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Finishing of Precision Generated Metal Optical Components

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FINISHING OF PRECISION GENERATED METAL OPTICAL COMPONENTS**

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Abstract

Diamond turning and precision generation of aspheric metal surfaces has promoted a change in lapping techniques due to the extremely close figure tolerances and surface finishes that have been achieved. In order to polish the unusual aspheric figures, we utilized special tooling, diamond abrasive, and silicon oil and techniques which we will describe in detail. Our studies include small flat diamond turned samples of copper, electroplated copper, electroplated silver, electroplated nickel and silver as well as large aspheres such as an f/0.75, 35 cm diameter copper ellipse. Results from cleaning studies on flat samples using ultrasonics and vapor degreasers will also be summarized. Interferograms of wavefront distortion and analysis of focal volume will be included as well as 10.6 μm reflectivity and a summary of laser damage experiments.

Introduction

The finishing of aspheric surfaces by highly skilled opticians is a time-consuming operation especially when the F/d ratio of the mirror is small and the slope changes are large. This dictates the size of the tooling and also puts limitations on the shape and rigidity of tooling.

The material is another limiting factor especially in the two cases that this paper is based upon. The first mirror was an f/.75 copper ellipse that was diamond turned at the Lawrence Livermore Laboratory (LLL). The second mirror was a 105° off-axis aluminum parabola that was generated by Frank Cooke Optical Co.

Polishing techniques vary from shop to shop and from optician to optician. Each technique is adapted to the available equipment and the peculiarities of the job. The major concerns of the approach we have been using is to achieve low surface roughness (10Å RMS) and eliminate as much as possible surface disturbance (micro-sleeks) while keeping reflectivity high and scattering low.

12" f/.75 Copper Ellipse

Laser damage on polished surfaces (1) is at the moment barely meeting the threshold level to be considered usable in a focusing system. Diamond turned optics meet and exceed the laser damage threshold level, (1) but scattering, due to the machine marks, causes a line image (Fig. 1). On the copper ellipse 90% of the energy fell within a 50 micrometer-diameter blur size. This measurement was done using a knife-edge test.

The ellipse was precisely generated, except for a 4-inch zone in the center (Fig. 2) that was measured as 1.1 micrometer high, the remainder of the test fell within λ/2 peak to peak at 6328Å as measured on a Twyman-Green Unequal Pass Interferometer (Fig. 3). In terms of most N.C. machining, this accuracy had never been achieved before for parts directly off a turning or generating machine. (Fig. 4) This would seem to make the optical finishing easier; however, having to start with a surface finish that was already better than could be polished makes for some nervous moments. Excellent polished surfaces have been produced with relative ease on flats and spherical parts, but when one is considering a 12-inch diameter f/.75 ellipse, the difficulties in producing a comparable surface become paramount.

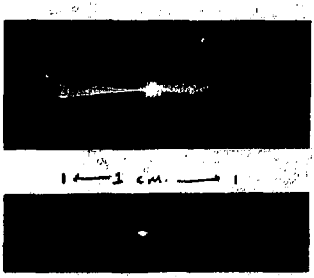

FIG. 1. Copper ellipse focal spot

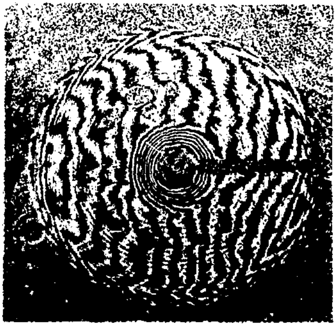

FIG. 2. Four pass interferogram at 0.6 μm of the copper ellipse after the first two days of polishing.

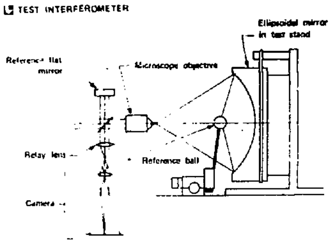

FIG. 3. Test interferometer using a Twyman-Green unequal arm, four pass set up and a 0.63 µm light source.

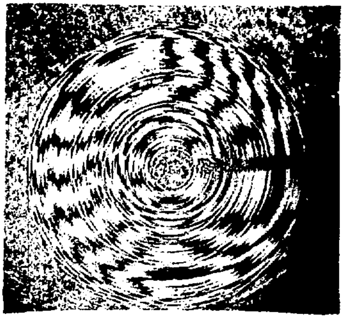

FIG. 4. Interferogram of the copper ellipse as machined.

The ellipse was mounted in an aluminum holder using ring support; centering and holding were done by 8 equi-spaced nylon tipped set screws. The polishing machine was a 22-inch Strasbaugh variable-tilt machine. ~~A pin~~ drive unit designed and built at LLL was mounted on the stroke arm for tool rotation. This gave the ability to run both stroke and spindle speeds very slowly and concentrate material wear at the tool contact point. It also balanced the tool and helped prevent any local "rocking" or tilting of the tool. In the working of local zones, the variable speed of the tool (0 to 175 rpm) gave good control on the rate and position of material removal.

The polishing tools were aluminum with the vertex radius of the ellipse machined on them. A number of different tools were used for any number of different reasons; star tools, ring tools, pie-shaped tools and a full size tool were all applied to the varying conditions of the surface. All of the tooling was pitch based (Gulgoz 64 Swiss pitch) with a beeswax and fine airplane silk coating. The construction of the tool was built around the use of diamond powder. The silk traps and holds the diamond to prevent the constant sinking and loss into the pitch. The wax softens the tool-to-surface contact, preventing the diamond from rolling and scratching.

The vehicle used to carry the diamond was #1 Centistoke Dow Corning Silicon Oil. I used both natural diamond (Pensco) and explosion formed synthetic diamond (du Pont). The final polishing was done with 1/4 micrometer diamond. The only difference I noticed between the two types of diamond was the synthetic appeared to cut faster and more consistently; the surface finishes were comparable.

The difference in polishing action of the diamond using the oil is quite remarkable. I would guess that the removal rate is twice as fast as when using water as a vehicle. The obvious advantage of the oil is its chemical neutrality of active surfaces like copper and silver. It enables an optician to figure an aspheric surface and not worry about surface corrosion. On larger surfaces the advantage is that when stopping a run, the optician does not have to worry about quickly cleaning the surface before it stains. Removal of the oil can be done using a solvent bath or vapor degreaser and ultrasonic cleaning. The cleaning process for these surfaces should be non-contact cleaning; any kind of wiping produces sleeks or roughens the surface. (1)

On spherical parts (6-inch diameter) that had been diamond turned, the polishing time to remove the machine marks and bring the surface to a clean condition was approximately 45 minutes. This copper is extremely soft, being in an annealed condition and has to be handled much more carefully than BeCu or OFHC unannealed.

The major reason for polishing the copper ellipse was first to remove the effects of the machine marks (Fig. 5a, 5b) which were more pronounced than the marks on diamond turned spheres or flats, then measure the image and the energy distribution and compare them to the as machined values. (Table 3) (Fig. 6) One of the interesting developments as polishing progressed was that as fringes smoothed out, the wavefront picture became clearer (Fig. 2) indicating the slope errors were hiding the true picture. This finding allowed corrections to be made on the subsequent silver-plated beryllium clamshells.

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FIG. 5a. Interferogram taken with same set-up of Fig. 2 except showing the effects of diamond tooling marks near the center.

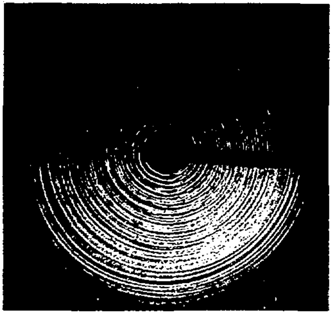

FIG. 5b. Machining marks: By blocking the reference beam the effects of the machining marks present in other interferograms are now more apparent.

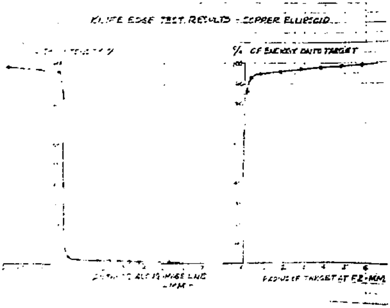

FIG. 6. Knife edge test of energy distribution in the focal spot of the as machined copper ellipse.

Roundness µm	0.32
Max. slope angle on part X 10^{-6}	40
Part surface error µm	1.11
Max. displacement at target µm	9.5

TABLE 1. As machined Copper clamshell figure error summary

The approach in polishing was to run a small ring-shaped tool using a fast stroke going from edge to center varying stroke position and spindle speeds and reduce the strong slope changes resulting from diamond turning without altering the basic figure. This was accomplished within 4 days time including testing. The fringes had been smoothed out enough to show a few other problems such as out of roundness and asymmetrical areas (Fig. 7a, 7b).

In the course of correcting these problems, I created some of my own. I used some overly flexible tooling and wound up with flat spots and zones. I did not vary the speed randomly or often enough, also the stroke positions should have been more random. These problems can be corrected by the use of a rigid full size tool to average and bridge the errors.

The surface quality approached the original cleanliness of the machined surface. The background condition was not as good, by that I mean micro-sleeking. I feel the surface can be polished as clean as a diamond turned surface. We hope to determine whether or not the damage threshold level is raised to equal diamond turned surfaces in our future studies.

Some of the data on 1.5-inch samples show promise especially the Nomarsky photographs of diamond turned polished copper samples. The surfaces appear as smooth as diamond turned surfaces. (2) The only problem is eliminating the micro-sleeking. The reflectivity at 10.6 µm was as high as 99.3% measured at Kirtland AFB (Table 2). Scatter levels were not as good due to the micro-sleek structure, the lowest total integrated scatter at 0.63 µm was 0.5%. At 1.06 µm the reflectivity dropped somewhat in comparison to diamond turned parts (Table 2,3)

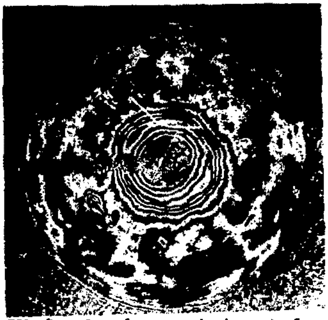

FIG. 7a. Interferogram showing out of roundness after polishing.

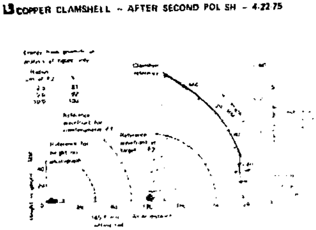

FIG. 7b. Summary of Figure: This summary of figure was obtained from an aralysis of interferograms taken of the copper ellipse after four days of polishing.

TABLE 2. Comparative values of reflectivity at 10.6 μm and 1.06 μm for the same mirror.

Mirror	10.6 μm reflectivity *± 0.002*	1.06 μm *reflectivity*	0.63 μm reflectivity	% total integrated scatter *0.63 μm*
Baker 2	0.992	0.971 ± 0.005	0.92	0.7
Baker 3	0.993	0.980 ± 0.007	0.92	0.6
Baker 4	0.992	0.978 ± 0.002	0.91	0.5

TABLE 3. Summary of 1.06 μm *reflectivity*(3)

ID	$R \pm \delta R(10^3)$	Comments
		Silver
L^3-7-Ag	0.988 ± 1	EP/HT/DT
L^3-5-Ag	0.990 ± 1	EP/HT/DT cleaned w/tissue
L^3-6-Ag	0.976 ± 2	EP/HT/DT/polished aqua dag/silicon oil, cleaned*
L^3-Ag (new)	0.985 ± 1	EP/HT/DT
Y-12D-35B	0.988	EP/DT
		Copper
L^3Cu78	0.989 ± 1	EP/HT/DT
L^3Cu44	0.956 ± 4	EP/DT/OCLI coated/Polished in aqua dag Si oil
Baker 10	0.973 ± 1	OFHC polished Si oil & DIAMOND
Spawr Cu	0.980 ± 1	OFHC polished
L^3-Cu-91	0.985 ± 1	OFHC DT
L^3-Cu-90	0.985 ± 2	OFHC DT
L^3-Cu-90	0.989 ± 1	Cleaned 30 sec. in vapor degreaser (TF freon at 122°F)
L^3-Cu-90	0.988 ± 1	Cleaned total 90 sec. in vapor degreaser (TF freon at 122°F)

EP = Electroplate HT = Heat Treated DT = Diamond Turned

* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Measurement of Nickel Surfaces for Roughness

Recently on 3 inch diameter nickel samples using 0.1 μm diamond we have been obtaining surfaces so smooth that it is hard to measure and attach any sort of value to it. Measurements were made using a Taylor Hobson Talystep profilometer with a stylus probe that is rectangular in cross-section (0.1 μm by 2.5 μm). The trace was digitized and fit to polynomials up to 4th order. In all cases, the deviation as less than 10 Å rms. (Fig. 8) This value will have to be substantiated because of a problem with stylus instruments such as the Talystep which occurs when the spatial wavelength of the surface irregularities is smaller than the largest dimension of the contacting area of the stylus. *Consider an extreme example.* It would be possible to take many straight pins and bunch them together such that all the points touched a plane. Measuring the "surface" formed by the pins with a stylus whose largest contact dimension was greater than the diameter of the pins could yield a trace which would indicate a surface with a 0.1 cm peak-to-valley deviation whereas the pins are in reality 50 cm long. We know that our nickel surface has micro-sleeks from our investigations with a Zeiss double objective micro-interferometer (after the design by Linnik) at 1000X and 100X. These sleeks are narrower than 1 μm, are about 0.1 μm deep and infrequently occur on the surface. We have not yet found a suitable method of taking these micro-sleeks into consideration when quoting the actual rms surface roughness. F.E.C.O. interferometry is limited in such studies by its resolving power along the surface. Laser damage studies (1) indicate that scratches influence pulsed laser damage threshold. The effects of such micro-sleeks or laser damage would be an interesting study.

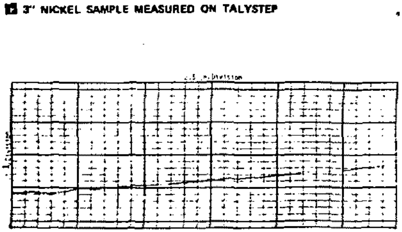
3' NICKEL SAMPLE MEASURED ON TALYSTEP

FIG. 8. Talystep profilometer of polished electroplated nickel sample demonstrating extreme smoothness.

Cleaning of Metal Optics

Cleaning of the optics is important for several reasons. First, it is important to remove the residue of the fabrication process from the part before any stain may be irreversibly formed. In general, the longer a stain is left on a surface the harder it is to remove. Periodic cleaning for many reasons is also required. Improper cleaning will degrade the laser damage by as much as 50% by scratching the soft surface.

A vapor degreaser is an effective non-contact method of cleaning the part. We have been able to remove some of the oil-alcohol residue from a diamond turned surface using TF freon at 50°C.

We have experienced catastrophic results from ultrasonic cleaning. A large (approximately 40 cm major axis by 20 cm minor axis) diamond turned OFHC CDA 101 copper mirror was ultrasonically cleaned for about 45 minutes using a solution of radiac (a detergent) and water. The surface of the mirror was damaged enough by the ultrasonic cleaning to require re-machining. The damage appeared very severe in small areas near the edge as if a stream of particles had hit the mirror obliquely, roughening the surface in a strip about 2 mm wide by 10 mm long. There were other blotchy appearing areas about 2-3 cm diameter where the finish appeared dull. Similar destructive results have been reported on fused silica in studies done in Australia. (4) Although these times are longer than would be prudently used in cleaning parts, House and co-workers have shown that even 30 minutes of ultrasonic cleaning decreases the laser damage threshold by 20%. House (5) found that radiac caused more degradation than the micro solution he used.

We feel that ultrasonics can be used to successfully clean metal mirrors if one limits the time. We have cleaned diamond turned electroplated copper and silver samples in freon. Inspecting the part with Nomarski differential interference contrast microscopy at 177X we could see no changes in the surfaces for accumulated cleaning of up to 8 minutes on the copper. We have not performed laser damage tests on ultrasonic cleaned samples. We plan to extend our study with more quantitative measurements of the effects of ultrasonic and vapor degreaser cleaning techniques.

Aluminum Parabola

The off-axis aluminum parabola was quite a different problem. The material presented a challenge being 6061 aluminum which had not been annealed, making it even more difficult to work. Samples of 6061 T6, which had been polished using the same methods had better than 85% reflectivity at 1.06 μm as measured on our Cary spectrophotometer.

The generation of the parabolic curve had been done by Frank Cooke using a continuous diamond belt with an almost line contact at the cutting point.[6] The belt followed a N.C. generated cam as the mirror was swung about the rotational axis of the mother parabola. This produced a very reasonable overall contour;

however, the steps in the cam reproduced heavily on the surface of the part, subsequent cuttings were much better after the cam was smoothed. The surface produced was fairly good in the continuous areas, from visual observations it approached the 15 microinch surface specification. In the stepped zones the damage was much worse. The diamond belt marks went deeper than I had anticipated, and the polishing time was increased accordingly. Initial polishing was done with a full sized plaster tool which was cast on the surface. The lap was pitch based with a painted film of beeswax on top. In the rough stages of polish, Linde "C" and Linde "A" were used with 5 cs. Dow Corning Silicon oil.

The parabola was mounted on a Strasbaugh cylindrical machine using a 2-axis rotating table allowing continual positioning of small tooling. After averaging the zones from generating with the full tool, I went to a 3-inch diameter ring tool of pitch with wax and using a long fast stroke bridged across the steps to quickly reduce their heights as uniformly as possible. While stroking with a constant length in both the "X" and "Y" directions, I manually rotated and changed positions to equally cover the mirror and average the polishing. Having this type of control while running was very necessary because of the shape and character of the part. Some handwork was done of localized zones, but most of the work was done by machine.

The testing was done using a series of Ronchi gratings; 50 line-inch up to 175 line-inch rulings were used. The parabola was collimated against a flat and its axial position was established from a reference flat which had been generated on the part. This allowed good repeatable positioning from run to run. The part is still in work and at the time of this writing the image size was measured at 0.023-inch in average diameter; this will be improved. Total man hours spent to get to this point were 140 hrs. So even with a well generated surface, the polishing time is becoming a significant factor in terms of price as well as scheduling.

Summation

Both of these mirrors were considered test pieces to be used to develop techniques and to demonstrate the optician's capabilities. The precise generation of these surfaces allowed the optician to concentrate on the other considerations such as the surface quality and the overall performance criteria. Too often, after many hours of grinding to generate a reasonable figure, these considerations are sacrificed in order to meet the schedule and the budget.

Acknowledgements

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