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Optimum removal in ion-beam figuring

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ABSTRACT

In an ion-beam figuring (IBF) process, the desired material removal, which is specified to the contour algorithm to calculate dwell time, decides the calculated process time and the resulted residual surface figure error. Usually, an IBF process with more removal consumes a longer process time, although the resulted residual error is smaller, whereas an IBF process with less removal needs only a shorter process time, but the resulted residual error is greater. Therefore, in order to balance the process time and the residual error, an optimum removal should be determined. In this study, the characteristic relationship between the process time and the residual error on different specified removals is investigated first. The investigation shows that for smaller removals, the residual error decreases rapidly while the process time increases slowly, and for larger removals, the process time increases rapidly without much decrease in residual error. This characteristic makes the figure-prediction curve (process times vs. rediual errors (RMS)) often in the shape of the letter "L". Therefore, the optimum removal can be determined at the corner of the curve. Finaly, experiments are performed to verify the proposed method.

1. Introduction

Ion-beam figuring (IBF) process is usually used in the final figuring of precision optics. In the process a beam of energetic ions are directly impacted toward a target substrate in a predictable and controlled way, and the surface material are selectively sputtered and removed in molecular units. The typical material removal rates range from several decades to several hundreds of nanometers per minute according to the specific process parameters. Owing to its characteristically noncontacting way to remove material, problems associated with tool wear and edge effects, which are common in conventional machining processes, are avoided. Additionally, since the substrate is not clamped during the figuring process, there is no postmachining workpiece distortion resulting from the relaxation of clamping stresses [1]. IBF has been demonstrated an effective process to machine both large [2,3] and small [1,4] precision optics.

The amount of the material removed in an IBF process is a convolution of the ion-beam shape (which is defined as beam function [4] or influence function [5]) and an ion-beam dwell function, defined over a two-dimensional area of interest. Therefore, determination of the beam dwell function from a desired material removal and a known beam function is a deconvolution process. Algorithms used in this process are known as contour algorithms, such as Fourier algorithm [6], iterative algorithm [3], matrix algebraic algorithm [7,8] and series expansion algorithm [1,4].

The first step of a contour algorithm is to determine the desired material removal, which decides the calculated dwell function and the resulted residual surface figure error. Usually, in a contour algorithm process, for a given initial surface figure error, if a less desired material removal is specified, the calculated dwell function is consequently small, which means a short process time, but as a result, the residual surface figure error is great. If a larger desired material removal is specified, although the resulted residual figure error is smaller, the calculated dwell function is greater, which means a longer process time.

Therefore, in order to balance the process time, which is determined by the dwell function, and the resulted residual error, the desired material removal specified to the contour algorithms should be considered and optimized. However, there is no literature dedicated to this issue, although the contour algorithms have been thoroughly investigated. In this study, efforts have been made to determine an optimum removal. The conventional method to determine the removal is discussed first, and then a new method is proposed to determine an optimum removal.

2. Conventional method

Since the real removal in an IBF process is always nonnegative, the specified removal should be nonnegative too. However, the data of a surface figure error from metrology usually contain negative elements. Therefore, in order to obtain a nonnegative removal, the error data is simply offset to be nonnegative in the conventional

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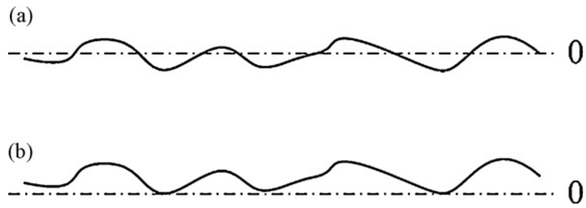

Fig. 1. Illustration of conventional method to determine specified removal. (a) Error profile from metrology; (b) determined specified removal R ($R \geq 0$).

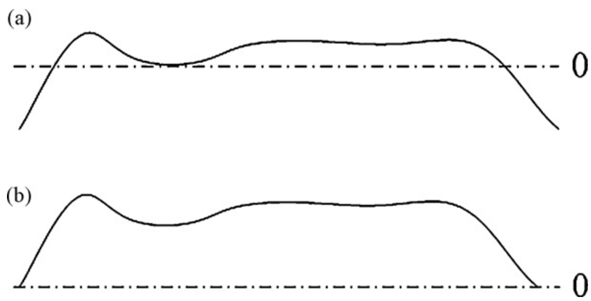

Fig. 2. Calculated result of error profile with edge fall. (a) Error profile from metrology; (b) determined specified removal R ($R \geq 0$).

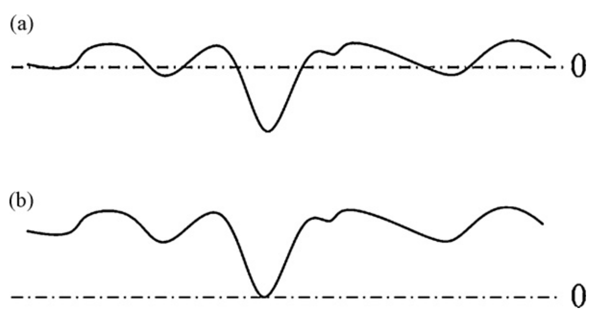

Fig. 3. Calculated result of error profile with pits. (a) Error profile from metrology; (b) determined specified removal R ($R \geq 0$).

method.

$$R = E - \min(E), \tag{1}$$

where R represents the desired material removal and E represents the surface figure error, $\min(E)$ is the minimum of E. This method is illustrated in Fig. 1. Due to the original surface figure error from metrology inevitably contain noises, E should be smoothed to reduce the influence of noises on the magnitude of $\min(E)$ before using in Eq. (1). For a smoothed figure error, the removal determined by Eq. (1) is reasonable.

However, for ultra-precision optics, in order to keep more details or higher spatial frequency information about the figure error, the original figure error from metrology is often used instead of the smoothed figure error. For original errors, since they contain more noises, and more edge-fall and pits, as shown in Figs. 2 and 3, the removals determined by Eq. (1) are not reasonable and tend to be greater, consequently causing longer process time.

3. Optimization method

In the conventional method of Eq. (1), the removal is the sum of the figure error and an invariable uniform removal. In our new method, to determine the removal flexibly, an adjustable uniform removal U is introduced to substitute the invariable $[-\min(E)]$.

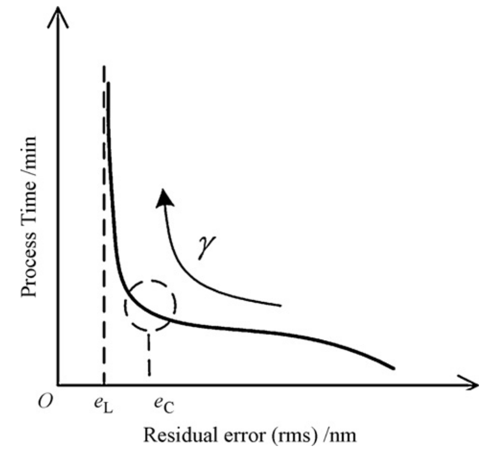

Fig. 4. Typical figure-prediction curve (process time vs. RMS value of residual figure error).

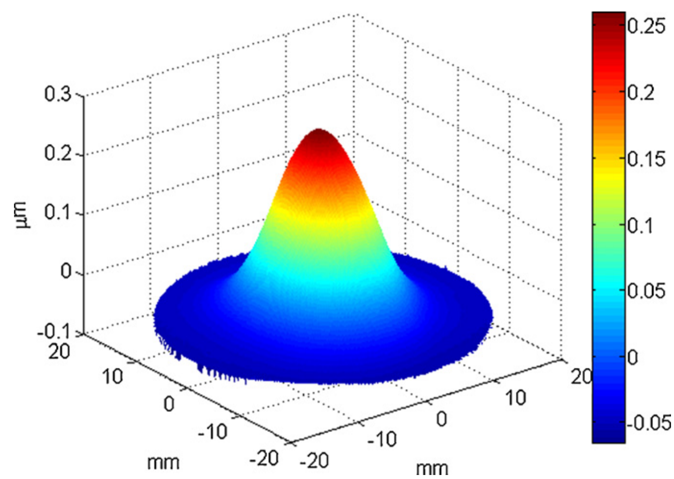

Fig. 5. Predetermined beam function from experiments.

Therefore, the new formula is

$$R = \begin{cases} E + U, & E + U \geq 0 \\ 0, & E + U < 0 \end{cases}. \tag{2}$$

Furthermore, the adjustable uniform removal U can be broken into two parts, i.e., $U = \gamma e$, where e is the RMS value of the figure error E, and γ is an adjustable parameter which controls the magnitude of the removal. Since e describes the mean deviations of the figure error, it contains the main information of the figure error. Therefore, the adjustable parameter γ is just a simple factor, and for different figure error, the optimum γ values experientially tend to be in the same range from 1 to 4.

Since the iterative algorithm is simple and has met with considerable success in practice [3,4,9], it is used in our investigation to calculate the dwell time. The iterative algorithm can be expressed as [4]

$$T_{n+1} = T_n + \xi E_n, \qquad E_n = R - B * T_n, \tag{3}$$

where T_n and E_n are the dwell time and the residual figure error after n computation iterations, ξ is a relaxation factor, and B is the beam function which will be described later in Section 4. The initial T_0 is often set to a proportion of the specified removal, usually $T_0 = R/B_0$, where B_0 is the integration of the beam function B. After several computation iterations, the final dwell time and the residual error can be obtained.