploughing force [17-19]. Popov and Dugin [18] determined the ploughing force using the method of comparing cutting forces at various wear positions of flank face, and discovered as well that ploughing force estimated using this approach is smaller than the one found by extrapolation method. In order to increase the accuracy, Popov and Dugin [19] later improved the above method to compare the forces at various extrusion area between the flank face and processed materials of work piece, and this comparison method is proved to be more reliable and acceptable.

Although the ploughing force had been measured or predicted by many experts, there exists no

widely accepted method to obtain the ploughing force. Moreover, the work piece materials used in the cited researches are mostly metals, and soft-brittle crystals have not been investigated. Also, turning has mainly been used in the above researches, and micro end milling is largely different from turning. In this work, a KDP crystal, which is an optical crystal with typical soft-brittle properties, is chosen as the target of our study. A theoretical model is established to predict the ploughing force, and it is verified by finite element method (FEM). How feed speed and cutting edge roundness (the feed speed represents feed per tooth in the follow pages) affect the ploughing force is studied. The energy consumption is also studied by carrying out the research on the specific ploughing force.

2. Separation of the ploughing force and shearing force

2.1 Theoretical model for estimation of ploughing force

The milling force is a fundamental factor for studying the cutting mechanism, pointed out by Wu et al. [10]. In macro end milling, the cutting edge effect could be neglected owing to the large ratio between the radius of cutting edge and tool diameter (around 10^{-6}), as shown by Lee and Dornfeld [20]. Several models to estimate the force in milling had been established in the works of Yun and Cho [21] and Tlustý and Macneil [22], and they were mainly assumed as expressed in Eqs. 1, 2 and 3, as following:

$$F_t = K_m b h \quad (1)$$

$$F_r = p F_t \quad (2)$$

$$h = f_t \sin \theta \quad (3)$$

Where F_r and F_t are the forces in radial and tangential directions. K_m is material coefficient of work piece, b is the width value, h represents the undeformed chip thickness. While p , θ and f_t are the proportional factor, position angle and feed speed, respectively.

The machining procedure in micro milling is expressed in Fig. 1. R is the tool radius. In coordinate

system O_1xyz (O_1 is the tool centers during $(j-1)^{th}$ tooth cutting), the feed and cross feed direction of work piece are set as x and y axis.

Fig. 1 The diagram of micro milling process.

The ratio between the radius of cutting edge and tool diameter is around 10^{-3} , and the cutting thickness almost has same value with the radius of cutting edge [20], so this radius can't be regarded as zero in micro end milling. Severe size effect which is shown as ploughing and rubbing is appeared on the machined area around the cutting edge [10]. In micro machining of ductile materials, the cutting force is composed by following two parts: (1) the ploughing force around the cutting edge caused by ploughing and rubbing effect; (2) the shearing force above the rake face. Srinivasa and Shunmugam [23], Malekian et al. [24] and Zhang et al. [25] presented that the cutting force can be described by three incrementwouls force components ($dF_{ij}(\theta)$, $dF_{rj}(\theta)$ and $dF_{aj}(\theta)$ cutting forces) working above a dz in an ideal rigid cutting procedure in micro milling, as expressed in Eq. 4:

$$dF_{ij}(\theta) = [K_{tc}h_j(\theta) + K_{te}]dz \quad (4a)$$

$$dF_{rj}(\theta) = [K_{rc}h_j(\theta) + K_{re}]dz \quad (4b)$$

$$dF_{aj}(\theta) = [K_{ac}h_j(\theta) + K_{ae}]dz \quad (4c)$$

Where K_{rc} , K_{ac} , and K_{tc} are the coefficients of shearing effect, which are mainly connected to the rake angle, the cutting parameters and the material properties of the work piece. These coefficients will be constant for a specific case of machining. K_{te} , K_{re} and K_{ae} are the coefficients related with cutting edge, and they can be calculated by the model established by Abdelmoneim and Scrutton [26]:

$$K_{te} = r_e \tau \left(\frac{2\theta_0}{\cos\theta_0} + \pi \sin\theta_0 \tan\theta_0 \right) \quad (5a)$$

$$K_{re} = r_e \tau (2\sqrt{3}\sin\theta_0) \quad (5b)$$

$$K_{ae} = K_{te} \sin(i) \quad (5c)$$

Where r_e is the radius for cutting edge roundness, τ is the work piece's shear stress, θ_0 and i are the angle of stationary point and the inclination angle of the cutting tool, respectively. Coefficients k_{te} and k_{re} are only defined by τ and θ_0 , and they are thus constant if the rake angle, the cutting parameters, and the material characteristics of the work piece are given. Thus Eq. 5 can be expressed as:

$$K_{te} = r_e k_{te} \quad (6a)$$

$$K_{re} = r_e k_{re} \quad (6b)$$

$$K_{ae} = r_e \sin(i) k_{te} \quad (6c)$$

In this paper, micro Cubic Boron Nitride (CBN) end mills with straight cutting edges are used in simulation and experiments, so the three incremental force components on the thrust direction (z direction) are the same for every dz element. When substituting K_{te} , K_{re} and K_{ae} from Eq. 6 to Eq. 4, the three-direction forces can be shown as:

$$F_t(\theta) = [K_{te} h(\theta) + r_e k_{te}] a_p \quad (7a)$$

$$F_r(\theta) = [K_{re} h(\theta) + r_e k_{re}] a_p \quad (7b)$$

$$F_a(\theta) = [K_{ae} h(\theta) + r_e k_{te} \sin(i)] a_p \quad (7c)$$

Where a_p is the depth of cut.

The three-direction force F_t , F_r and F_a at a cutting angle of θ could be decomposed into the F_x , F_y and F_z (forces in coordinate system O_1xyz), are given below:

$$\begin{pmatrix} F_x(\theta) \\ F_y(\theta) \\ F_z(\theta) \end{pmatrix} = \begin{pmatrix} -\cos\theta & -\sin\theta & 0 \\ \sin\theta & -\cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} F_t(\theta) \\ F_r(\theta) \\ F_a(\theta) \end{pmatrix} \quad (8)$$

Submitting Eqs. 3 and 7 into Eq. 8, the forces can be illustrated as:

$$F_x(\theta) = a_p f_t k_{cx} + a_p r_e k_{ex} \quad (9a)$$

$$F_y(\theta) = a_p f_t k_{cy} + a_p r_e k_{ey} \quad (9b)$$

$$F_z(\theta) = a_p f_t k_{cz} + a_p r_e k_{ez} \quad (9c)$$

Where k_{cx} , k_{cy} , k_{cz} , k_{ex} , k_{ey} and k_{ez} can be expressed as:

$$k_{cx} = -(K_{tc} \cos\theta + K_{rc} \sin\theta) \sin\theta \quad (10a)$$

$$k_{cy} = -(-K_{tc} \sin\theta + K_{rc} \cos\theta) \sin\theta \quad (10b)$$

$$k_{cz} = K_{ac} \sin\theta \quad (10c)$$

$$k_{ex} = k_{te} \cos\theta + k_{re} \sin\theta \quad (10d)$$

$$k_{ey} = -K_{te} \sin\theta + K_{re} \cos\theta \quad (10e)$$

$$k_{ez} = K_{ae} \quad (10f)$$

From the Eqs. 5 and 10, it can be concluded that k_{cx} , k_{cy} , k_{cz} , k_{ex} , k_{ey} and k_{ez} are only related to rake angle, the cutting parameters, and the material properties of work piece. So, in Eq. 9, the cutting force becomes direct ratio with the radius of cutting edge r_e , if all above factors are given. In the first part of the cutting force equation, $a_p f_t k_{cx}$, $a_p f_t k_{cy}$ and $a_p f_t k_{cz}$ can be considered as a shearing force, while in the second part, $a_p r_e k_{ex}$, $a_p r_e k_{ey}$ and $a_p r_e k_{ez}$ can be considered as a ploughing force mainly related to a blunt cutting edge. Therefore, the cutting force could be shown as:

$$F = a + b r_e \quad (11)$$

Where factors a and b are constant if the rake angle, the cutting parameters, and the material characteristics of the work piece are given. a is shearing force, and $b r_e$ is the ploughing force.

Based on these derivations, one indirect method to decompose the cutting force into shearing force and ploughing force components is put forward: A linear fitting for cutting forces at non-zero radii of cutting edge is carried out to get the force at zero radius, then the obtained truncate value is shearing force. The ploughing force has the same value to the total force subtracting above obtained truncate value.

2.2 Validation of the theoretical model for estimation of ploughing force by FEM simulations

In order to validate the theoretical model for estimation of ploughing force, the cutting forces under non-zero cutting edge radii and zero cutting edge radius should be obtained. Then the comparison between the cutting force at zero cutting edge obtained by an extrapolated fitting of other cutting forces under non-zero cutting edge radii and the directed obtained cutting force at zero cutting edge radius is carried out to validate the theoretical model. The zero cutting edge radius can be got by FEM simulation, but can't be got from experiments because the zero cutting edge radius is not existed in actual cutting. Moreover, the FEM simulation in this paper had been validated in our previous published paper [27]. So, we use the FEM simulation rather than experiments to validate the theoretical model. Furthermore, the experiments in Section 4 will validate the model indirectly.

The FEM simulation is carried out utilizing ABAQUS/Explicit software. The relationship between strain ε_0 and stress σ of the KDP crystal obtained by Chen [28] can be expressed in Eq. 12. The CBN micro end mills with straight edge are used in the simulation, and can be considered as a rigid body to reduce the computation quantity.

$$\sigma = \begin{cases} 33.2 \times 10^3 \varepsilon_0 & (\sigma \leq 360\text{MPa}) \\ 2.4 \times 10^3 \varepsilon_0^{0.417} & (\sigma \geq 360\text{MPa}) \end{cases} \quad (12)$$

This FE model adopts the geometric separation criterion, and sets the allowable value of maximal displacement based on the maximal strain. The micro end mill and work piece are defined to rotate

around the axis of tool and move in feed direction, respectively. A penalty friction formulation is chosen in the interaction model, and the coefficient for friction is set to 0.3 by referencing the works of Chen et al. [27] and Zong et al. [29]. To keep the high mesh quality, an adaptive mesh feature is used. The simulation of micro end milling of KDP crystal is schematically expressed in Fig. 2. To verify the model, four radii of cutting edge are selected. The detailed cutting parameters and radii of cutting edge used in the simulation are shown in Table 1.

Fig. 2 The simulation of micro milling process for soft-brittle crystal.

Table 1 The detailed cutting parameters for simulation

Radius of cutting edge r_e (μm)	Diameter d (μm)	Spindle speed n (r/min)	Feed speed f_t ($\mu\text{m}/\text{z}$)	Depth of cut a_p (μm)
0, 2, 4, 6	500	30, 000	5	6

The FEM simulation had been validated in our previous published paper [27]. The method is that the comparisons between the simulated and experimental milling force in cross feed, thrust and feed directions are studied under different spindle speed and depth of cut. Good agreements both in the magnitudes and trends are obtained from the comparisons between the predicted and the measured cross feed force and thrust force.

As stated in Section 2.1, the cutting force achieves the largest value on the cutting angle of 90° . The reason is that the cutting thickness reaches the largest on position angle of 90° . While the force in the cross feed direction also contributes to the most of the force on above cutting position.

Therefore, the above component force on the cutting angle of 90° (it will be regarded as cutting force in the following analysis) is chosen to verify the model in Section 2.1.

The cutting forces under the radii of cutting edge of 0, 2, 4 and 6 μm are calculated from FEM, and the fitting line is obtained under the radii of cutting edge of 2, 4 and 6 μm , shown as blue line in Fig. 3. The cutting force can be presented via a linear function ($F=ar_e+b$), because the determination coefficient (R^2) is larger than 0.99 (a and b are the constants). The intersection with the Y-axis of a linear fit through the 3 points is at 0.153 N, the directly calculated cutting force (by FEM simulation for a radius of cutting edge of zero) is at 0.142 N. As the difference between extrapolated and directly calculated value is only 7.7 %, this shows that the proposed theoretical model can generate a good estimation for both the shearing and ploughing force components.

Fig. 3 Verification of separation method in FEM.

3. Experimental study

3.1 Experiment installation

The experiments are conducted on a milling center (KERN MMP2522, made in Germany), as shown in Fig. 4 [8]. The repeatability of positioning is $\pm 1 \mu\text{m}/20 \text{ mm}$, and the maximum spindle

speed of this micro milling center is 40,000 r/min. KDP crystal is chosen as the work piece, and its dimension is $95 \times 27 \times 14$ mm. Several micro CBN end mills diameter of $500 \mu\text{m}$ have been bought in our lab. Then cutting edges are detected by an atomic force microscope (Nanosurf® CoreAFM) and radii of cutting edge are fitted by Matlab® (R2013), respectively. Four micro end mills with radii of 1.9, 2.8, 4.2 and $5.3 \mu\text{m}$ which are among the all brought micro end mills are selected. One of micro CBN end mills with the radius of cutting edge of $2.8 \mu\text{m}$ used in the experiments and cutting edge radius measurement are shown in Fig. 5.

Fig. 4 Experimental setup for micro milling center, **a.** actual set-up, **b.** schematic illustration [8].

Fig. 5 One of micro CBN end mills with the radius of cutting edge of $2.8 \mu\text{m}$ used in the experiments and cutting edge radius measurement, **a.** rake face, **b.** flank face, **c.** the fitting of the radius of cutting edge of $2.8 \mu\text{m}$.

3.2 Design for experiments

To research the ploughing and shearing force which are closely connected with the radius of

cutting edge r_e and feed speed f_t , the feed speed is set to 1, 3, 5, 7, and 9 $\mu\text{m/z}$. The constant length for machined grooves is set to 3 mm. The depth of cut is set as a uniform value of 6 μm for all four tools because it can't influence the undeformed chip thickness. Table 2 shows the detailed geometrical parameters of micro end mill and cutting parameters.

Table 2 The detailed geometrical parameters and cutting parameters

Radius of cutting edge r_e (μm)	Feed speed f_t ($\mu\text{m/z}$)	Spindle speed n (r/min)	Diameter d (μm)	Depth of cut a_p (μm)	Cutting length l (mm)
1.9, 2.8, 4.2, 5.3	1, 3, 5, 7, 9	30, 000	500	6	3

3.3 Calculation of the specific cutting force

Normally, the ratio between mean forces and mean machining area is stipulated as the specific force k_c (Lai et al. [30] and Li and Wu [31]). In this paper, the mean cross feed force F over 100 revolutions is used as the mean cutting force. The ratio of the volume V to perimeter l in a half cutting circle is defined as the mean machining area. So, the equation to express the specific cutting force in this paper is shown as:

$$k_c = F/(V/l) \quad (13)$$

The volume of the area $CDEF$ with the depth of cut a_p equals to the volume V , since it is removed during the j^{th} tool pass which is shown in Fig. 1. The volume V and perimeter l can be expressed as:

$$V = 2Rf_t a_p \quad (14)$$

$$l = \pi R \quad (15)$$

3.4 Cutting force analysis and evaluation for the machined surfaces

During experiment, a dynamometer (Kistler® 9256C2) and a charge amplifier (5233A) are applied to acquire the cutting force signals. The sampling frequency of 10 kHz is chosen to record the cutting force. Labview V.7.2™ and Matlab® (R2013a)™ are used for signal acquisition and post-processing.

The cutting force over 100 revolutions is calculated for each data array. The cutting force and measurement error are the mean and deviation of collected cutting force, respectively. The morphology of machined work piece is detected by a SEM (FEI®).

4. Results and discussion

Figure 6 illustrates the force versus the radius of cutting edge under different feed speed in detail. When the feed speed is relatively small, such as 1, 3, and 5 $\mu\text{m}/\text{z}$, the cutting force nicely grows with the radius of cutting edge, and that confirms the theoretical model which is established for estimating the ploughing force in Section 2. However, when the feed speed is relatively large, such as 7 and 9 $\mu\text{m}/\text{z}$, the cutting force is not linearly depending upon the cutting edge roundness, while it for radii of cutting edge of 1.9 and 2.8 μm becomes even larger than it for radii of cutting edge of 4.2 and 5.3 μm . This can be explained as follow: The theoretical model for estimation of ploughing force in this paper is established under the assumption of micro machining ductile materials. The brittle cutting mode has not been considered in this theoretical model. In our previous published paper [8], the brittle cutting mode was appeared in micro end milling of KDP crystal which is shown as many cracks and white areas on the machined surface when the ratio of feed speed to radius of cutting edge is beyond 3. In this paper, the ratio of feed speed to radius of cutting edge is beyond 3 under three cases, namely the feed speed is 7 and 9 $\mu\text{m}/\text{z}$ for a radius of cutting edge of 1.9 μm , and the feed speed is 9 $\mu\text{m}/\text{z}$ for a radius of 2.8 μm . In order to verify the brittle cutting mode when the cutting conditions are under above three cases, the morphology of machined grooves with ductile cutting mode and one of above cases is studied and shown in Fig. 7. The feed speed of 3 and 9 $\mu\text{m}/\text{z}$ for a radius of cutting edge of 1.9 μm is chosen in Fig. 7. Figures 7a and b show a perfect machined surface, manifesting that the ductile cutting is appeared under the condition of the feed speed of 3 $\mu\text{m}/\text{z}$ for a radius of cutting edge of 1.9 μm . On the other hand, Figures 7c and d show many cracks are emerged on the machined surface, manifesting that the brittle cutting mode is arisen under the

feed speed is $9 \mu\text{m/z}$ for a radius of cutting edge of $1.9 \mu\text{m}$. So, the above three cases should be excluded when analyzing the ploughing force in this paper.

Fig. 6 The change of cutting force with the radius of cutting edge under different feed speed.

Fig. 7 Images for the machined grooves under different feed speed and radius of cutting edge, **a.**, **b.** $f_t = 3 \mu\text{m/z}$,

$r_e = 1.9 \mu\text{m}$, $f_t/r_e = 1.58$, **c.**, **d.** $f_t = 9 \mu\text{m/z}$, $r_e = 1.9 \mu\text{m}$, $f_t/r_e = 4.74$.

When we exclude those cases where brittle machining is clearly observed (feed speed is 7 and 9 $\mu\text{m/z}$ for a radius of cutting edge of 1.9 μm , and the feed speed is 9 $\mu\text{m/z}$ for a radius of 2.8 μm), the remaining measurements of Fig. 7 are now shown in Fig. 8. It then again confirms the theoretical model in Section 2 that the force rises quasilinear with the radius of tool edge for all feed speed with the cutting process under the ductile cutting mode.

Fig. 8 The force versus the radius of cutting edge under different feed speed (excluding the cutting parameters would leading to brittle cutting).

Figure 9 illustrates the change of force versus the feed speed under various radii of edge. The force rises with the feed speed for all radii of tool edge. The force grows with the augment of radius of tool edge which is mainly led by the increase of ploughing force with the radius under the condition that the feed speed is less than 5 $\mu\text{m/z}$. However, with the feed speed larger than 5 $\mu\text{m/z}$, the cutting force under radii of cutting edge of 1.9 and 2.8 μm increases more quickly than the cutting force under radii of 4.2 and 5.3 μm , and finally becomes largest with the feed speed of 9 $\mu\text{m/z}$. This is mainly caused by brittle cutting mode when the feed speed is 7 and 9 $\mu\text{m/z}$ for a radius of cutting edge of 1.9 μm , and the feed speed is 9 $\mu\text{m/z}$ for a radius of 2.8 μm .

The ploughing and shearing force can also be received from the theoretical model in Section 2. As stated above, the brittle cutting mode would emerge at certain condition, so the cutting force should

include shearing, ploughing and brittle cutting force components under this condition. Figure 10 shows the quadratic fit curves for the ploughing force equaling the cutting force after subtracting shearing force (dashed line). The ploughing force is shown as solid lines. The dotted lines are the cutting force subtracting shearing force. The difference between the solid line and dotted line is the brittle cutting force (for above three cutting parameters with brittle cutting mode). The brittle cutting force is 2.86 times larger than the ploughing force when the ratio of feed speed to radius of tool edge is 4.7 under the conduction that the feed speed is $9 \mu\text{m/z}$ with the radius of $1.9 \mu\text{m}$.

Fig. 9 The change of force versus the feed speed under various radii of cutting edge.

The shearing force grows nicely with the augment of the feed speed with the feed speed less than $5 \mu\text{m/z}$, but the shearing force increases sharply with the feed speed larger than $5 \mu\text{m/z}$. This may be caused by that the cutting thickness is almost thicker than the radius of tool edge for the feed speed larger than $5 \mu\text{m/z}$. The ploughing force and its proportion increase with the augment of the feed speed and radius of cutting edge. The reason is that more materials flow and are removed under the cutting edge with a larger radius of cutting edge and feed speed.

The ploughing force is smaller than the shearing force for all feed speed values, and this is favorable for the machined surface quality, when the radii of cutting edge are at relatively small values, such as 1.9 and $2.8 \mu\text{m}$. When radii of cutting edge are at relatively large values, such as 4.2

and $5.3 \mu\text{m}$, the ploughing force becomes equivalent or larger than the shearing force (for the feed speed less than $5 \mu\text{m/z}$), leading to poor surface quality; When the feed speed becomes larger than $5 \mu\text{m/z}$, the ploughing force will smaller than shearing force which is again helping to realize good surface quality. However, the heavy tool marks will be generated on the surface of work piece with the large feed speed which is in the end also leading to poor machined surface quality. So, in conclusion a micro mill with small radius of cutting edge or a micro mill with large radius (under the condition that the feed speed is nearly equivalent to the radius) are both highly advised for micro end milling of soft-brittle crystal. In micro end milling of KDP crystal, the severe ploughing effect can increase the machined surface roughness. While micro cracks, tool marks and so on can also increase the machined surface roughness. The machined surface roughness can monitor the machined surface quality in micro end milling of KDP crystal. The machined surface quality mainly represents machined surface roughness in this paper.

Fig. 10 The change of ploughing force and shearing force with the feed speed under various radii of cutting edge.

Also the change of specific force versus the feed speed under various radii of cutting edge has been studied, as illustrated in Fig. 11. The total specific force nonlinearly descends with the growth of the feed speed with the feed speed less than $5 \mu\text{m/z}$ for all four radii of cutting edge, while they become less or more constant with the feed speed larger than $5 \mu\text{m/z}$ (excluding again the three

cutting conduction with brittle cutting mode). This nonlinear change of the specific cutting force leading to poor surface quality of work piece in micro machining [8, 32]. So, the reasons behind this phenomenon should be now investigated in more detail.

Fig. 11 The specific force versus the feed speed under various radii of cutting edge.

Figure 12 shows the change of specific ploughing force and specific shearing force with the feed speed under various radii of cutting edge. The specific ploughing force decreases sharply when the feed speed is increasing from 1 to 5 $\mu\text{m/z}$ for all radii, and the larger radii of cutting edge lead to a sharper decrease of the specific ploughing force. While the specific ploughing forces are almost constant when the feed speed is larger than 5 $\mu\text{m/z}$. The reason for above phenomenon is that the ploughing and rubbing effects are severe when the feed speed is less than 5 $\mu\text{m/z}$, and these effects weaken gradually with the increasing feed speed. The sudden increase under the feed speed of 9 $\mu\text{m/z}$ for the radius of cutting edge of 2.8 μm may be caused by the severer brittle cutting effect with relatively large radius of cutting edge. The specific shearing force decreases with the feed speed arising from 1 $\mu\text{m/z}$ to 5 $\mu\text{m/z}$, and the slope of specific shearing force is less than the slope of specific force for ploughing effect. The specific shearing force turns into almost constant with the feed speed larger than 5 $\mu\text{m/z}$. So, the increased specific cutting force is mainly caused by ploughing effect, especially for micro end mills with a blunt cutting edge roundness.

Fig. 12 The change of specific ploughing force and specific shearing force with the feed speed under various radii of cutting edge.

5. Conclusions

This study investigated the ploughing force in micro milling of soft-brittle crystals. A theoretical model is built to estimate the ploughing force. It can decompose the cutting force into shearing force and ploughing force components by following approach: A linear fitting for cutting forces at non-zero radii of cutting edge is carried out to get the cutting force at zero radius of cutting edge of tool, then the obtained truncate value is shearing force. The ploughing force has the same value to the total force subtracting above obtained truncate value. The ploughing force arises quickly with the growth of radius of cutting edge, and the shearing force is always larger than ploughing force helping to enhance the machined surface quality when radius of cutting edge is less than $2.8 \mu\text{m}$. A micro mill having sharp edge roundness is beneficial for the machining process in the micro end milling of a soft-brittle crystal. The increased specific force is mainly caused by the ploughing effect, especially for the micro end mill with large radius of cutting edge. Above results could explain how ploughing effect influence the micro milling process theoretically. A small feed speed would lead to high consumption of cutting energy and severe ploughing effect, while the heavy tool marks will be generated on the surface of work piece with the large feed speed which is in the end also leading to

poor machined surface quality. Therefore, a micro mill with small radius of cutting edge or a micro mill with large radius (under the condition that the feed speed is nearly equivalent to the radius) are both highly advised for micro milling of soft-brittle crystal. This result could be applied in micro milling of soft-brittle crystal. The theoretical model for estimation of ploughing force established in this paper has not including the brittle cutting mode. We have to eliminate the brittle cutting mode cases when we using this model. The theoretical model which can eliminate the brittle cutting mode automatically is highly encouraged in further studies.

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