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An investigation on laser-induced damage resistance of KDP optics repaired by different micro-milling strategies

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Abstract

Although micro-milling has been regarded as the most promising method to repair the micro-defects on KH_2PO_4 (KDP) optics surfaces, residual tool marks are inevitably generated on the repaired surfaces and would pose a direct impact on the laser-induced damage (LID) threshold of repaired KDP optics. In this work, a residual tool marks model was developed to characterize the repaired surface morphologies processed by different milling strategies (e.g. layer-milling and spiral-milling strategies). Then the predicted tool marks were utilized to built a light-filed intensity modulation model to reveal the relationship between the residual tool marks and its related optical performance. The practical of LID tests well verified the simulation results. It was revealed that the milling strategies indeed have a significant influence on the ultimate LID resistance of KDP optics after repair through impacting the generation of residual tool marks. The spiral-milling method with a smaller path interval can produce a laser-friendly repaired surfaces, which have a equivalent laser-induced resistance with the original fly cutitng surface, while the layer-milling method has a higher machining efficiency. Therefore, an optimized repair procedure, adopting layer-milling path as rough milling and spiral-milling as fine milling, was proposed for pratical engineering application in ICF facilities in the future.

Keywords: micro ball-end milling, tool marks, milling strategy, laser induced damage threshold

1. Introduction

Micro-milling has been identified as the most promising approach to repair the surface defects on the large-aperture KH_2PO_4 (KDP) optics, which are the currently the unique candidate in the laser-driven inertial confinement fusion (ICF) facilities [1]. But in practical micro-milling processes, residual tool marks are inevitable generated on the repaired surfaces, which would pose a significant impact on deteriorating the laser-induced damage (LID) threshold of repaired KDP optics.

Recently, layer-milling and spiral-milling strategies have been attempted to improve the repaire efficiency and surface qualities [2]. But few attention has been paid to reveal the effect of the residual tool marks induced by different milling strategies on the practical LID resistance of repaired KDP optics.

In light of this, this work aim to investigate the effect of milling strategies on the LID resistance of repaired KDP optics. Firstly, a residual tool marks model was built. Then, light-field intensification induced by tool marks were performed based on FEM. Finally an optimized milling strategy was proposed to acquire the laser-friendly repaired surface morphologies.

2. Repaired surface profile model

In this study, layer-milling and spiral-milling strategies were used to repair the KDP optics. The essential difference between these two kinds of milling strategies is the trajectory of the cutter in milling process [2]. In the layer-milling process, the damaged material is normally removed by layer-by-layer with a path interval of 40 μm, while in the spiral-milling process the cutter can fabricate the predesigned contours along a spiral trajectory with a constant path interval, ranging from 5 μm to 30 μm in a step of 5 μm, as shown in Fig.1(a). The generation of tool marks is the result of the geometric tool-workpiece intersection between successive cutting paths in the dynamic milling process [3]. Thus, a shaded area ABC, named residual tool mark, will be inevitable left on the machined surface after successive cutter passes (see in Fig.1(b)).

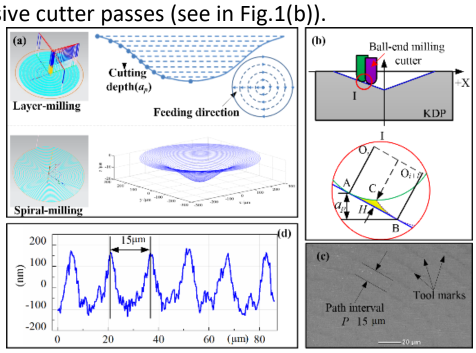

Fig. 1. (a)The schematics of layer-milling and spiral-milling strategies [2]; (b) the generation mechanism of residual tool marks; the surface morphology (c) and cross-sectional profiles (d) of spiral-milled contous with a path interval of 15 μm.

Fig.1(c) displays the surface topography of one practical repaired conical contour as weel as the generated residual tool marks. It can be seen that residual tool marks on repaired surfaces are clearly visible and mainly distribute perpendicular with the feed direction. The section profiles presented in Fig. 1(d), verifies that residual height of these tool marks are about several hundred nanometers, which is very close to the working laser wavelength in ICF facilities, indicating that the residual tool marks would play a non-negligible impact on the surface quality and the ultimate optical performance of repaired KDP optics

Therefore, a theoretical model based on homogeneous matrix transformation (HMT) was proposed to predict the conical repaire contours using different milling strategies. Fig.2(a) displays the simulated profiles of residual tool marks at the bottom of conical contours (width: 800 μm × height: 20 μm), which were processed by layer-milling and spiral-milling, respectively. It can be seen that the fluctuations of residual tool marks on the spiral-milled surface is slight than of layer-milled surfaces. Thus, the spiral-milling process has a more powerful ability than layer-milling to produce more slightly tool marks with lower residual height. Moreover, it is worthy to note that there is an obvious residual pit left on the center of layer-milled contour bottom. This residual pit have a very larger residual height and may play a detrimental effect on the optical performance of repaired optics. By calculating the surface roughness and residual height of simulated contours, it was found the the simulated results are consistent well with the experimental results, as illustrated on Fig. 2(a) and (d), validating the accuracy of the proposed model.

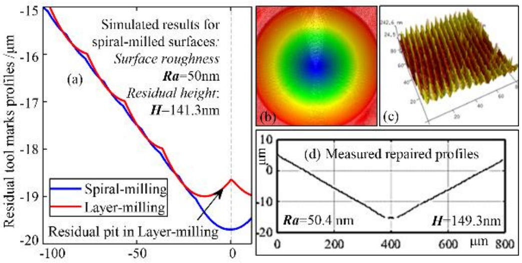

Fig. 2. (a) The predicted residual tool marks by spiral-milling and layer-milling methods; (b-d) the measured results of spiral-milled surfaces.

3. Light-field intensification simulation

Once the simulated profiles of residual tool marks are obtained, a finite element model can be built to calculate the light-field intensity modulation inside the micro-milled KDP optics, which adopted these predicted residual tool marks.

A time-harmonic plane electromagnetic wave with transverse electric (TE) model was adopted as the incident laser and its electric field intensity was normalized as 1V/m. Because the light intensity is proportional to the square of electrical field, therefore, the light-field intensification induced by different tool marks can be calculated by solving Maxwell equation with FEM method. Meanwhile, a maximum relative light intensity modulation (IR_{max}) can be introduced to characterize the laser damage resistance of repaired optics with various tool marks:

$$I_{R\max} = \frac{I_{\max}}{I_0} \quad (1)$$

where I_0 is the ideal light intensity inside the original KDP crystal without any tool marks, and I_{max} is the maximum light intensity in the case of modulation by tool marks. Note the larger I_{Rmax} is, the more probably to induce laser damage the optics are.

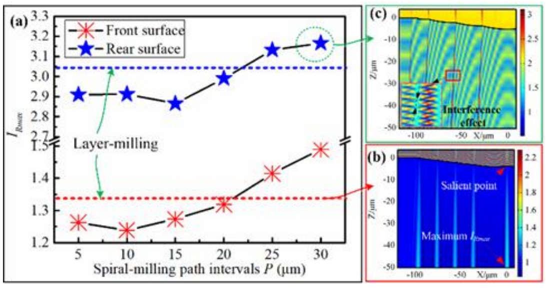

Fig.4 (a) The simulated I_{Rmax} induced by layer-milled and spiral-milled tool marks, and the relared light-field distribution.

Fig.4 shows the evolution of I_{Rmax} induced by different tool marks with respect to various path intervals on front- and rear-surfaces of micro-milled KDP optics, respectively. It was found that the residual tool marks indeed can cause significant diffraction effect inside the repaired KDP optics, giving rise of a stronger light-field intensification. And owing to interference effect, the I_{Rmax} on rear-surface is always higher than that on front surface. Besides, no matter for front- or rear-surfaces, the I_{Rmax} always keeps a similar pace with the increase of path intervals used in spiral-milling process. Moreover, it is interesting to find that spiral-milled tool marks can have a weaker effect in the light-field intensification if adopting a small path interval (< 20 μm), compared with layer-milled tool marks.

4. Laser damage tests

To better understand the role of residual tool marks in the LID resistance of repaired optics, a series of laser damage tests were performed on the spiral-milling and layer-milling repaired KDP optics as well as the original flycutting surfaces. The detailed information about the laser damage test system and the laser parameters can be found in Ref.[4]. And the measured LID threshold for different samples as well as the typical LID surface morphologies were presented in Fig. 5.

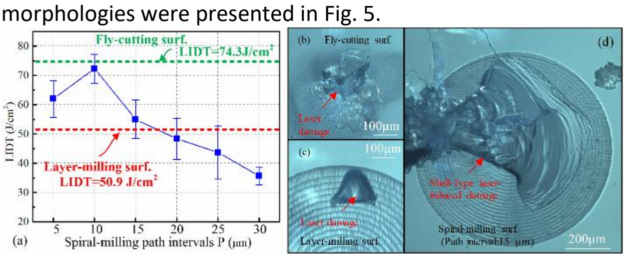

Fig.5 (a) The measured LID threshold for flycutting, spiral-milling and layer-milling KDP optics, and (b) the tupical morphologie of laser damage.

One can see that the spiral-milling could produce a better laser-friendly surfaces for repaired KDP optics than layer-milling strategy. For instance, only shell-type damage came into being on spiral-milled surfaces, the occurrence of which has been identified to associate with higher laser fluence. Moreover, the spiral-milled surfaces with 10 μm path interval have a very close LID threshold with the original flycutting surfaces. Therefore, spiral-milling with a path interval of 10 μm is strongly suggested as the fine milling procedure to improve the LID resistance of KDP optics after faster rough machining by layer-milling method.

5. Conclusion

By simulating the light-field intensification induced by different residual tool marks, it is revealed that whether the spiral-milling is better than layer-milling or not for the optical performance of repaired KDP optics is dependent on the path interval used in the spiral-milling process. And the practical laser damage tests show that, compared with layer-milled surfaces, the spiral-milled surfaces with a path interval of 10 μm have a higher LID threshold, similar with that of original fly cutting surfaces.Therefore, adopting layer-milling path as rough milling and spiral-milling as fine milling was proposed as an optimized strategy for the future engineering repair of KDP optics in ICF facilities.

Acknowledgments

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