1995 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

INVESTIGATION OF ION-BEAM MACHINING METHODS FOR REPLICATED X-RAY OPTICS

Prepared By:	Thomas W. Drueding
Institution:	Boston University Aerospace and Mechanical Engineering Department
NASA/MSFC:	
Office:	Astrionics Laboratory
Division:	Optics and Radio Frequency
Branch:	Optical Fabrication
MSFC Colleagues:	James W. Bilbro Robert W. Rood

INVESTIGATION OF ION-BEAM MACHINING METHODS FOR REPLICATED X-RAY OPTICS

1. Introduction

The final figuring step in the fabrication of an optical component involves imparting a specified contour onto the surface. This can be expensive and time consuming step. The recent development of ion beam figuring provides a method for performing the figuring process with advantages over standard mechanical methods. Ion figuring has proven effective in figuring large optical components [1-7].

The process of ion beam figuring removes material by transferring kinetic energy from impinging neutral particles. The process utilizes a Kaufman type ion source, where a plasma is generated in a discharge chamber by controlled electric potentials [8]. Charged grids extract and accelerate ions from the chamber. The accelerated ions form a directional beam. A neutralizer outside the accelerator grids supplies electrons to the positive ion beam. It is necessary to neutralize the beam to prevent charging workpieces and to avoid bending the beam with extraneous electro-magnetic fields. When the directed beam strikes the workpiece, material sputters in a predicable manner. The amount and distribution of material sputtered is a function of the energy of the beam, material of the component, distance from the workpiece, and angle of incidence of the beam. The figuring method described here assumes a constant beam removal, so that the process can be represented by a convolution operation. A fixed beam energy maintains a constant sputtering rate. This temporally and spatially stable beam is held perpendicular to the workpiece at a fixed distance. For non-constant removal, corrections would be required to model the process as a convolution operation. Specific figures (contours) are achieved by rastering the beam over the workpiece at varying velocities. A unique deconvolution is performed, using series-derivative solution[9] developed for the system, to determine these velocities.

The two main advantages of the ion machining process are that it is non-contacting and highly predictable. The non-contact nature eliminates the problems of tool wear and edge effects encountered in most standard polishing techniques. The process also avoids rib structure print through and warping due to loading stresses on the workpiece. Holding beam parameters constant ensures beam stability, and results in a predictable and highly deterministic removal process. This allows for rapid convergence of the process to required specifications, resulting in a significant time and cost savings.

Early work on the ion figuring of optical components was performed by Gale [10]. This work was expanded at the University of New Mexico by Wilson, et. al. [5-7]. The initial experiments involved figuring of 30 cm fused silica, Zerodur and copper optics with a 2.54 cm ion beam source. Allen, et. al. developed an ion figuring system for large optics at Eastman Kodak [1-4]. The Kodak Ion Figuring System (IFS) is capable of processing components up to 2.5 m by 2.5 m using several ion sources of up to 15 cm diameter. Other current research is being carried out at Oak Ridge National Laboratory. Their system is capable of figuring up to a 60 cm size component [11].

The new Precision Ion Machining System (PIMS) research facility at NASA's Marshall Space Flight Center is currently focused on the figuring of small ($\approx$10 cm diameter) optics using a 3 cm ion source. The initial experiments were performed figuring 8 cm diameter fused silica and chemical vapor deposited SiC. These experiments confirmed the effectiveness of the system[12]. Issues of concern in ion beam figuring process include; beam stability, the surface properties of the workpiece, workpiece heating, and dwell function computation. Beam stability effects the predictability and accuracy of the removal process, while workpiece surface properties and heating influence the effectiveness of the process. The effects on the surface roughness are reported in earlier work[13].

2. Precision Ion Machining System

The PIMS machining apparatus itself is constructed around a surplus sputtering vacuum chamber. Fitted inside the chamber is a 3 cm, Kaufman filament type ion source driven by a programmable power supply. A computer controlled translation stage is fitted to the floor of the chamber, below the ion source. The workpiece holder is placed on the translation stage that provides translations and rotations of the workpiece. The motion of the system as well as the ion source power supply is controlled by a 80386 based personal computer. In the configuration, the workpiece is moved and the ion beam source is held in a fixed position above the workarea. The system is shown in the computer model of Figure 1.

The surface contour measurements are taken using a ZYGO Mark IVxp interferometer with a 4 inch aperture. For computing rastering parameters, the surface map is transferred to a personal computer. Surface roughness measurements are taken using a WYKO 3-D optical profilometer. The sample workpieces are circular and 80.0 mm in diameter.

The Precision Ion Machining System was successful in figuring 8 cm diameter fused silica and chemical vapor deposited SiC samples[12]. A 1 cm aperture was used for correcting a near flat, fused silica sample. Small apertures are useful for making finer corrections on optical components, but they are limited by the reduce volumetric removal rate. Subsequent iterations failed to improve surface contours because of an apparent non-constant removal caused because insufficient area was covered by the ion beam. Non of the workpieces experienced significant increases in surface roughness.

Any removal method, such as ion figuring, which has a Gaussian profile will suffer from a variation in removal from the edge of a workpiece to the center. To prevent the variation, removal must take place beyond the workpiece itself. In previous experiments,

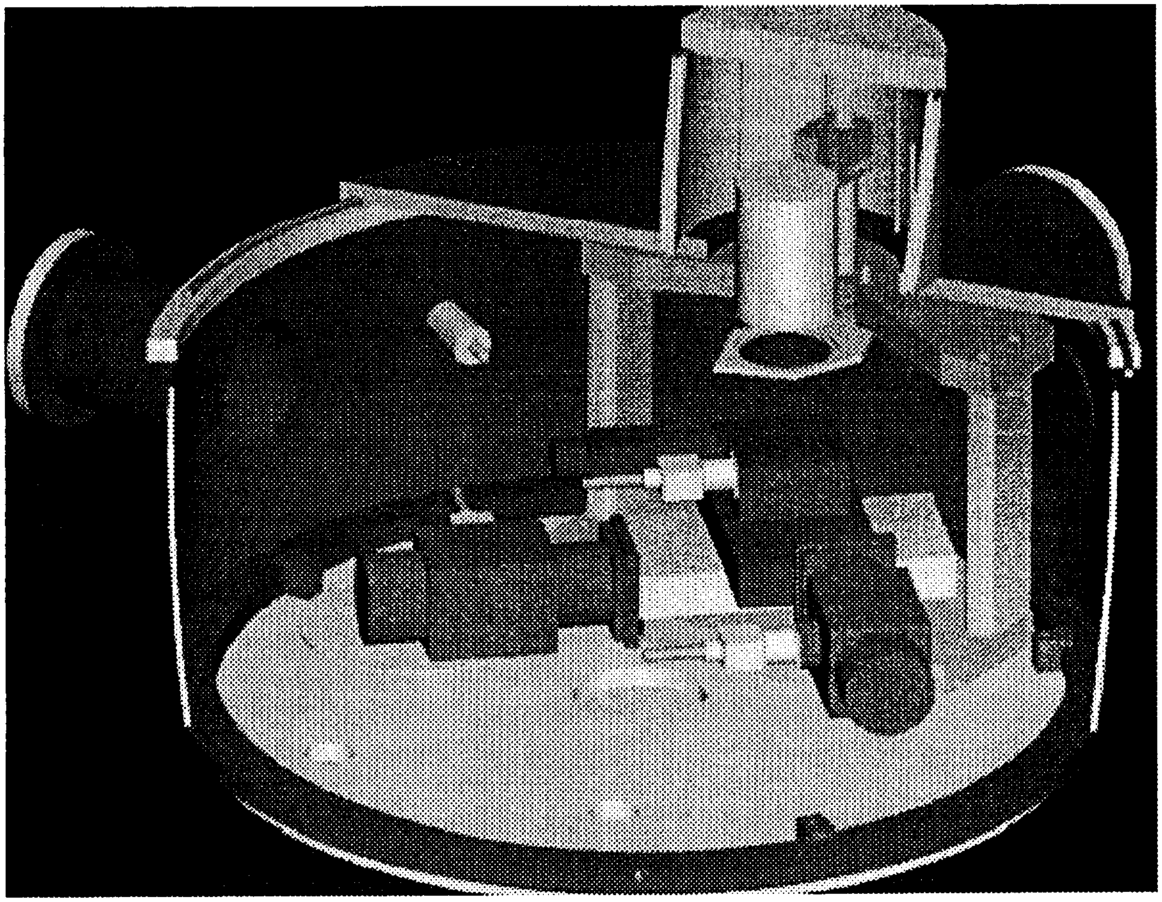

Figure 1 Solid model of the ion figuring system components. The ion source is supported on two posts above the translation and rotation stage assembly. These components are housed in a 1 meter diameter, cylindrical vacuum chamber.

we chose limits that were too small, resulting in the removal variation. The limits were chosen in an effort to reduce machining time, as an increase in machining limits results in a proportionally larger amount of area to be machined and thus a longer machining time. However, this decrease in time was accompanied by an decrease in accuracy, and also prevented us from improving a workpiece over successive iterations. This summer experiments were performed using appropriate limits. This resulted in effective iterations of the process. An initial flat fused silica sample with and a deviation of 1088 nm rms, was figure to 271 nm rms in the first iteration, and then corrected to 114 nm rms in the subsequent iteration.

3. Plans for X-Ray Replication Optics

Future projects involve implementing ion-beam machining techniques in the fabrication of x-ray optics[14]. Ion-beam machining is proposed as a method for the final figuring of a mandrel for replicating optics. This will require significantly expanding the capabilities of the Precision Ion Machining System, currently in operation at the Optical Fabrication Branch. Advanced x-ray telescopes consist of a large number of nested cylindrical mirror shells with the reflecting surface on the inside of each shell. Replicated x-ray mirrors are produced by electroforming a thin shell optic over a figured polished mandrel. The mandrel is diamond turned electroless nickel over an aluminum substrate. The electroformed mirror shell is made from pure nickel deposited in a state of minimum stress. A cryo separation technique is used to remove the mirror from the mandrel. Since a large number of x-ray mirrors are used in an x-ray telescope, a large number of mandrels must be produced, and is important to develop precise and cost-effective methods for manufacturing these mandrels. It has been demonstrated that ion-beam figuring is an effective method for final figuring of normal incidence optics[1-7,12]. We propose these methods be extended and the Precision Ion Machining System be expanded to assist in fabricating grazing incidence optics. By investigating the effectiveness of this technique we plan to demonstrate that ion-beam machining is an important new technology in the production of x-ray optics.

The Precision Ion Machining System can be expanded to handle small cylindrical workpieces. This will require a large vacuum chamber, and modification of the translation system, to hold the mirror mandrel. New computational (deconvolution) and control methods for machining cylindrical workpieces will be developed, based on previous research for figuring near-normal incidence optics. Operating parameters that will be determined include: the ion-beam removal rate and shape; effects on the resulting surface finish and translation motor tolerances. The relative effectiveness of ion-beam machining process with respect to current methods must be test by figuring sample mandrels.

4. Conclusions

The Precision Ion Machining System at NASA's Marshall Space Flight Center was reconstructed and tested. A new graphical control interface was developed for the system. Experiments were performed using corrections to a previous problem with removal variations, cause by insufficient machining range. This resulted in effective iterations of the process. An initial flat fused silica sample with and a deviation of 1088 nm rms, was figure to 271 nm rms in the first iteration, and then corrected to 114 nm rms in the subsequent iteration. Initial plans were also developed for expanding the system for assisting in the fabrication of replicated x-ray optics.

5. References

1 Lynn N. Allen, John J. Hannon, and Richard W. Wambach. "Final surface error correction of an off-axis aspheric petal by ion figuring," *Advances in Fabrication and Metrology for Optics and Large Optics*, SPIE, 1543, 1991.

2 Lynn N. Allen and Robert E. Kiem. "An ion figuring system for large optics fabrication," *Current Developments in Optical Engineering*, SPIE, 1168, 1989.

3 Lynn N. Allen, Robert E. Kiem, and Timothy S. Lewis. "Surface error correction of a Keck 10m telescope primary segment by ion figuring," *Advances in Fabrication and Metrology for Optics and Large Optics*, SPIE, 1531, 1991.

4 Lynn N. Allen and H. W. Romig. "Demonstration of an ion figuring process," *Advances in Fabrication and Metrology for Optics and Large Optics*, SPIE, 1333, 1990.

5 S. R. Wilson. "Ion beam figuring of optical surfaces," Master's thesis, University of New Mexico, 1987.

6 S. R. Wilson and J. R. McNeil. "Neutral ion beam figuring of large optical surfaces," *Current Developments in Optical Engineering*, SPIE, 818:320-323, 1987.

7 S. R. Wilson, D. W. Riecher, and J. R. McNeil. "Surface figuring using neutral ion beams," *Advances in Fabrication and Metrology for Optics and Large Optics*, SPIE, 966:74-81, 1988.

8 H. R. Kaufman, P. D. Reader and G. C. Isaacson, "Ion Sources for Ion Machining Applications," AIAA Journal, **15**(6): 843-847, June 1977.

9 T. W. Drueding, T. G. Bifano, and S. C. Fawcett. "Contouring Algorithm for Ion Figuring," Precision Engineering, January 1995, **17**(1).

10 A. J. Gale, "Ion Machining of Optical Components", Optical Society of America Annual Meeting Conference Proceedings, November, 1978.

11 Charles L. Carnal, C. M. Egert, and Kathy W. Hylton. "Advanced matrix-based algorithm for ion beam milling of optical components", presented at the *Society of Photo-Optical Instrumentation Engineers*, 1992 International Symposium on Optical Applied Science and Engineering, 1992.

12 T. W. Drueding, S. C. Fawcett, S. R. Wilson, and T. G. Bifano. "Ion Beam Figuring of Small Optical Components", *Optical Engineering*, December 1995, **34**(12).

13 S. C. Fawcett, T. W. Drueding, and T. G. Bifano, "Neutral Ion Figuring of CVD SiC", *Optical Engineering*, **33**(3):967-974, March 1994.

14 M. Ghigo, O. Citterio, P. Conconi, R. Loi, and F. Mazzoleni. "Perspectives of ion-beam polishing of mandrels for x-ray replication optics", *X-Ray and Extreme Ultraviolet Optics*, SPIE, 2515:56-62, 1995