Optimization of scanning path under ion beam cleaning process based on thermal effect

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Abstract. Ion beam figuring (IBF) is an advanced machining technology for high precise optical component. For brittle materials with high thermal expansion coefficient such as KDP crystal, thermal effect is an intractable problem due to the accumulative heat introduced by incident ions on optical surface. Asymmetrical heating induces rapid changes of thermal stress and once the thermal stress exceeds the mechanical strength, the component may crack or break. In this paper, the number of scanning rows was factorized to various combinations with times of scanning and the number of moving rows. Temperature field and thermal stress of each combination were simulated using finite element analysis software ANSYS. Comparing with the results, the much better combination was found. With optimized scanning path, peak of thermal stress is lower than that of traditional scanning path. Especially, peak of tensile stress on X-distance and Y-distance were reduced obviously. At last, a law for optimization was established: when times of scanning and the number of scanning rows are equal or approximately equal, the thermal stress appears lower.

1. Introduction

Ion beam figuring (IBF) is an advanced machining technology for high precise optical component. It is utilizing a beam of low-energy ions to directly bombard target substrate in vacuum and raster-scan target surface in order to remove the material [1-3]. However, during IBF process, kinetic energy of incidence ions transfers to substrate atoms by collision in the vacuum environment and most energy deposited on optics as heat, increasing the temperature of optics. For brittle materials with material properties of softness, brittleness, high thermal expansion coefficient such as KDP crystal, thermal effect is an intractable problem due to the accumulative heat introduced by incident ions on optical surface [4]. Asymmetrical heating induces rapid changes of thermal stress and once the thermal stress exceeds the mechanical strength, the component may crack or break [5-7]. the IBF has been using to cleaning the iron powders embedded into the soft surface of KDP crystal in MRF process and enhancing the laser-induced damage resistance [8-10]. to lower thermal effect is of vital importance in ion beam cleaning.

Precedingly, our team researched the model of energy deposited and temperature field on optics under ion beam bombardment and optimized the technological parameters [11-13]. In this paper, the method of stepping over adjacent paths is applied to optimize the moving paths of ion beam. The number of scanning rows was factorized to various combinations with times of scanning and the number of moving rows. Temperature field and thermal stress of each combination were simulated
using finite element analysis software ANSYS. Comparing with the results, the much better combination was found and a law for optimization was established.

2. Ion beam cleaning procession

As shown in Fig. 1, an ion beam bombards the center of the optical component along the Z direction. The beam current distribution on an optical surface obtained Gaussian distribution. IBF is aimed at cleaning iron powder embedded from MRF by removing the contaminative layer with uniform depth. Ion beam directly bombards toward KDP surface in vacuum by raster-scanning the surface with a constant velocity. As shown in Fig. 2, ion beam continuously moves in uniform speed in X direction, while moving spasmodically and fleetly in Y direction.

3. Scanning path optimization method

The number of scanning rows is signed as \( n \). if \( n \) is a composite number, it can be factorized to various combinations. For example, \( n=20 \), it can be factorized to combinations of 1×20, 2×10, 4×5, 5×4, 10×2 and 20×1. In ion beam cleaning, the number before multiple sign means times of scanning, while the number after multiple sign means numbers of scanning rows. So, scanning paths of 2×10, 4×5, 5×4, 10×2 combination is shown in Fig. 3. And 1×20 is the same as 20×1, shown in Fig. 2.

Figure 1. Sketch map of ion beam bombardment

Figure 2. Scanning path of ion beam cleaning

Figure 3. Various combinations of scanning paths: (a) 2×10; (b) 4×5; (c) 5×4; (d) 10×2
4. Results and discussions

Sizes of KDP crystal is 100×100×10mm. Assume incidence ion energy $\epsilon = 600$ eV Ar$^+$ ion, peak of beam current density $J = 3.12$ mA/cm$^{-2}$, beam current distributing parameter $\sigma = 9$ mm. For KDP crystal, with thermal physical properties of optical components shown in Table 1, the power of a thermal source simulated by TRIM progress is

$$P = 14256 \exp \left( -\frac{x^2 + y^2}{2 \times 0.009^2} \right)$$

4.1. Thermal effect under ion beam cleaning

Fig. 4 shows the temperature field simulated using finite element analysis software ANSYS (APDL) during ion beam cleaning process with scanning path shown in Fig. 2. Peaks of temperature and thermal stress during ion beam cleaning are shown in Fig. 5 and Fig.6, respectively.
4.2. Peak of temperature

Fig. 7 shows the curves of peak temperature on KDP crystal surface with scanning paths of 1×20 (20×1), 2×10, 4×5, 5×4 and 10×2. Serial arrangement is 1×20 (20×1) > 10×2 > 5×4 > 4×5 > 2×10, based on peak temperature ranking from high to low. The law is: numbers before multiple sign rank from large to small, numbers after multiple sign rank from small to large. Sign the moving time of ion beam from left to right is t. For 2×10 combination, time interval between the adjacent path is 9t, while it is 4t, 3t, 1t and 0t for 4×5, 5×4, 10×2 and 20×1 (1×20), respectively. The longer of time interval between the adjacent paths, the lower of peak temperature is. Longer time interval is benefit to reduce the superimposed effect of temperature field.

![Figure 7. Curves of peak temperature](image)

4.3. Peak of thermal stress

Fig. 8 shows curves of peak tensile stress on KDP crystal with scanning path combinations of 1×20 (20×1), 2×10, 4×5, 5×4 and 10×2 combination. Serial arrangement is 1×20 (20×1) > 2×10 > 10×2 > 5×4 > 4×5, based on peak tensile stress on X-distance ranking from high to low. It reduces 44.7% from 11.3MPa of 1×20 (20×1) to 6.25MPa of 5×4. Serial arrangement is 10×2 > 1×20 (20×1) > 2×10 > 5×4 > 4×5, based on peak tensile stress on Y-distance ranking from high to low. It reduces 32.2% from 14.3MPa of 10×2 to 9.7MPa of 4×5. And Serial arrangement is 10×2 > 1×20 (20×1) > 2×10 > 5×4 > 4×5, based on peak tensile stress on X-distance ranking from high to low. It reduces 2.5% from 7.72MPa of 10×2 to 6.25MPa of 4×5. Scanning path such as 4×5 and 5×4 combination is benefit to reduce peak tensile stress on X-distance and Y-distance obviously.

Fig. 9 shows curves of peak compressive stress on KDP crystal with scanning path combinations of 1×20 (20×1), 2×10, 4×5, 5×4 and 10×2 combination. Serial arrangement is 1×20 (20×1) > 2×10 > 10×2 > 5×4 > 4×5, based on peak compressive stress on X-distance ranking from high to low. It reduces 5.2% from -44.25MPa of 10×2 to -41.96MPa of 4×5. Serial arrangement is 1×20 (20×1) > 2×10 > 10×2 > 5×4 > 4×5, based on peak compressive stress on Y-distance ranking from high to low. It reduces 6.7% from -41.77MPa of 1×20 (20×1) to -38.98MPa of 4×5. And Serial arrangement is 1×20 (20×1) > 2×10 > 10×2 > 5×4 > 4×5, based on peak compressive stress on X-distance ranking from high to low. It reduces 4.05% from -26.59MPa of 1×20 (20×1) to -25.5MPa of 4×5. Scanning path such as 4×5 and 5×4 combination is benefit to reduce peak compressive stress.

So, for thermal stress, the better scanning path is 5×4 or 4×5 combination. That is to say: when times of scanning and the number of scanning rows are equal or approximately equal, the thermal stress appears lower. Resemble as “Product must be, the sum of two equal numbers is minimum” in Mathematics.

If the number of scanning rows \( n \) is a prime number, it will round up to a composite number \( n' \). And the composite number \( n' \) can be factorized to a combination with two approximately equal numbers. For example, if \( n = 13 \), then \( n' = 16 \), which can be factorized to 4×4; if \( n = 71 \), then \( n' = 72 \), which can be factorized to 8×9.
Figure 8. Curves of peak tensile stress: (a) X-distance; (b) Y-distance; (c) Z-distance.

Figure 9. Curves of peak compressive stress: (a) X-distance; (b) Y-distance; (c) Z-distance.
5. Conclusion

To reduce the thermal effect during ion beam cleaning, the number of scanning rows was factorized to various combinations with times of scanning and the number of moving rows. Temperature field and thermal stress of each combination were simulated using finite element analysis software ANSYS. Comparing with the results, the much better combination was found. With optimized scanning path, peak of thermal stress is lower than that of traditional scanning path. Especially, peak of tensile stress on X-distance and Y-distance were reduced obviously. At last, a law for optimization was established: when times of scanning and the number of scanning rows are equal or approximately equal, the thermal stress appears lower.

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