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FABRICATION OF OFF-AXIS PARABOLIC MIRRORS

M. J. Bezik
H. L. Gerth
R. E. Sladky
C. A. Washington

August 1978

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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FABRICATION OF OFF-AXIS PARABOLIC MIRRORS

H. L. Gerth
R. E. Sladky
Fabrication System Department

M. J. Bezik
C. A. Washington

Chemical and Plastics Department
Y-12 Development Division

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Oak Ridge Y-12 Plant

P. O. Box Y, Oak Ridge, Tennessee 37830

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ABSTRACT

This report describes the fabrication process, including metal preparation, copper electroplating, single-crystal-diamond turning, optical inspection, and polishing, used to manufacture the focusing mirrors for the 10-kJ laser fusion experiment being conducted by the Los Alamos Scientific Laboratory.

Fabrication of these mirrors by the techniques described resulted in diffraction-limited optics at a 10.6 μm wavelength.

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SUMMARY

The focusing element for the 10-kJ laser fusion experiment being conducted by the Los Alamos Scientific Laboratory (LASL) consisted of a copper-plated aluminum substrate with a thickness of 76 mm and a 406-mm diameter. The reflecting surface had an off-axis parabolic contour with a focal length of 785 mm. Twelve identical elements were manufactured for this experiment. The fabrication sequence consisted of rough machining and heat treating a Type 6061-T6 aluminum substrate, electroplating a copper layer on the mirror surface, machining an accurate contour and optical finish using a single-crystal diamond tool, optically inspecting the results, and polishing out the remaining tool marks. All operations were done at Y-12 with the exception of the polishing which was done at the University of Arizona's Optical Sciences Center.

The finished mirror is diffraction limited at a 10.6- μ m wavelength. Estimates indicate that the mirrors were produced at two thirds the cost and one sixth the time when compared with conventional manufacturing techniques.

INTRODUCTION

In recent years, the high-energy laser has been developed to a state of reality. As its development progresses, more and more applications for its use are found. One application presently being pursued is the attainment of controlled nuclear fusion for power generation by bombarding tiny targets containing nuclear fuel with high-power laser beams. The energy gained by the resulting fusion reaction would then be used to generate electric power for commercial use. LASL is conducting a research program in this area. Their program will bombard targets with energy from high-power carbon dioxide lasers.

In this application, geometric constraints require that the laser energy be generated at a remote location and transported to the target (see Figure 1). Highly reflective metal mirrors are needed to accomplish this feat. They direct the energy through evacuated tunnels and

Figure 1. LASER AMPLIFIERS AND TARGET CHAMBER. (10-kJ, 8-Beam, CO₂ Laser)

focus it into a very small volume containing the target. The mirrors must be highly reflective to achieve an efficient transmission of the energy, and low absorption is required to prevent mirror damage caused by overheating. Extremely accurate control of the reflective surface contour is required in order to focus energy into the target volume.

Fabrication of these metal reflective mirrors at the Oak Ridge Y-12 Plant^(a) presented a considerable challenge. Two choices for fabrication techniques were considered: (1) conventional lapping and polishing, and (2) single-point turning by using single-crystal diamond tools. The conventional lapping and polishing of metal mirrors is, of course, well established. However, this process is costly and requires long fabrication times. This problem

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

is especially true when aspherical shapes are required such as the off-axis parabolas needed to focus the energy onto the target. Substantial quantities (50 - 70) of high-quality mirrors (flats and parabolas) were needed for this phase of the program. Much larger quantities (500 - 700) are needed for the later phases. This technique for fabrication was considered not to be feasible because of its inherent high cost and long fabrication time. The second fabrication technique that showed promise was single-point turning, using single-crystal diamond tools. This technique is beginning to emerge from the role of a laboratory phenomenon. Historical development of single-point diamond turning will not be described here, but is the subject of the documents that are listed in the reference section of this report.^{1 - 7}

Figure 1 is an artist's concept of the experimental equipment of which these mirrors are a part. As can be seen, there are eight laser amplifiers. Each amplifier produces a 1.25-kJ beam of energy in a 1 to 2-nanosecond pulse which is directed into the target chamber. A flat turning mirror then directs the beam to one end of the target chamber. A focusing mirror redirects and condenses the beam into a small volume containing the target. Fabrication of the focus mirror is the subject of this report.

PRODUCTION OF OFF-AXIS PARABOLIC MIRRORS

MIRROR FABRICATION

Mirror Configuration

The mirror configuration is described in Figure 2. Aluminum alloy (Type 6061-T6) was used for the substrate, with copper electroplated on the mirror surface. Mirror-surface

Figure 2. DIMENSIONS OF THE PARABOLIC FOCUS MIRROR FOR THE LASER TARGET CHAMBER. (All Linear Dimensions are in Inches)

specifications allowed a total contour error of $1.9 \mu\text{m}$ and a surface finish of 64 nm , peak to valley. A total of 12 mirrors were made for this project—eight mirrors to be used in the system and four to be reserved as spares. Fabrication of the mirrors involved five major areas: (1) metal preparation, (2) electroplating, (3) finish machining, (4) optical inspection, and (5) polishing. Each of these areas is discussed in the following sections of this report.

Metal Preparation

This area of fabrication involves the preparation of the aluminum substrate for plating. The substrate was cut from a piece of Type 6061-T6 aluminum stock that was approximately 100 mm thick. The diameter was machined to 0.76 mm oversize; the front and back sides were machined flat and parallel also to 0.76 mm over thickness. A heat treatment to relieve residual stresses was then performed. The heat treatment involved the following operations:

(1) heat in an air furnace at 520 to 538° C for four hours; (2) quench in 30 to 40% Ucon "A"(b) solution that has been preheated to 55° C; (3) age at 170 to 182° C for eight hours.

The material, being properly stress relieved, was machined to remove warpage resulting from the stress relieving, then the diameter was machined to size. Finally, the front and back sides were machined flat and parallel to the final thickness. Figure 3 shows the substrate at this

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Figure 3. FOCUS-MIRROR SUBSTRATE AT THE INTERMEDIATE STAGE OF FABRICATION.

stage of fabrication. The next step was to contour the front surface. From Figure 2 it can be seen that the contour is really a portion of a parabola. Since the axis of the parabola is not coincident with the axis of the substrate, the parabolic portion is considered an "off-axis"

(b) Polyalkylene glycol, marketed by Tenaxol, Inc, Milwaukee, Wisconsin.

parabola. This shape can be easily machined if the substrate is positioned properly and rotated about the axis of the parabola. A geometrical layout will also show that six substrates can be machined at the same time in the same fixture. Figure 4 shows such an arrangement of the fixture, giving the basic dimensions; Figure 5 shows the fixture undergoing final machining.

In order to maintain proper substrate orientation within the fixture, a socket for an alignment pin was inserted into the substrate back (see Figure 2 for the alignment pin location). Each substrate was then placed into one of the large recessed holes on three jack screws. The jack screws were adjusted to maintain a 760- μ m gap between the fixture and the bottom of the substrate. The recess in the fixture was 1.5 mm larger in diameter than the substrate. Two small pieces of shim stock were used to center the part, leaving a 760- μ m gap around the substrate perimeter. The substrate was rotated until a pin could be inserted through the fixture and into the alignment hole in the back of the substrate. This pin assured a proper rotational position in the fixture. An RTV rubber compound (Hardman DPR 336) was pumped into the gap between the part and fixture and allowed to solidify. The shim stock, alignment pin, and jack screws were then removed. This procedure allowed the substrate to be mounted in the fixture in a very stress-free condition. Figure 6 is a pictorial drawing that shows this configuration. The rubber liner between the fixture and substrate holds firmly without permitting a concentrated load to exist that might warp the substrate.

After the fixture was loaded with six substrates and their relative location documented, the assembly was placed on a vertical tracer lathe where the parabolic contour was roughed into the front surface with a conventional button tool. Figure 7 gives a view of the substrates in the fixture after the rough contouring operation has been completed. Next, the parts were pushed out of the fixture by inserting the jack screws. An inspection for dimensional accuracy was then performed.

Electroplating

The plating process involved electroplating copper onto the contoured surface of the aluminum substrate. The copper thickness was requested to be a minimum of 1.02 mm. This amount of copper makes it possible to refinish the mirror surface several times.

The 6061 T-6 aluminum alloy lends itself very well to preplate preparation by standard procedures used at the Y-12 Plant. The major deviation in the procedures used from those widely employed in industry is the long time of treatment in the zincate solution.

Detailed preplate and plating procedures are outlined in Table 1, and it can be seen that five-minute soaks in the standard, high-concentration sodium zincate solution are used for both the first and second zincating steps. This period is much longer than is the usual practice, but is used as a result of Y-12 testing, which indicated better and more consistent results with regard to adhesion.

Another variation in practice is Y-12 Plant's test for the amount of adhesion of the strike. A common practice in industry is to heat the copper-struck aluminum part in an oven, quench

Figure 4. BASIC CONFIGURATION AND DIMENSIONS OF THE FIXTURE USED TO CONTOUR THE LASER FOCUS MIRRORS. (All Linear Dimensions are in Inches)

it in water, and examine the part for the presence of blisters in the surface which would indicate a lack of adhesion. Sometimes the procedure calls for a 24-hour wait before the examination. The adhesion test used on this set of substrates consisted of vigorously wet scrubbing the struck surface with a clean, stiff-bristle, stainless steel brush and immediately

171200

Figure 5. FINAL MACHINING OF THE FIXTURE USED TO CONTOUR THE LASER FOCUS MIRRORS.

Figure 6. ARRANGEMENT OF THE SUBSTRATE MOUNTED IN THE FIXTURE.

Figure 7. FOCUS-MIRROR SUBSTRATES IN THE FIXTURE AFTER ROUGH MACHINING.

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Table 1
ELECTROPLATING PROCEDURE FOR THE FOCUS MIRROR EXPERIMENT

Surface Preparation of the Aluminum Substrates

1. Vapor degrease three cycles in perchloroethylene.
2. Water rinse.
3. Pickle in 35 wt % nitric acid for five minutes at room temperature.
4. Water rinse.
5. Etch in 10 wt % sodium hydroxide for three minutes at room temperature.
6. Water rinse.
7. Pickle in 35 wt % nitric acid for five minutes at room temperature.
8. Water rinse (zincate immediately).

Zincate Process⁽¹⁾

1. Zincate five minutes at room temperature.
2. Water rinse.
3. Pickle in 35 wt % nitric acid for one-half minute at room temperature.
4. Water rinse.
5. Zincate for five minutes at room temperature.
6. Water rinse (strike in cyanide copper immediately).

Cyanide Copper Strike⁽²⁾

1. Strike in cyanide copper, going in with the current at 26.9 - 37.6 mA/cm² (25 - 35 A/ft²) for one minute, then reducing the current density to 16.2 mA/cm² (15 A/ft²) for 20 minutes.
2. Water rinse.
3. Wet scrub the face of the part with a stiff, clean, stainless steel brush.
4. Examine the strike closely for blisters.

Masking and Fixturing

1. Mask the sides and rear of the mirror with plater's tape and Micro Flex (polyvinylchloride).
2. Attach the electrical connection and mirror support.
3. Scrub the mirror face with abrasive cleanser.
4. Water rinse.
5. Pickle the part in 10 vol % sulfuric acid for 30 seconds at room temperature (go directly to the plating bath).

Plating⁽³⁾

1. Enter the part in the bath with the current on.
 2. Plate at 16.1 mA/cm² until the desired thickness is obtained (~ 93 hrs).
 3. Remove the part from the plating bath and water rinse.
 4. Remove the fixturing and masking.
 5. Visually inspect.
 6. If satisfactory, ship.
-

(1) Zincate Solution:

sodium hydroxide (NaOH)	525	g/l
zinc oxide (ZnO)	98	g/l
iron (III) chloride (FeCl ₃)	0.98	g/l
rochelle salt	9.8	g/l

(2) Cyanide Copper Strike Solution:

copper (I) cyanide (CuCN)	41.2	g/l
sodium cyanide (NaCN)	48.8	g/l
sodium carbonate (Na ₂ CO ₃)	30.0	g/l
rochelle salt	60	g/l

(3) Copper Plating Solution (Cu Bath 1):

copper (II) sulfate (CuSO ₄ · 5H ₂ O)	67.5	g/l
sulfuric acid (conc) (H ₂ SO ₄)	172.5	g/l
chloride (add as HCl)	50	mg/l
Cu Bath Hi (initially; thereafter 1/3 ml/A hr)	5.3	ml/l

examining the surface for blisters. As a backup to the in-process adhesion test, each plated substrate was subjected to a thermal cycle and then scanned ultrasonically to determine whether there were any delaminations at the copper/aluminum interface. One of the 10-kJ-system substrates was found, by ultrasonic examination, to have a delamination. Consequently, it was reprocessed. This failure was the first since instituting the long zincating times and the stiff-wire-brush test approximately two years ago.

In preparing the substrates for plating, there is a substantial advantage in treating the bare part without masking and with a minimum of fixturing. This modification in the procedure results in a greatly reduced handling of the part and helps to assure that it does not become contaminated before the cyanide copper strike is applied. Some of the first 10-kJ substrates to be plated were placed in a fixture after vapor degreasing and remained in the fixture through the preplate preparation, the cyanide copper strike, and the bright acid copper plating steps. The fixture, in this case, was a plastic, pocket-type fixture that was shaped to fit the contour of the substrate rather closely (see Figure 8). The substrate was simply dropped into the fixture and the gap between the fixture and the part was caulked with room-temperature-vulcanizing silicone rubber.

Difficulty was experienced with leaking of this fixture and consequent etching of the aluminum resulting from a long contact time with some of the preplate preparation solutions. Most of the substrates were simply hung on a stainless steel hook for processing through the vapor degreaser, the preplate preparation, and the copper strike. The preferred method of attaching such a hook is by threading it directly into a drilled and tapped hole in the back of the substrate. If there are holes (tapped or not) which should be protected during these operations, it is no problem to plug them after the vapor-degreasing step.

Figure 8. POCKET-TYPE FIXTURE USED IN PLATING SOME OF THE EARLY SUBSTRATES.

The better method of fixturing these substrates for application of the bright acid copper plate is illustrated in Figure 9. When using the fixture shown here, the entire surface of the substrate, except for the area to be plated, is masked off with pressure-sensitive tape or a polyvinylchloride (PVC) lacquer. Masking on the sides of the substrates is stopped short of the face of the part to allow the copper plate to wrap around the corner and ensure that the entire face is plated. The heavy plastic fixture bolted onto the back of the part provides a support for the lightweight, picture-frame shield. This type of shield serves to reduce the amount of buildup of copper on the edge of the face and improves the distribution of copper over the face of the substrate. No study was made of the plate-thickness distribution, so observations concerning the efficiency of the shielding shown in Figure 9 are somewhat subjective. The stainless steel hook which serves to support the substrate in the plating bath also carries the cathode connection. It is masked off so that it will not be plated.

Figure 9. SETUP FOR COPPER PLATING THE MIRROR SUBSTRATES. [Substrate is Round (406 mm D x 76 mm T), Representative of Fixturing for other Sizes and Shapes; Anodes are High-Phosphorus Copper Bars]

readings were taken and current adjustments were made hourly on a 24-hour basis. Thus, the total faradays of plating current and the total weight of copper deposited are accurately known.

The plating bath used to plate these substrates is one that was selected some years ago on the basis of evaluations by the Air Force Weapons Laboratory of diamond-turned copper deposits from a number of different copper-plating baths. It is a bright acid copper bath of the composition given in Table 1. The additives used are marketed by the Sel-Rex Corporation under the trade name of "Cu Bath". Since the additives are proprietary and, thus, their composition is unknown, there were no analytical methods which could be used to control their concentrations in the plating bath. Additions of the additive were made at the rate of 0.33 ml per ampere hour of plating current, which is the recommendation of the vendor.

The bath was analyzed periodically for the major constituents (copper sulfate and sulfuric acid), and any necessary adjustments were made. The chloride ion concentration was also determined and maintained at approximately 50 ppm.

On at least one occasion when the appearance of the electrodeposit indicated a serious problem with the plating bath, the bath was removed to auxiliary tanks and treated with activated carbon to remove suspected organic contamination. Such contamination may come from organics introduced into the plating system from the masking tape or lacquer, by breakdown of the additives, or by accident.

The heavy copper plating of these substrates was carried out in a polyethylene tank, approximately 900 mm on a side. Figure 9 shows the plating-bath solution being supplied to a distributor lying on the bottom of the tank under the substrate. The distributor consisted of three parallel lengths of perforated PVC pipe. The solution issuing from the perforations flows upward across the face of the substrate. The only agitation at the surface being plated is that provided by this vertical flow. Other pumps circulate the plating bath through filters to remove any particulate matter.

The plating current rectifiers were not current controlled, but current

As indicated in Figure 9, the distributor was situated on the bottom of the plating tank from which a pumped stream of solution issued and flowed across the surface of the cathode. This arrangement did not provide a high degree of agitation at the cathode surface and is believed to be largely responsible for the fact that the as-plated surface was often marred by a few-too-many small nodules, but these imperfections were not so severe that the plate could not be diamond machined to a surface of acceptable quality. On rare occasions, the plating defects were an almost whisker-like growth on the plated surface; and, when this problem occurred, the bath was treated with activated carbon to remove any organic contamination. This treatment appeared to be effective and restored the electrodeposits obtained from the bath to their usual quality.

The occurrence of nodules on the plated surface should not be thought of as a merely cosmetic problem. If such nodules are very heavy, they will have an area of depressed plate at their bases, due to robbing the current which would have gone to that area. Also, the crystal regime to which the nodule belongs may be different from the major crystal regime, resulting in an occasional nodule being "plucked out by the roots" during machining, leaving a flaw in the surface. Evidence is now available that shows that improved agitation at the surface of the cathode can greatly improve the quality of the plated surface. A better characterization of the plating bath is needed in order to better relate the physical condition of the electrodeposit to the chemical condition of the plating bath.

Finish Machining

Each substrate was visually inspected after returning from the plating operation. Copper nodules as high as 1.5 mm were found on the face of several substrates; others were completely clear of nodules. All the substrates had an irregular buildup of plating material around their sides which had to be removed before the substrates would fit into the recesses in the fixture.

The diamond-turning machine used to finish machine the substrates is a highly modified, two-axis, numerical-control, horizontal-axis turning machine. Figure 10 is a recent photograph of the machine. The machine has a large air-bearing spindle and an eddy-current, direct-drive motor. The slides are supported on air bearings and their position sensed with laser interferometers. Vibration of the machine is prevented by isolating it from its surroundings. Additional details about the machine can be found in a report by Gerth and Hewgley.³

The substrates were then mounted in the fixture, using the same technique described earlier. Care was exercised to assure that each substrate was placed in the same recess that it had occupied before. This precaution helped to maintain proper alignment. (Refer to Figure 7 for the substrate and fixture configuration.) At this stage, the substrates had been copper plated and were ready for final contouring. Mounting and alignment to within a 25- μ m axial runout was accomplished without incident. The surface was rough contoured with a button tool of 3.75-mm radius. Several machining passes of a 250- μ m cutting depth were required

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Figure 10. DIAMOND TURNING MACHINE USED TO FABRICATE THE FOCUS MIRRORS.

to remove the nodules and provide a fresh contour of copper plate over the entire part surface. This step was very time consuming because the spindle motor, sized to machine the optical finish, did not have enough torque to easily drive the button tool. (Forces for the finish-diamond-tool cut are much lower than those experienced during roughing). This lack of power necessitated stopping the tool feed every ten minutes and allowing the spindle to accelerate to a reasonable speed. Tool feed and depth of cut were varied in an attempt to achieve the maximum metal-removal rates. Maximum usable spindle speed was 2500 rad/min, and a minimum speed of 500 rad/min was allowed. Thus, approximately 40 hours of machining time were required to rough machine a set of six substrates.

After this preliminary work was completed, the parts were ready for diamond machining. A diamond tool of a 3.175-mm radius was placed in the tool holder such that the rake angle was -87 mrad and the clearance angle was 105 mrad. In order to achieve a good surface finish, a mineral-oil lubricant (Gulfcut 11D) was used. Chips were prevented from scratching the surface by removing them with a vacuum chip collector as they were formed. Figure 11 shows the tool, lubricator, and chip-collector configuration used to diamond machine a mirror. Note that the chip collector (a copper tube with vacuum applied) is positioned directly over the tool. As the chip is formed, it is sucked directly into the collector by the air flow generated by the vacuum inside the collector. In this arrangement,

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Figure 11. TOOL-LUBRICATING AND CHIP-COLLECTION TECHNIQUE FOR DIAMOND TURNING.

chips are not given the opportunity to rub the freshly cut surface, thereby destroying its surface finish. Also note that the lubricant (Gulfcut 11D) is applied slightly above and ahead of the cutting tool. (In Figure 11, the tool moves from right to left during a cut.) The lubricant flow rate is adjusted so that the oil flows onto the surface without bouncing off. When the lubricant and chip collector are positioned properly, a heavy film of oil is present where the chip is being formed. The lubricant helps to protect the surface by washing the chip into the collector. All chips and about 75% of the oil are collected by the chip collector.

The procedure for positioning the tool with respect to the fixture is complicated by the inability to set the tool at the spindle centerline and then cut the contour. This ideal setting is not possible because of the cutting-tool configuration. Figure 12 shows a 37-mm-diameter

boss in the center of the fixture (Surfaces A and B). This boss was used as a reference to locate the flat and 30-degree conical features near the outer edge of the part (Surfaces C and D). This reference was accomplished by establishing a coordinate system on the fixture, as indicated in Figure 12. The origin was located on the spindle centerline and the face of the boss. The boss was faced and its cylindrical surface turned. Measuring the resulting boss diameter with a precision micrometer provided enough information to position the tool at the origin. Surface C was cut and the Y-axis-position laser read to determine the position of Surface C with respect to the X axis of the coordinate system. Surface D was cut by programming the machine to cut a 520-mrad slope and recording the X and Y coordinates at the start of the cut. This procedure provides adequate information to locate Surfaces C and D and Point E (see Figure 13) with respect to the coordinate system previously established.

Figure 12. FIXTURE, SHOWING THE SURFACES THAT ARE USED TO ESTABLISH THE TOOL LOCATION.

Knowing the location of Surfaces C and D with respect to the center of rotation, the diamond tool was set as follows: The tool was positioned in front of Surface C and moved along Path I (Figure 13) until the surface was touched. This step positioned the tool along the Y axis parallel to the spindle centerline. Following Path II, the tool was moved toward the spindle centerline and then toward the part, 5.1 mm beyond Surface C. The tool was moved radially outward (away from the spindle centerline) until Surface D was touched. This action established the radial position of the tool. The tool was then positioned at Point E by moving back 5.1 mm and radially outward 8.798 mm. With a proper set of the tool, normal numerical control procedures were used to generate the contour.

The following parameters were used to produce the mirror contour:

Spindle Speed	715 rad/min
Tool Feed Rate	1.25 mm/min
Tool Radius	3.175 mm
Clearance Angle	105 mrad
Rake Angle	105 mrad (negative)
Depth of Cut	5.08 μm
Coolant	Gulfcut 11D
Chip Collection	vacuum

Two consecutive finish passes were required to achieve the final accuracy. The first pass was made to determine the contour errors present in the machining system; the second pass generated a contour representing the machine's best capability at that time. The errors located in the first pass were compensated by altering the tool-path control tape. The finished focus mirrors are seen in Figure 14.

Optical Inspection

Figure Measurement - One of the most effective diagnostic devices for machine-tool development is the capability of inspecting the surface immediately after machining. When the errors become evident, remedial measures can be applied and the part remachined without repeating the costly setup procedures. To accomplish this desirable capability, an interferometric inspection system was built and installed on the machine tool slide. A single-pass interferometer, which was a modified Mach-Zehnder design, was selected for this work.^{5,6} The optical schematic layout is given in Figure 15. The beam from a helium/neon laser is spatially filtered and expanded to about 25 mm in diameter. At the beam divider, part of the beam passes through to a lens which focuses the light to a point from which it expands to fill the collimating lens (400 mm OD). The lens is a plano-aspherical lens that was fabricated at the University of Arizona Optical Sciences Center specifically for this application. The collimated light illuminates the paraboloid which focuses it to a point on the axis of the machine-tool spindle. The Tinsley interferometer is positioned at this point so that the f/2 beam expander collects the light, recollimates it, and sends it to the beam divider which acts as a beam combiner. The reflected beam from Beam Divider 1 (Figure 15) is sent into the back of the interferometer by two folding mirrors. This light, combined with the light from the paraboloid at the beam combiner, produces fringes which are displayed on a screen for viewing and photographing.

Figure 13. TOOL PATH USED TO SET THE DIAMOND TOOL.

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Figure 14. PARABOLIC MIRRORS THAT HAVE BEEN DIAMOND TURNED ON THE MACHINE AND ARE READY FOR ON-MACHINE INSPECTION.

When the optical components were set up, they were carefully aligned to be parallel to the axis of the machine spindle. To collimate the light passing through the large lens, a mirror was placed in front of it at Test Point B and the beam-expanding lens was focused until the light was collimated. A small mirror placed at Test Point A turned the system into a Twyman-Green interferometer for evaluation of the lens system.

The entire system was mounted on a large table attached to the X slide of the diamond turning machine, as noted in Figure 16. Suitable interference fringes were obtained which were very stable. Mechanical vibration was minimal because of prior machine modifications. Atmospheric turbulence did not significantly affect the fringes in the machining area. Fringes could be viewed while the spindle was rotating slowly. When additional cuts were made on the mirrors, the optical elements were covered with plastic to prevent contamination of the optical components by the cutting fluid. After the cut was finished, alignment was rechecked quickly and another inspection of the mirrors was made. This technique provides a rapid evaluation of tool-path errors. The repeatable errors were then compensated for by altering the programmed tool path to provide an improved contour accuracy.

Figure 15. OPTICAL LAYOUT OF THE INTERFEROMETER USED FOR ON-THE-MACHINE TESTING OF OFF-AXIS PARABOLOIDS.

An interferogram made with this interferometer is shown in Figure 17; fringe spacing is 317 nm. The herringbone pattern displayed in this interferogram is the result of nonstraightness

Figure 16. INTERFEROMETER EQUIPMENT MOUNTED ON THE DIAMOND TURNING MACHINE.

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Figure 17. INTERFEROGRAM OBTAINED FROM ON-THE-MACHINE INSPECTION OF AN OFF-AXIS PARABOLOID. (Mirror 7783-50-1488)

errors in the slide drive system. The herringbone periodicity corresponds to the pitch of the lead screws. A modification planned for the near future should alleviate this problem. The fringe system was digitized and analyzed, using the FRINGE II computer code for analyzing interferograms. The code determined that the peak-to-valley figure error for this mirror was 2.946 waves, or 75 microinches. The third-order aberrations were 0.4 wave of astigmatism, 2.2 waves of coma, and 1.4 waves of spherical aberration. A second, later set of mirrors, which showed a similar contour, was remachined with a compensated numerical control tape which produced a better figure on one edge of the mirror.

After the machining was completed, the mirrors were removed from the fixture and some of the mirrors were tested in the free state in an optical inspection laboratory. This testing was very difficult to accomplish since there were no fiducial marks on the mirror that could be

used for alignment. Astigmatism and coma were generally larger, due to the optical-alignment difficulty. With better alignment aids in the future, it will be possible to more accurately determine whether removal of the mirrors from the machining fixture has any effect on the surface contour.

Surface Finish - The surface finish of large mirrors can be examined, using the double-beam and multiple-beam microscopes.^{4,7} The double-beam interference microscope does not require contact with the part, and there is little danger of scratching it. The multiple-beam interference microscope requires that a small, reflective flat be placed in contact with the part, but this step almost always mars the surface. The danger of a deep scratch is much greater if the surface is curved, as it is with the paraboloids. Fringes, however, are more distinct with this technique and provide a better picture of the surface. This technique was used along with the double-beam technique since it was important to understand the machined surface finish. Since subsequent polishing was planned, this work would remove any scratches introduced by the measurements. Typical pictures from the microscopes are given in Figure 18. Both pictures show the tool cusps in the copper surface; however, the waves which are so apparent on the interferograms of the contour (see Figure 17) are too wide for the field of view of the microscope objectives. The surface finish measured from the multiple-beam picture was 145 nm ($5.7 \mu\text{in}$), peak to valley, or 28 nm ($1.1 \mu\text{in}$), AA.

Polishing

Optical polishing these mirrors was necessary to obtain the surface finish required by

(a) Double-Beam Microscope. (50X)

(b) Multiple-Beam Microscope. (164X)

Figure 18. SURFACE-FINISH PHOTOGRAPHS OF PARABOLOIDAL MIRROR 7097-25-2937. (Both Pictures were Made by Using Green Light, so the Fringe Spacing is $10.8 \mu\text{in}$; from the Multiple-Beam Picture, the Peak-to-Valley Cusp Height is $5.7 \mu\text{in}$ and the AA is $1.1 \mu\text{in}$)

the customer. The polishing process was developed and executed by the Optical Sciences Center, University of Arizona.

A method was developed for removing the microripple (tool cusps) from the single-point diamond-machine mirrors. The process used conventional hand-polishing techniques and laps of sufficient rigidity to bridge the microripple, yet soft enough not to scratch the metal mirror surface. Substantial surface material had to be removed in some cases. Therefore, careful repeated testing of the mirror contour was required in order to prevent figure degradation. The polishing showed a reduction in scattering and improvement in surface roughness. A test of one of the mirrors indicated it would give diffraction-limited performance at $10.6 \mu\text{m}$. The polished surface was nearly as free of mechanical defects (scratches and pits) as was the original diamond-turned surface. A detailed account of the polishing process is provided in the Appendix.

APPENDIX

POLISHING SINGLE POINT DIAMOND TURNED MIRRORS

R. E. Parks, R. E. Sumner and R. E. Strittmatter
Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

A method of removing the high frequency microripple from single point diamond machined mirrors has been developed. The process uses conventional hand polishing techniques and laps of sufficient rigidity to bridge the microripple yet soft enough not to scratch the metal mirror surface. Substantial material must be removed from the mirror surfaces in some cases and the surface figure may be degraded unless careful testing is done during the process. We present photographs showing the reduction in scattering and improvement in mirror surface roughness as the result of the polishing. Phase-contrast microphotographs also show that the polished surface is almost as free of mechanical defects (scratches and pits) as the original virgin turned metal surface.

Key words: Metal mirrors; microripple; polishing; scattering; single point diamond turned mirrors.

1. Introduction

We present a series of pictures of 400 mm diameter single point diamond turned copper off axis parabolas before, during and after polishing to remove the microripple. Before polishing, the scattered light in the visible is sufficiently intense to make proper alignment difficult to impossible. Double pass interferograms contain little useful information.

After polishing, the image forms a tight core, a double pass interferogram is easy to interpret and a microphotograph of the surface shows the absence of turning marks.

2. Test Methods

In order to assess the results of the polishing procedures, several methods of testing the off axis parabolas were used. A point source microscope was used to examine the image formed by the mirrors while a modified Fizeau type interferometer was used to measure the surface contour. In order to study the surface on a smaller scale, a Leitz metallographic microscope with a 10X differential interference contrast objective was used.

Figure 1 shows the parameters of the mirror and its optical test. The focus of the test instrument is placed in coincidence with the focus of the parabola. The light, after being collimated by the parabola, is autoreflected by an optical flat placed perpendicular to the optical axis of the parabola. After a second reflection in the parabola the light returns to the original focus after suffering twice from the defects in the surface of the parabola.

In order to examine the return image from the parabola, a point source microscope was placed with its objective focus at the focus of the parabola. Figure 2 shows the design of the microscope and the position of the camera used to photograph the image. A 20X objective was used to insure filling the $f/1.9$ cone angle of the mirror. Illumination was provided by an optical fiber drawn down to a diameter of 0.3mm and bent parallel to the axis of the microscope. The image size projected by the 20X objective was $15\mu\text{m}$.

In figures 4 (a,b,c) the upper spot of light is light back scattered by the fiber and is not representative of the source size itself. The lower spot of light (elongated horizontally in figures a and b) is the return image from the mirror at several stages of polish.

In order to assess the surface figure of the mirror, a modified Fizeau type interferometer^[1] was used as illustrated schematically in figure 3. In this application the advantage of this interferometer is that the $f/1.9$ acceptance cone of the parabola can easily be filled without resorting to a rather expensive fast diverging lens required by some interferometers. The pinhole spatial filter in the interferometer as reflected in the beamsplitter cube is placed at the focus of the parabola. Interference is then obtained between the return wavefront from the parabola and the reflection off of the spherical reference surface on the beamsplitter cube. The fringes may then be photographed directly using a 35mm camera equipped with an $f/1.5$ or faster lens or by projection through a large Erfle eyepiece onto Polaroid film. The results of this test procedure with the interferometer are shown in figures 5 (a,b,c). The improvement in fringe representation is a result of polishing the mirror.

In order to examine the surface of the mirror itself, a Leitz metallographic microscope was used. The microscope was equipped with a 10X differential interference contrast (Nomarski type) objective. Results of this examination are shown in figures 6 (a,b,c) all to the same scale.

3. Polishing Procedure

Before discussing the process worked out for polishing the microripple from these mirrors a possible misunderstanding should be clarified. The impression has perhaps been given that these mirrors do not represent the state-of-the-art or are in some way much worse in terms of microripple than can be generally expected of diamond turning. In fact these mirrors do represent something very close to the state-of-the-art for what these mirrors are; namely they represent a parent parabola of $f/0.37$ some 2 meters in diameter with a mass in the neighborhood of 300kg. This piece was turned on a modified Excellto N/C lathe accurate to $\pm 0.4 \mu\text{m}$ of the desired average contour over an annular band 40 cm wide. Components smaller in size and whose contours are not aspheric have vastly superior surface finishes. Small spheres and flats generally look as good and often much better than can be obtained using conventional polishing techniques.

These remarks regarding the polishing of these mirrors are intended to illustrate that methods exist to improve the quality of large aspheric mirrors which suffer from scattering in the visible rather than degrading in any way the extremely powerful technique that diamond turning has shown itself to be. In fact we consider the turning and polishing processes to be complimentary techniques rather than competing ones.

The polishing process we have developed is a two step procedure; the first removes the microripple with a firm or stiff lap but somewhat degrades the cosmetic appearance of the surface, the second step restores the cosmetic appearance to that obtained from the turning lathe but less the microripple.

The stiff lap was made by melting a quantity of beeswax and straining the same through cheesecloth. To the molten wax, an equal volume of $0.3 \mu\text{m}$ alumina (Linde A) was added and thoroughly mixed. If a lesser quantity of alumina is used, the mixture may be too thin to stay mixed and the compound will settle out. The mixture is then poured onto a lap base; we used a 10 cm diameter base.

After the mixture has cooled, the lap is beveled and channeled to give 2.3 cm facets. The lap is then softened by moistening with kerosene. After 5 minutes or so the lap is ready for use. We found that if the wax had been softened with a small quantity of turpentine when it was molten, the lap would be almost soft enough that it could be used on copper with soapy water as a lubricant without scratching. Extreme care was needed with this lap to avoid damage. This is why we simply turned to kerosene as a lubricant. The lap slowly dissolves in use but it takes real effort to make the lap scratch copper deeply.

Before applying the lap to the work, the mirror should be carefully beveled with a clean, fine file and the bevel polished out using Pellon or felt and Linde C. The risk of picking up a burr from the edge is too great to forget this step. After beveling, the filled wax lap is rubbed perpendicularly to the turning marks using a generous amount of kerosene for lubrication. The slurry should turn black immediately indicating a good cutting action. To judge progress, simply flush the surface with clean kerosene. The surface will appear scuffed or lightly brushed and the evenness of polishing is indicated by the uniformity of the brushed appearance. This surface degradation has no particular depth and will polish out quickly during the second step of the process.

The idea of a lap that slowly dissolves may not sound like a good idea at first but it has several definite advantages. For one, it is very soft, something necessary for a metal as soft as copper. In addition, being an oil, the kerosene keeps the metal from oxidizing allowing one to leave his work for a time without the worry of corrosion or etching. Further, one of the easiest ways of picking up a scratch is for some of the metal that has been polished off the mirror to cake up on the lap. This is avoided because there are no hard surfaces on the lap for the metal to affix to. Finally, the lap continues to supply fresh compound at a uniform rate as the lap is used. We have found the alumina filled wax lap and kerosene to be a very successful method for removing the microripple in diamond turned mirrors.

Once the ripple is reduced to the desired level and the figure is satisfactory, we proceed to the second step of the process to restore the original brightness to the copper surface. First clean up the surface by a thorough flushing with kerosene followed by acetone. It is difficult to completely remove the wax film. Don't worry and don't be tempted to wipe it off with any sort of physical means. This usually spells disaster. Any remaining wax film will come off during the second step.

For a lap we use 2 to 4 mm thick open cell polyurethane sheeting which we obtain from upholstery or fabric shops for something like \$2 a square meter. Cut the sheeting into a piece 30 cm square and wash thoroughly with filtered water. The least contaminant at this point can ruin everything. Make a paste of Linde A, dishwashing detergent (Liquid Ivory, etc.) and water. Make a ball of the foam sheeting, dip into the paste and uniformly scrub the mirror surface. Use mild to moderate pressure and a buffing motion. Too great a pressure will eventually scratch, too light a pressure will take too long.

Very quickly the slurry will turn black indicating material removal. Continue a uniform polishing action while keeping the surface wet with additional filtered water. To inspect progress, flush the surface with well filtered water. A clean piece of the polyurethane sheeting thoroughly wet may be used to help with the clean-up. The remarkable thing about the polyurethane sheeting is its ability to be used as a cleaning cloth on soft copper without scratching.

Discretion must be used when polishing with the urethane sheeting. Ideally, polishing should be continued until the brushed appearance from step one is gone but no farther. The second step should not be used for removing heavier scratches but rather the first step carried on longer until a uniform brushed surface is obtained with no heavy scratches. The problem with using the foam sheeting too long is the same problem that arises whenever a "soft" lap is used, the softer areas of the surface polish faster than the harder areas. This leads eventually to an orange-peel surface. Before reaching this stage the copper begins to show evidence of low level wide angle scatter. A high intensity light focused on the surface will show a haze developing on the surface if the foam is used too long. The only solution then is to go back to the soft filled wax lap to get a smooth but brushed surface and then repeat the foam lap treatment for a shorter time.

If the wax lap finish on the surface is well done to start with, the finish obtained with the foam lap can be spotless, not a sign of scratches or pits. The finish or specularly is at least as good as the virgin turned surface except now of course all the ripple and consequent scattering are removed.

After finishing with the foam lap, wash the mirror thoroughly (including all the edges) with filtered water followed by distilled water. The water should bead off the clean surface. Then flush with CP acetone or CP methanol and blow dry in a sheet with dry nitrogen. This final cleaning step is important so that no water or other residue is left on the copper to potentially stain or etch the surface.

4. Results and Conclusions

Now that the polishing process has been explained we would like to return to the photographs obtained during the testing of various stages in polishing. The photographs in Fig. 4 show the reduction in scattering as the microripple is removed. Fig. 4a shows a mirror just as it came from the SPDT lathe. The light, in fact, scattered far off the illustration, this being the central third. The herringbone pattern is caused by the deeper of the turning marks. Because these mirrors are off-axis sections, the turning marks are roughly unidirectional and thus the scattering is principally perpendicular to the grooves as in the case of a diffraction grating. This preferential scattering is particularly bothersome in the visible because astigmatism is the principle aberration caused by misalignment of an off-axis parabola. The astigmatism also causes a lengthened image and it is very difficult to separate the effects of the scattering from the astigmatism due to misalignment. This makes it all but impossible to line up a SPDT off-axis section if the microripple is too severe.

Fortunately, the polishing procedure very quickly corrects this problem, the finest microripple structure being the first to polish out. Fig. 4b shows the return image after polishing one of the 400 mm copper mirrors for about an hour with the filled wax lap. Although the image is still considerably longer than it is high, the herringbone pattern is gone and there is a definite although elongated core. After another 3 hours polishing with the wax lap and then cleaning up the surface with polyurethane foam sheet, we get the image shown in Fig. 4c. Here the image is 3-4 times the source size of $15\text{ }\mu\text{m}$ and is in fact geometrically small enough that this mirror will give diffraction limited performance at $10.6\text{ }\mu\text{m}$.

The interferograms in Fig. 5a through c show the same mirror at the same stages described above. Again in Fig. 5a notice the difficulty in trying to sort out astigmatism from other effects. Even the interferometer is not useful for alignment purposes when used double pass off of the parabola. After the high frequency ripple has been polished off, the fringes become readable with some difficulty in Fig. 5b. Residual turning marks are still easily apparent in the surface of the mirror as seen in the fringes. At the completion of the polishing in Fig. 5c the surface appears smooth with only the slightest indication of residual ripple at the edges of the mirror.

The microphotographs in Fig. 6a through c show equally dramatic changes in the surface of SPDT mirrors. Fig. 6a shows the untouched mirror while Fig. 6b is after 1 hour of polishing. On a small scale all the ripple is gone, there being just a hint of occasional residual ripple. Following further polishing including work with the foam lap, the surface looks almost as homogeneous as the turned except that the ripple is gone.

In conclusion, we have developed a method of removing the microripple from single point diamond turned surfaces in an easily performed, conventional manner. The method leaves the surfaces cosmetically as clean and bright as the originally turned surfaces yet free from the scattering caused by the microripple. Although the figure of the surfaces can be changed by the polishing, careful monitoring and correction can be used to avoid figure degradation and in fact if need be the figure can be improved.

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Figure 1. Parameters of double pass autocollimation test of 400 mm diameter off-axis parabolic segment.

Figure 2. Point source microscope used to examine return image from off-axis parabolic segment. The source is fiber optic cane drawn to a 0.3 mm point.

Figure 3. Schematic of the Shack interferometer used to measure wavefront errors in the parabolic segments.

(a)

(b)

(c)

Figure 4. Return images off of parabolic segments as photographed using the point source microscope. The upper light spot is scattered light from the source itself. (a) Very elongated return image from an unpolished SPDT off-axis parabola. (b) Return image from the same mirror after removing the majority of the microiripple using a Linde A filled wax lap. The polishing time was about one hour. (c) Same mirror after the completion of the second step of polishing.

(a)

(b)

(c)

Figure 5. Double pass interferograms obtained with the Shack interferometer showing the mirror surface ripple as a function of polishing time. (a) Typical surface irregularity of an unpolished SPDT off-axis parabola. (b) Same mirror surface after one hour of polishing. (c) Same mirror after the completion of the second step of polishing.

(a)

(b)

(c)

Figure 6. Microphotographs of the surface of a SPDT copper off-axis parabola at different polishing times. A 10X differential interference contrast objective was used. (a) A virgin SPDT mirror. (b) Surface after polishing one hour with filled wax lap. (c) Surface at the completion of polishing.

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