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Effect of milling modes on surface integrity of KDP crystal processed by micro ball-end milling

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Abstract

Micro-milling has been widely considered as the most promising method to repair the micro-defects on the surface of KH_2PO_4 (KDP) crystal. However, achieving an ultra-smooth repaired surface by ball-end milling remains a longstanding challenge for KDP crystal due to its soft-brittle properties. In micro ball-end milling of KDP crystal, selection of milling mode is the prerequisite to determine the integrated combination of other cutting parameters (e.g. spindle speed, feed rate and the depth of cut). In this paper, with the aim to investigate the influences of the milling mode on the surface integrity of KDP brittle crystal, the micro-groove experiments were carried out comprehensively. All the milling modes were considered (pull-milling, push-milling, up-milling and down-milling) and corresponding cutting parameters selections were also examined. The results demonstrated that the pull-milling and down-milling are both conducive to ductile mode machining, while the push-milling and up-milling cause adverse impacts on the machined surface integrity. In addition, the optimal combination of cutting parameters were also recommended to guide the mitigation of micro-defects on the surface of KDP crystal by micro ball-end milling process.

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Keywords: Surface integrity; Milling modes; Micro ball-end milling; Ductile-mode machining; KDP crystal.

1. Introduction

KH_2PO_4 (KDP) crystal is currently the only available candidate for optical switching and frequency doubling in the laser-driven inertial confinement fusion (ICF) facilities because of its excellent nonlinear optical and electro-optical properties [1]. However, some micro-defects such as cracks, pits, laser damage spots would appear on the KDP surface during both the diamond ultra-precision machining and laser pre-irradiating processes [2]. These micro-defects would grow rapidly under the subsequent high-power laser irradiation and hence severely downgrade the optical performance and service life of KDP crystal components. Therefore, the most economical way is to repair the optical component by replacing those original defects with predesigned smooth contours in consideration of the time-consuming and costly process of crystal growth, which is termed as “optical recycle loop strategy” [3]. Compared with other machining methods, which include femtosecond laser ablation, CO_2 laser processing and washed etching, micro ball-end milling has been comprehensively deemed as the most promising method to repair the micro-defects on the surface of KDP crystal by Lawrence Livermore National Laboratory.

Owing to the soft and brittle properties of crystal, it is pretty easy to machine in brittle-mode and result in brittle fractures. With the aim to achieve a fracture-free surface, the factors, which play significant impacts on the ductile cutting of KDP crystal, have been extensive researched during the past years. Xiao [4] made the first attempt to investigate the brittle-ductile transition in micro flat milling of KDP crystal and proposed the theoretical model of calculating the critical chip thickness of brittle–ductile transition. Afterwards, Chen [5,6] explored the influence of geometrical parameters (e.g. rake angle, relief angle and cutting edge radius) of micro ball-end mills on the tensile stress and cutting force in the cutting process of KDP crystal, and then the specialized micro polycrystalline diamond ball-end mills were designed and fabricated by adopting these obtained optimal parameters.

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Besides, it was also found that size effect exerts a negative effect on the surfaced quality when the ratio of feed per tooth to cutting edge radius is less than 1 in micro ball-end milling process of KDP crystal by Chen and her colleagues [7]. However, these previous studies employed the same milling mode (pull-milling), ignoring other modes (push-milling, up-milling and down-milling). In the micro ball-end milling process, selection of milling mode is actually the prerequisite to determine the integrated combination of the other cutting parameters (e.g. spindle speed, feed rate and the depth of cut) [8,9].

In the interest of understanding of the relationship between the milling mode and surface integrity in milling process, considerable researches have been published during the past decades. Vakondios [10] employed regression analysis to investigate the impact of the milling strategy on the surface roughness of an Al7075-T6 alloy. Chen [11] reported that milling mode plays a critical role on the cutting speed when high speed milling of H13 die steels, causing various residual stresses on the machined surface, by geometrical analysis and experimental study. And a pushing milling mode with tool inclining in the feed direction, benefiting the machined surface quality, was recommended by Matras [12] to cutting 16MnCr5 with ball-end mill. However, these researches mainly concentrated on metal cutting at macro scale, and very few focused on the high speed milling of brittle material at micro scale. While Ono [13,14] and Foy [15] discussed the effect of tool inclination angle on the cutting regime transition in glass micro milling, the comprehensive comparison about the influence of various milling mode on the brittle-ductile transition in micro milling of brittle material has not been reported.

From the introduction above, we can see that the effect of tool inclination angle on the surface integrity in micro ball-end milling process has not been clearly understood yet. Especially, few attention has been paid on the cutting of KDP crystal with micro ball-end mills. In fact, these micro cracks and pits caused by improper selection of tool inclination angle would not only decrease the quality of repaired surface but also be more likely to induce local light intensification and potential laser damage of KDP crystal optics in ICF [2,16]. Thus, it is of great practical and theoretical significance to investigate the effect of tool inclination on the surface quality of KDP crystal that machined by the way of micro ball-end milling process.

In summary, this article aims at micro ball-end milling of KDP crystal, and studies the effect of tool mode and cutting parameters on the surface integrity of KDP crystal experimentally, so as to provide guidance for repairing the micro-defects on KDP optics in ductile-mode with micro ball-end mills in ICF.

2. **Experimental setup and procedure**

2.1 Milling mode in micro ball-end milling process

When repairing the micro defects on KDP crystal by replacing those original defects with predesigned smooth Gaussian contours, four typical types of milling modes engage in the cutting process generally, as shown in Fig. 1. It can be seen that the inclination direction of ball-end mill parallels to the feed direction or cross-feed direction. Meanwhile, the lead angle a and tilt angle β are the tool inclination angle along and perpendicular to the feed direction, respectively. If the lead angle a and tilt angle β are positive, the cutting processes are in pull-milling and downing-milling modes; If they are negative, the cutting processes are in push-milling and up-milling modes. In general, different milling modes could produce distinct impacts on the mechanical and thermal loads generated in the high speed milling process, eventually affecting the brittle-ductile transition and machined surface quality of KDP crystal.

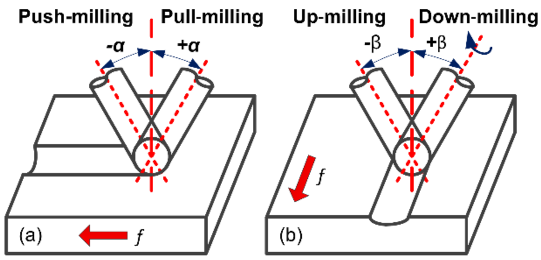

Fig. 1. Schematic diagram for various milling modes: (a) push-milling and pull-milling; (b) up-milling and down-milling.

All the micro groove experiments are performed on a homebuilt miniature five-axis vertical spindle machine tool, as shown in Fig.2. The high-speed motorized spindle utilized in this setup is the NAKANISHI's with the highest rotational speed of 80, 000 rpm. Besides, the spindle is attached to a rotating units adopting Akribis' with enough motion accuracy. Meanwhile, the feed motion of micro-milling system is provided using Parker company's linear motion units with 0.1 μm resolution and ±0.35 μm/10mm straight-line positional precision. In addition, the whole workstation is placed on a granite table to reduce the negative effect of vibration.

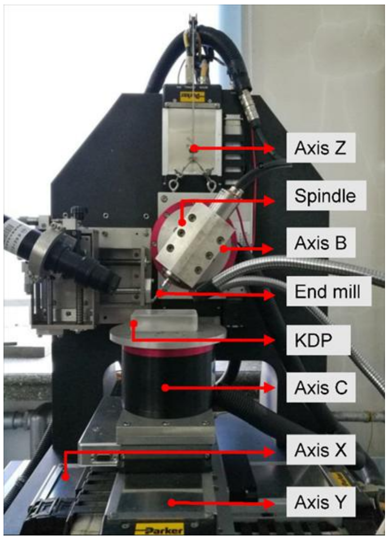

Fig. 2. Images of the homebuilt 5-axis vertical spindle machine tool.

The workpiece used in the experiments was a well fly-cut KDP crystal. A planar area (30 mm×25 mm) was firstly machined on the surface by flat end milling to ensure the same depths of the machined micro-grooves. The cubic boron nitride (CBN) micro ball-end mill with radius of 250 μm was employed in the cutting experiments. The micro milling tool possesses two cutting edges and is featured a helix angle of zero degree (SSBL 200, NS Tool).

In order to investigate the influence of milling modes on the surface integrity of micro-milled KDP crystal, the comprehensive micro groove experiments related to the above four types milling modes were carried out systematically. And the spindle speed as well as feed rate were also set as variable parameters. Table 1 presents the detailed cutting parameters. An ultra-depth 3D microscopy system (VHX 1000E, Keyence) was used to observed the morphology of machined grooves.

Table 1. Parameters of micro-groove milling experiment.

Milling parameters	Variation Range
Milling modes	pull-milling, push-milling, up-milling and down-milling
Spindle speed $n/\times10^4$rpm	0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5
Feed rate f/mm·min^{-1}	20, 40, 60, 80, 100, 120, 140, 160
Depth of cut a_p/μm	14
Tool inclination angle α/°	15

3. Results and discussions

3.1 Effect of milling modes on the machined surface integrity

In this section, the invariable cutting parameters were configured at spindle speed of 1 $\times10^4$ rpm and feed rate of 5 0 mm·min^{-1}. The lower spindle speed contributes to differentiate the effect of milling modes on the machined surface integrity. The morphologies of micro groove surface generated under different milling modes are shown in Fig. 3.

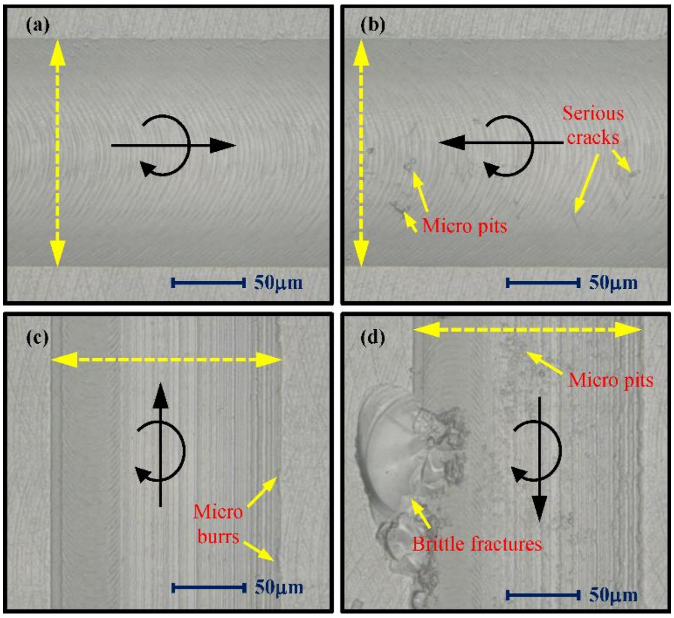

Fig. 3. Morphologies of micro groove surface for different milling modes: (a) pull-milling; (b) push-milling; (c) up-milling; (d) down-milling

Figure 3(a) depicts the micrograph of micro groove produced under pull-milling mode. It can be seen the almost fracture-free surface with regular tool marks appeared on the groove, demonstrating ductile cutting. The collected fan-shaped chips further proved the ductile mode machining has been obtained, as shown in Fig. 4. However, some distinct micro brittle pits as well as cracks could be observed on the groove machined under push-milling mode, as shown in Fig. 3(b). The reason is that the effective cutting speed of push-milling process is less than that of pulling-milling process [11]. As seen from Fig. 3(c), the groove machined by down-milling process was under ductile removal mode. These regular tracks parallel to the feed direction also indicated that the material was removed by plastic deformation rather than crack propagation. Some micro burrs appeared on the right edge groove were mainly due to the extrusion effect of high cutting speed cutting. When it comes to the groove machined under up-milling mode, micro pits at the bottom could be seen clearly in Fig. 3(d). In up-milling process, the undeformed chip thickness (UCT) usually starts from zero when the cutting edge contacts with the workpiece and increases with the rotation of ball-end mill. Thus, the UCT is definitely less than the minimum chip thickness required for chip formation at the beginning of the cut because of the size effect [7], and the material are removed by ploughing. Meanwhile, there were heavy brittle fracture on the left edge of groove. One potential reason is that the maximum UCT in the cutting process exceeds the critical chip thickness of brittle-ductile transition. That means brittle removal mode prevails and heavy fracture is likely to take place. One the other hand, the cutting speed on the left edge of groove is less than that on the right edge due to the speed gradient property and inclination of ball-end mill [11, 15]. Thus, it can be concluded that the pull-milling and down-milling modes are both conducive to ductile mode machining, while push-milling and up-milling modes cause adverse impacts on surface integrity of KDP crystal.

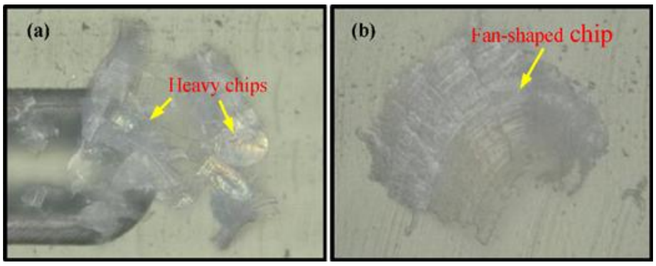

Fig. 4. Morphologies of chips for micro groove under pull-milling mode

3.2 Effect of feed rate on the machined surface integrity

In this section, the experimental results related to feed rate are discussed. The feed rate was set from 20 to 160 mm·min^{-1} in the step of 20 mm·min^{-1} with constant spindle speed as 1×10^4 rpm.

The morphologies of micro groove surface machined by pull-milling process at various feed rate are shown in Fig. 5. It can be found that the micro groove machined at feed rate of 10 mm·min^{-1} was approximately under ductile removal mode from Fig. 5 (a). But there were many micro pits on the entry region. This is because the feed rate is too small, causing the UCT below than the minimum chip thickness of forming chips, and eventually result in the appearance of ploughing effect. When the feed rate rose at 30 mm·min^{-1}, the machined groove possessed clear and regular tool marks (Fig. 5 (b)), which means the cutting process was completely in ductile cutting. Fig. 5 (c) shows the groove produced at the feed rate of 80 mm·min^{-1}. A slight of brittle fracture occurred on the exit edge of groove. The reason for this phenomenon was that the UCT exceed the critical chip thickness of brittle-ductile transition. Along with the rotation of ball-end mill, the workpiece material being processed would accumulate and enlarge the actually cutting thickness, causing the formation of brittle fracture [6]. Meanwhile, the cutting edge usually disengages from the workpiece to air at the end of the cut. Therefore, the tensile stress was introduced and made the cracks incline to propagate into the neighboring material consequently. With the feed rate arriving at 140 mm·min^{-1}, both the number and size of brittle fracture soared, as shown in Fig. 5 (d). The excessive feed rate accounted for this phenomenon.

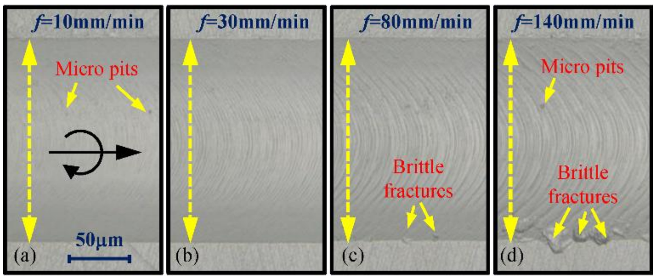

Fig. 5. Morphologies of micro groove surface machined at various feed rate under pull-milling mode

Figure 6 shows the morphologies of micro groove machined by push-milling process at various feed rate. It can be seen that

the fracture-free surface was achieved for the groove machined at feed rate of 10 mm·min^{-1} from Fig. 6(a) . Some piled chips appeared along the entry edge due to the extrusion effect at the beginning cutting stages [5]. When the feed rate increased at 30 mm·min^{-1}, the tool marks ,which were clearly visible, indicated the cutting process was also under ductile removal mode, as shown in Fig. 6(b). But some slight cracks appeared on the bottom of the groove because of the high UCT. Fig. 6 (c) and (d) displayed the micro groove machined at the feed rate at 80 mm·min^{-1} and 140 mm·min^{-1} , respectively. These grooves witnessed an upward trend of brittle fractures with large size along the exit edge of the groove. At the same time, more cracks appeared on the bottom of the groove, whose size and density also increased with the feed rate. In addition, micro pits near the entry edge of groove revealed the same characteristic as these cracks in term of their size and density when the feed rate increased.

It can be concluded that the surface machined under push-milling mode at the same feed rate possessed more defects compared with that machined under pull-milling mode. This is mainly because the UCT under this case is larger than that under pull-milling mode when keeping all cutting parameters at same value [4]. Besides, inclining ball-end mill opposite to the feed direction (push-milling mode) would generate smaller effective cutting speed than that parallel to the feed direction (pull-milling mode). In general, higher cutting speed is beneficial for the ductile removal of material due to the thermal soften effect [15]. Therefore, the excessive UCT and smaller cutting speed in push-milling process jointly resulted in a relatively poor surface integrity.

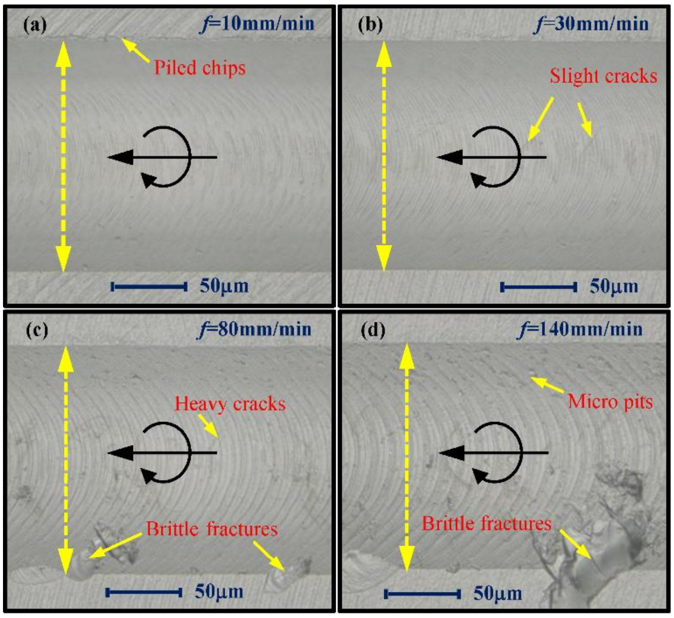

Fig. 6. Morphologies of micro groove surface machined at various feed rate under push-milling mode

The morphologies of micro groove machined by down-milling process at various feed rate were presented in Fig. 7. It can be seen that the micro groove machined with the feed rate at 10 mm·min^{-1} possessed a fracture-free surface, as shown in Fig. 7 (a). The clear tracks parallel to the cutting edge profile were visible though a slight of micro burrs occurred on the right edge of machined groove. Meanwhile, Fig. 7 (b) displays that the machined groove at feed rate of 30 mm·min^{-1}, which was approximately under ductile removal mode. And with the increase of feed rate, micro burrs on the groove have decreased. When the feed rate reached at 80 mm·min^{-1}, a great deal of cracks begun to appear near the left edge of machined groove, as shown in Fig. 7 (c). The reason is that the lower cutting speed resulted in the crack propagation [4]. From Fig. 7 (d), for feed rate of 140 mm·min^{-1}, serious cracks occurred on the left side of machined groove. The excessive feed rate as well as the UCT could be used for explaining this phenomenon. Overall, although down-milling process usually creates some micro cracks and burrs on the machined surface, it does not result in severe brittle fracture. At the same time, selecting the appropriate feed rate could contribute to prevent cracks.

Figure 8 shows the morphologies of micro groove machined by up-milling process at various feed rate. From Fig. 8(a), the surface machined at feed rate of 10 mm·min^{-1} had a great deal of micro brittle pits on it, indicating that the cutting process was almost in brittle removal mode. This is because the material in the cutting area was under severe ploughing effect, which cause the cutting edge to rub over the groove surface rather than removing the material with chips on every tool pass [6,7]. When the feed rate reached 30 mm·min^{-1}, many brittle fracture were presented near the left edge of machined groove, as shown in Fig. 8 (b). The reason is that the part of cutting edge engaged in the left edge of groove is near the tool tip of ball-end mill and so possesses lower cutting speed, which is against the ductile removal mode. In addition, a noticeable trend was observed as the size and amount of brittle fracture went up gradually on the left edge of machined groove from Fig. 8 (c) and Fig. 8 (d). As mentioned above, this change was attributed to the increase of feed rate, resulting in the formation and propagation of brittle fracture quickly.

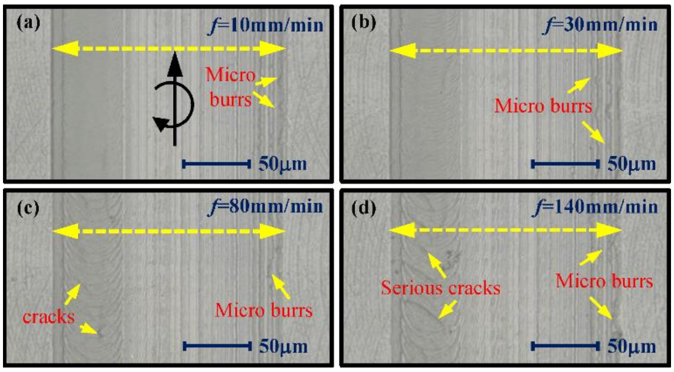

Fig. 7. Morphologies of micro groove surface at various feed rate under down-milling process

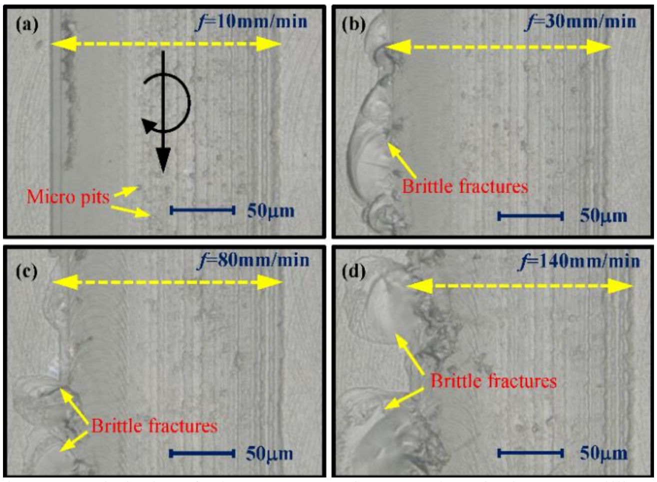

Fig. 8. Morphologies of micro groove surface at various feed rate up-milling process

It is clear that selecting an appropriate combination of feed rate and milling mode exerts a critical impact on achieving ductile removal. The pull-milling and down-milling mode with the feed rate of 30 mm·min^{-1} were recommended for fracture-free machining of KDP crystal by micro ball-end milling process.

3.3 Effect of spindle speed on the machined surface integrity

To investigate the effect of spindle speed on the machined surface integrity, several micro groove experiments with the spindle speed various from 0.5×10^4 to 5.5×10^4 rpm, sharing the same feed rate of 30 mm·min^{-1} were carried out.

The morphologies of micro groove surface machined at various spindle speed are shown in Fig. 9. From Fig. 9 (a), it can be seen that although the regular tool marks were clearly visible on the surface, plenty of brittle fractures appeared on the exit edge of machined groove, demonstrating that the pulling-milling process with the spindle of 0.5×10^4 rpm is usually under brittle removal mode. With the increase of spindle speed (1.5×10^4 rpm), the amount of brittle fracture decreased gradually but there was a slight of micro brittle fractures left on the bottom of machined groove, as shown in Fig. 9 (b). Meanwhile, micro pits were also occurred near the entry edge due to the ploughing effect [7]. According to the Fig. 9 (c) and (d), for spindle speed of 3×10^4 rpm and 5×10^4 rpm, the surface integrity improved obviously, and there was no distinguished brittle fracture on them. While some micro pits still existed on the surfaces, the number of them do not change as the spindle speed increases. Thus, the spindle speed of 3×10^4 rpm could be considered as the critical spindle speed of brittle-ductile transition, which is same as that in flat-milling of KDP crystal [4]. In addition, some piled chips occurred on the entry edge of machined groove because of the extrusion effect of cutting edge.

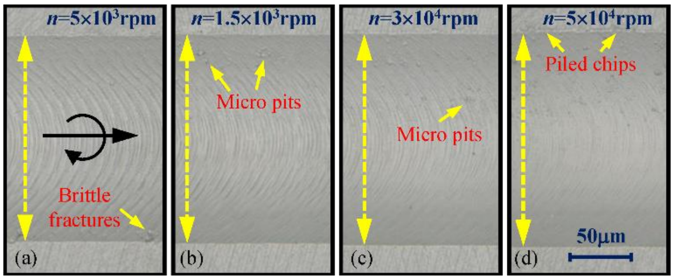

Fig. 9. Morphologies of micro groove surface at different spindle speeds of pull-milling mode.

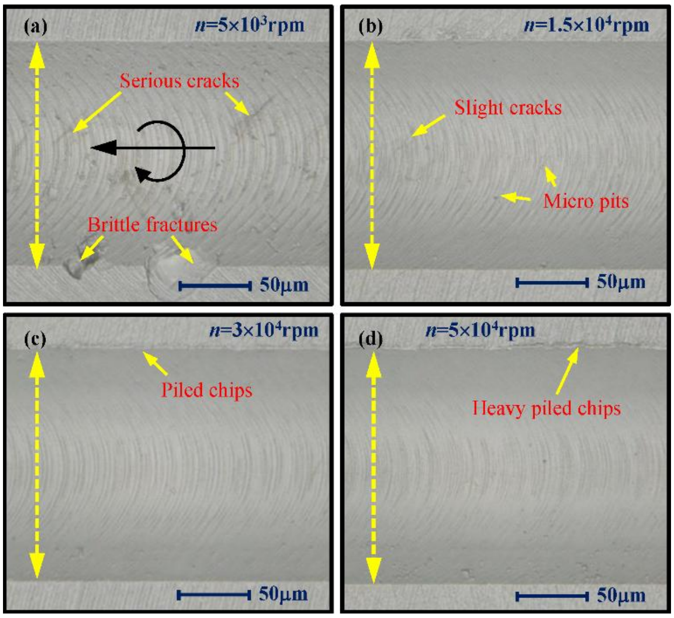

Fig.10. Morphologies of micro groove surface at different spindle speeds of push-milling

Figure 10 shows the morphologies of micro groove machined by down-milling process at various spindle speed. From Fig. 10 (a), a rough surface with serious cracks could be observed on the bottom of surface machined at spindle of 0.5×10^4 rpm, indicating the cutting process was in brittle cutting. Meanwhile, some brittle fractures occurred near the exit edge. When spindle speed arrived at 1.5×10^4 rpm, some slight cracks still remained on the groove base but their dimensions reduced significantly, as shown in Fig. 10 (b). Along with the rise of spindle speed, the surface quality saw a deceasing trend of cracks, and a fracture-free surface could be seen on the groove machined at the spindle speed of 3×10^4 rpm from Fig. 10 (c). Afterward, the surface quality displayed the constant stability with the rise of spindle speed. But heavy piled chips appeared on the entry edge due to the extrusion effect of high cutting speed (Fig. 10 (d)) [6]. Thus, it can be concluded that increasing the spindle speed can enhance the surface integrity machined by push-milling mode, and the excessive spindle speed could cause material pile up. Thus, the spindle speed need be selected appropriately.

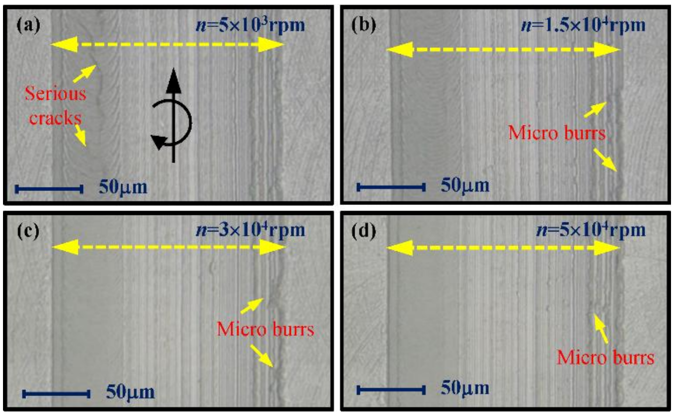

Fig.11. Morphologies of micro groove surface at different spindle speeds of down-milling

The morphologies of micro groove machined by down-milling process at various spindle speed were shown in Fig. 11. There were plenty of serious cracks on the surface machined at spindle speed of 0.5×10^4 rpm, as shown in Fig. 11 (a). However, with the spindle speed increasing at 1.5×10^4 rpm, some micro burrs appeared on the right edge of groove while cracks disappeared on the left edge according to the Fig. 11 (b). When spindle speed arrived at 3×10^4 rpm, the surface integrity became perfect with no cracks, as shown in Fig. 11 (c). And the amount of micro burrs also reduced gradually. When it comes to the groove machined at spindle speed of 5×10^4 rpm, the discernible tracks could be observed clearly on it parallel to the feed direction, indicating the surface was generated under ductile removal mode.

Figure 12 shows the morphologies of micro groove machined by up-milling process at various spindle speed. It can be seen that a totally rough surface filled with brittle fractures and micro pits was produced on the groove machined at feed rate of 10 mm·min^{-1} from Fig. 12 (a). But with the rise of spindle speed (1.5×10^4 rpm), the effective cutting speed also increased, making the size and amount of brittle fracture decrease quickly [4], as shown in Fig. 12 (b). When the spindle speed arrived at 3×10^4 rpm and 5×10^4 rpm, respectively, the micro pits could be found anywhere on the groove surface though brittle fracture disappeared from Fig 12. (c) and (d). That is to say, the cutting process under up-milling mode is always in brittle cutting and corresponding machined surface integrity has nothing to do with spindle speed.

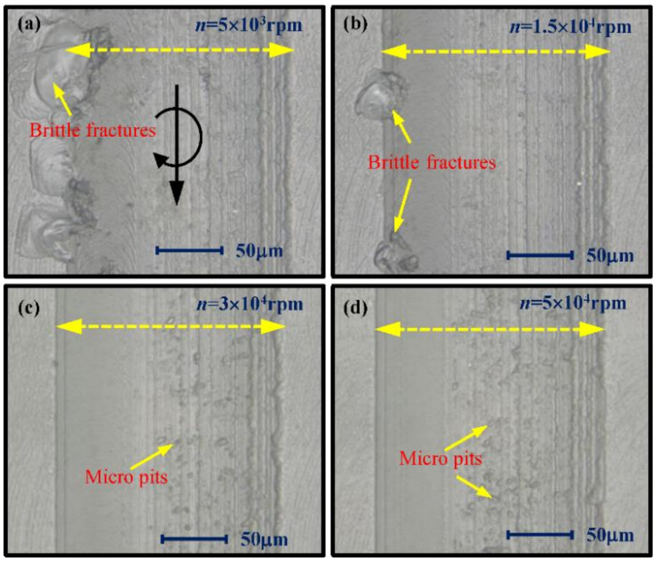

Fig.12. Morphologies of micro groove surface at different spindle speeds of up-milling

4. Conclusion

It has been illustrated in this study that the milling mode can have significant influence the surface integrity of KDP crystal processed by micro ball-end milling. The results demonstrate that pull-milling and down-milling are both beneficial for ductile mode machining of KDP crystal, while the push-milling and up-milling cause negative effects on producing a fracture-free surface on KDP crystal. In addition, the optimal combination of cutting parameters (feed rate: 30 mm·min^{-1}, spindle speed: 3×10^4 rpm) could be used to provide cutting parameters reference for the mitigation of micro surface-defects on KDP crystal by micro ball-end milling process.

Acknowledgements

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