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Ultra-precision surface finishing using pulsed ion beams

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Abstract
Ion beam figuring (IBF) is nowadays widely used in ultra-precision optics fabrication as the final correction step to achieve shape accuracies on the nanometer level. Similar to other deterministic sub-aperture machining technologies local material removal is controlled by dwell time data obtained by a de-convolution of the target topography and the tool function. Assuming a stable tool function and thus a constant removal rate, a certain amount of dc offset removal is inevitable due to the mechanical limits of the CNC motion system. In some cases this dc offset removal contributes significantly to the overall machining time. Furthermore, higher dynamics in the etching process is required to be able to effectively target mid-spatial frequency surface structures. Introducing pulse width modulation (PWM) technique to the ion beam source both requirements can be met.

The high voltages applied to the beam source for ion extraction and acceleration are quickly switched on and off with a constant frequency of several kHz while the duty cycle can be controlled in a range between 1% and 99% leading to an additional control feature of the material removal besides the local dwell time. By combination of both the dc removal can be minimized. Highly dynamic changes of the etching rate are realized by the PWM method. In the presentation the capabilities in ultra-precision optical surface manufacturing such as partial area etching or seamless stitching of sub-areas is demonstrated and the advantages over the conventional IBF technology are discussed.

Ion beam figuring, ultra-precision surface machining, pulse width modulation

1. Introduction

Ion Beam Figuring (IBF) is one of the deterministic ultra-precision surface correction methods used in optical surface manufacturing amongst other technologies like magneto-rheological finishing, computer-controlled polishing or fluid jet polishing. IBF is nowadays widely used as the final correction step to achieve shape accuracies on the nanometer level [1]. The principles of deterministic correction using dwell time methods generally also apply to IBF. Hence, the local material removal is controlled by dwell time data obtained by a de-convolution of the target topography, or the error topography, respectively, and the tool function. IBF machinery is based upon a high precision CNC motion system to accomplish the required local dwell times by providing an appropriate relative movement between tool and target surface.

Owing to the permanent generation of accelerated ions that form a steady ion current onto the surface a constant material removal rate and thus a temporarily stable tool function of ideally nearly Gaussian shape is achieved. Although the material removal rate of the IBF process is in the order of several nanometers per second only, a certain amount of dc offset removal is inevitable due to mechanical limits of the CNC motion system. In some cases, this dc offset removal contributes significantly to the overall machining time. Furthermore, the efficiency of mid-spatial frequency structures removal is limited due to dynamics restrictions.

By introducing pulse width modulation (PWM) technique to the ion beam source the dynamical characteristics of the motion system can be virtually enhanced [2]. Thus, both problems can be addressed. PWM has been adapted to the ion beam source control unit to switch quickly on and off the high voltages that are applied to the beam source for ion extraction and thus beam formation. Highly dynamic changes of the etching rate are realized by the PWM method. By combination of both PWM and dwell time method, the dc removal can be minimized to nearly zero.

2. Experimental setup

A conventional ion beam figuring system for precision surface processing usually consists of a 3- or 5-axis CNC motion system mounted in a high vacuum. The motion system performs a relative raster path or spiral motion scheme of the ion beam with respect to the surface. The ion beam source is made of a vessel containing RF excited argon plasma. The vessel is terminated on one side by a multi-hole grid system where two high voltages are applied to extract and accelerate positive ions out of the plasma and direct them towards the substrate surface. Material removal is accomplished by sputtering. A steady ion beam current carrying ion energies between 200 eV and 2 keV acts as the standard IBF tool.

Additional hardware is required to modulate the ion beam intensity. The recently designed high voltage switching device consists of two high voltage switching modules and fast interface logic to receive axis position synchronous pulse width information from a CNC axis controller. This specialized high voltage switch interconnects the high voltage power supply and the ion beam source. Fig. 1 shows schematically the setup for position synchronous PWM. Switching is performed with a constant frequency of several kHz while the duty cycle can be controlled in a range typically between 1% and 99%. A duty cycle range of close to 2 orders of magnitude transforms a given axis system into one with a virtual maximum velocity of exactly these 2 orders of magnitude higher than before. This leads to an additional control feature of the material removal besides the local dwell time.

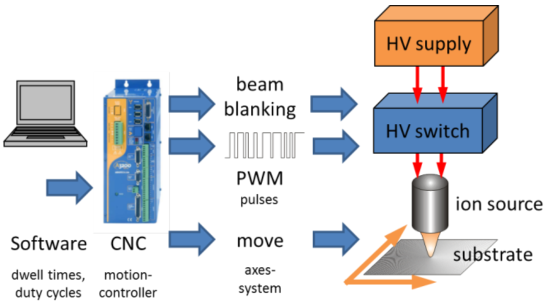
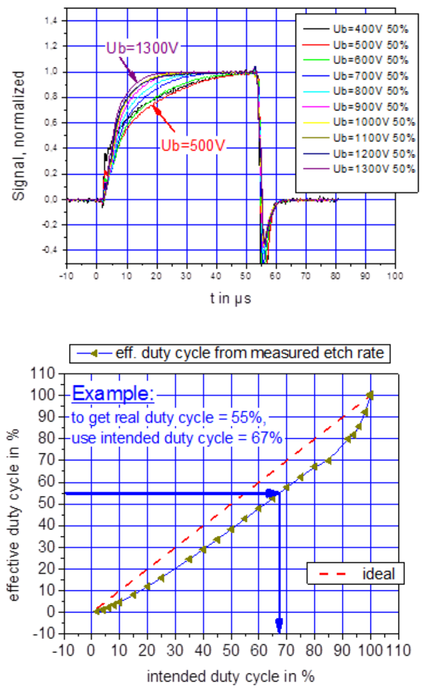


Figure 1. Principle of controlling the CNC axis system and the high voltage switch to pulse width modulate the ion beam source

3. Results

3.1. Time resolved recording of emitted ion current

Time resolved recordings of the ion current emitted by a PWM-modulated RF-driven ion beam source are shown in fig. 2(a). The diagram shows normalized current signals for a duty cycle of 50%, where one of the high voltages (beam voltage *Ub*) is a parameter. The magnitude of *Ub* clearly influences the steepness of the leading edge of the ion current pulse as well as the inclination of the pulse top. The influence of RF-power and gas flow on the shape of the leading edge is similarly strong whereas the influence of the second high voltage (accelerator voltage) was found to be of minor importance. The tailing edge usually shows a pronounced undershot. During this period of time electrons are emitted by the source. The variable shape and steepness of the leading edge implicate a non-linear dependency of the resulting etching rate on the actual duty cycle. The shape of the plot in fig. 2(b) represents a typical trend, but slope and curvature are depending on the set of parameters used for operating the ion beam source, such as gas flow, RF power, or beam voltage. In fact it turned out to be necessary to calibrate the system for each set of those parameters.



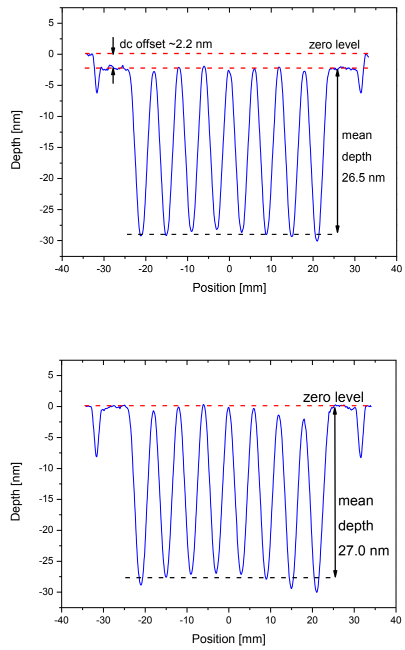
(a)

(b)

Figure 2. (a) Time resolved recording of emitted ion beam current, pulse shape vs. beam voltage, (b) calibration curve for linearizing the etching rate depending on duty cycles

3.2. Etching test

Fig. 3(a) and (b) show profiles of sinusoidal test structures etched on a substrate using the conventional dwell time method and PWM, respectively. The dc offset removal of 2.2 nm in fig. 4(a) occurs due to the permanently "beam on" condition and application of a certain minimal dwell time determined by the maximum motion velocity of the CNC axis system. This offset is nearly completely suppressed in fig. 4(b), which means a saving of processing time of approx. 10% for the current case. Thus, depending on lateral dimensions and amplitudes of error structures on an optical surface dc offset reduction can significantly reduce machining time.



(a)

(b)

Figure 3. Etching of sinusoidal structures w/o PWM (a) and using PWM (b). The base removal has been nearly completely suppressed

4. Summary

In the paper a method for pulse width modulation of ion beams used for ultra-precision surface correction is presented. By using this method beam intensity can quickly be adjusted between 1% and 99% of its maximum value. In this way the mechanical limits of the axis system can be virtually enhanced. Measurements of ion beam currents and etching rate show a non-linear dependency on the duty cycle which can be calibrated to linearize the material removal.

A combination of the conventional dwell time method and PWM during the ion beam figuring process results in a suppression of the dc offset removal and thus in significant machining time savings.

References

[1] Arnold T, Boehm G, Fechner R, Meister J, Nickel A, Frost F, Haensel T, Schindler A, *Nucl. Instrum. Meth. A* **616** (2010) 147-156

[2] Patent DE10 2005 017 632.1