rf

UCRL - 76822 Rev. 1
PREPRINT
Conf-750730--2

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

1.06 μm 150 psec LASER DAMAGE STUDY OF DIAMOND TURNED, DIAMOND TURNED/POLISHED AND POLISHED METAL MIRRORS

T. T. Saito, D. Milam, P. Baker, and G. Murphy

July 24, 1975

This paper was prepared for presentation at the 7th Annual Laser Induced Damage in Optical Materials, July 29-31, 1975, Boulder, Colorado

1.06 μm 150 psec Laser Damage Study of Diamond Turned, Diamond Turned/Polished and Polished Metal Mirrors †

T. T. Saito*, D. Milam, P. Baker, and G. Murphy, Lawrence Livermore Laboratory
Livermore, California 94550

ABSTRACT

Using a well characterized 1.06 μm 150 psec glass laser pulse we have studied the damage characteristics for diamond turned, diamond turned/polished, and polished copper and silver mirrors less than 5 cm diameter. Although most samples were tested with a normal angle of incidence, some were tested at 45° with different linear polarization showing an increase in damage threshold for S polarization. Different damage mechanisms observed will be discussed. Laser damage is related to residual surface influences of the fabrication process. Our first attempts to polish diamond turned surfaces resulted in a significant decrease in laser damage threshold. The importance of including the heat of fusion in the one dimensional heat analysis of the theoretical damage threshold and how close our samples came to the theoretical damage threshold will be discussed.

Key words: Damage threshold; diamond turned optics; copper mirror, 1.06 μm polishing; dark field photography.

† Work performed under the auspices of the U.S. Energy Research and Development Administration.

* Detached duty from the Air Force Weapons Laboratory, Laser Division, Kirtland AFB, NM 87117

INTRODUCTION

Metal mirrors are of interest to the high power pulsed laser programs because of the high reflectivity and good thermal conductivity. Diamond[1] turning of metals offers expanded design flexibility to incorporate fast parabolas or unusual shapes such as compound axicons or ellipses. In addition, diamond turning may offer considerable cost benefits over dielectrics for large diameter optics which will require refinishing due to laser damage.

This paper presents our study of laser damage on metal mirrors. We shall discuss the experimental arrangement, preparation of the samples, and demonstrate the degradation effects of polishing or even rubbing/cleaning diamond turned silver. Comparisons of our results to other studies of polished copper at different wavelength and pulse length indicates that a similar damage mechanism is present for less than 500 nsec pulses.

EXPERIMENTAL APPARATUS

A schematic of the damage facility in the laboratory is shown in Fig. 1. The source consists of a mode-locked oscillator and pulse selector, two YAG preamps, and two glass rod amplifiers. Fast diodes A and B monitor waveforms of the pulse train and of the switched-out pulse. Integrating diodes C and D measure the energy of the switched-out pulse before and after amplification. The output energy is controlled by setting the amplification. Typical beam parameters in a plane normal to the beam at the test sample's surface are;

Energy	-	.0 - 0.5 joules
Beam profile	-	nearly Gaussian
Beam diameter	-	~mm at 1/e level
Pulse duration	-	150 ± 25 psec

The damage experiment is also shown in Fig. 1. A Galilean telescope is adjusted to serve as a focusing element, with the beam waist being 4-8 meters distant as required. The reflection from the front surface of a bare BK-7 wedge is centered on an aperture placed in front of the calorimeter. The aperture is chosen to correspond to the approximate diameter of the beam at the e^{-2} intensity level, and the centering of the aperture is photographically certified at the beginning of each day of operation. This calorimeter serves as the fundamental monitor of pulse energy.

The reflection from the rear surface of the BK-7 wedge is incident on a 40% - 100% mirror pair used to form multiple replicas of the beam profile existant in the sample plane. The images are recorded on polaroid film so that the results of each firing can be viewed immediately thereby avoiding the possibility of operating with significant undetected problems with the beam profile. The polaroid photos also furnish an instant estimate of the incident energy density. We have found these estimates to be reproducible to 20% as substantiated with much more ellaborate methods.

The replicas are also recorded on 1-Z plates. From five to nine firings can be recorded on each plate. The most intensely exposed of these is reduced using the Photocal routine.[2] That serves to calibrate absolutely the exposure vs. film density curve for that particular plate. The film densities resulting from the remaining shots recorded on the same plate can then be interpreted without recourse to Photocal.

Photocal is a sophisticated generalized computer routine developed by our colleague Dr. Joe Weaver for providing the energy density on the sample.

After the exposure versus film density (i.e., the H & D curve) for the plate is determined, a hundred by hundred matrix of optical density versus position is established by repeated scans of a spot. The optical density and H & D curves are used to yield the relative intensity as a function of position in the sample plane and a three-dimensional computer picture is produced. Using the total energy measurements from the calorimeter the program can then calculate the peak energy density taking into consideration intensity spikes and other departures from true Gaussian profiles.

Values obtained from the reduction of 1-Z plates are qualitatively compared with the polaroid beam photographs to insure that no significant data reduction errors have been made. The incident energy densities of a set of firings can be ranked from least to greatest by simply counting the number of replicas recorded on polaroid film for each firing. The reduction of 1-Z data should yield the same ranking.

Since the Gunn calorimeters appear to be accurate to within about 3-5%, energy densities determined in these experiments should mirror that accuracy. Estimates of the energy made from the same 1-Z plate but without the 100 x 100 matrix are accurate to 10%. The estimates of energy density from just the polaroid pictures are accurate to 20%.

The pulse width is determined by using a streak camera. We did not measure the pulse width for each shot. We have many thousands of laser firings, and have periodically measured the pulse width to be 150 ± 25 psec.

EXPERIMENTAL TECHNIQUE

Sample Preparation. The diamond turned samples were all electroplated on copper or brass substrates. Lea Ronal[a] silver and copper pyrophosphate electroplating were used. Most of the samples were heat treated by placing

(a) Produced by Sel-Rex Corporation, Nutley, N.J.

them in a beaker with oil and slowly raising the temperature to 150°C, maintaining 150°C for one hour, and then removing the beaker from the heat source and allowing the beaker/oil/mirror blank to cool to room temperature. The heat treating process was used to relieve the residual stresses from the electroplating.(3) The samples were then diamond turned. Some of the samples were diamond turned simultaneously in batches of 18. After they are diamond turned and while the spindle is spinning, isopropyl alcohol is used to rinse the cutting oil off the samples.

Some of the diamond turned samples were polished using techniques which will be described in detail elsewhere.(4) Based on the success of others (5,6) in using India Ink, we used suspended carbon particles (Acqua Dag) to polish some of our samples. Other samples were polished with diamond and silicon oil. Our lap was made of pitch, bees wax, and silk.

Immediately before the laser damage test, the samples were rinsed with various solvents in an attempt to remove the residual film. Eastman lens cleaner left such a bad residue on some parts that they were not tested. We found the best results came from rinsing the samples first with acetone, and then removing the residual acetone film with alcohol. Further studies of cleaning of diamond turned optics are being planned.

Laser Damage Testing Unless specified, all tests were performed at a nominally normal angle of incidence. Experiments were also performed with a 45° (±2°) angle of incidence with p or s polarization. The sample was placed on a stage which had translation stages in directions perpendicular to the direction of laser propagation. Each shot number and the corresponding coordinates of illumination were recorded along with any observations made before firing, during firing (viewed through laser safety glasses), or after firing. We found small emissions of light could be seen during the firing without seeing any damage using a dark field illumination technique. Before and after the firing we inspected the surface by dimming the room lights and illuminating the sample with a bright (white) microscope light. Residue films from the cleaning process, scratches as well as laser damage could be easily seen. Newnam has reported that the most sensitive technique in his experiments was the visual determination of scattering of an auxilary low power cw laser.[7] Similar to Newnam we found light scattering to be the best technique for determining damage.

Dark Field Illumination Photographs We have adapted Hizney's photographic technique to present the surface defects which we saw during the laser tests.[8,9] The simple experimental set-up is shown in Fig. 2. A white light source illuminates the sample such that the specular beam misses the camera which photographs the scattered light. Fig. 3 is a series of photographs taken in sequence. A diamond turned copper mirror was photographed as received from the diamond turning lab as shown in Fig. 3a. Figure 3c and 3d were taken immediately after 3b but by increasing the exposure time. This tecnhique has several advantages:

1. It is easy and economical to set up.
2. It may lend itself to an easily describable and therefore reproducible technique.
3. It can give 100% part inspection.

4. It presents artifacts (especially residual films) which are not easily observed with even Nomarski microscopy.

We plan further investigations of this technique with the possibility of establishing a quantitative technique for measuring cleanliness.

It was very difficult to find the laser damage sites when using a microscope, even with a Nomarski differential interference contrast accessory. The best success in doing optical microscopy was to place the sample on the translation stage while illuminating it from the side with the high intensity white light source. We could then see the laser damage spot and translate the sample until the light from the microscope coincided with the site of interest. Simply scanning the sample with normal observation usually resulted in overlooking the damage sites, because of the very small differences in the background surface and laser damage in some sites.

Theoretical Calculations Since our 150 psec pulse length is so short, a one-dimensional heat transfer model is adequate for calculating the damage threshold. The laser light is absorbed and heats a cylinder whose base is the same as the cross section of the laser on the mirror and whose height is $(\pi\alpha t/4)^{1/2}$ where t is the pulse length and α is the thermal diffusivity in cm^2/sec. The incident laser energy density, E_I, with pulse width t needed for a temperature rise, ΔT to the melting temperature is a function of the density ρ, and the specific heat s, and the absorption A of the laser light as given by equation 1.

$$E_I = \frac{\Delta T \rho s}{2A} (\pi\alpha t)^{1/2} \quad (1)$$

In order to change phase from a solid to a liquid, the heat of fusion H must be included requiring additional energy E_2.

$$E_2 = \frac{H\rho}{2A} (\pi \alpha t)^{1/2} \qquad (2)$$

We have not included the heat of vaporization because we are calculating the threshold energy density, E_{th} which is the sum of E_1 and E_2. (It is not necessary to vaporize the mirror in order to see a change in the surface.)

$$E_{th} = \frac{(\pi \alpha t)^{1/2}}{2A} (\Delta TS + H) \qquad (3)$$

This calculation assumes a uniform intensity beam, but is valid for our experiment since the $1/e^2$ radius is so much greater than the thermal diffusion length. Note the $t^{1/2}$ time dependance of the damage threshold.

Theoretical damage thresholds are calculated for various metals and are presented in Table I using typical absorption for 1 μm. These absorption values are based on Goldstein's work, 1 μm reflectivity and light scattering measurements.[10]

The requirement for including the heat of fusion has been demonstrated by our experiments as silver samples have been illuminated at 4 j/cm^2 without exhibiting laser damage.

If copper, gold, and silver mirrors each had the same absorption, copper would have the highest theoretical damage threshold. Copper is theoretically better than silver or gold because of the higher specific heat and heat of fusion. Gold has the lowest theoretical damage threshold of the three.

TABLE 1

THEORETICAL PREDICTION OF DAMAGE THRESHOLD FOR 150 PSEC 1μm PULSE

Material	A	α cm²/sec	ρ gm/cm³	ΔT °C	S j/gm °C	E_1 j/cm²	H j/gm	E_2 j/cm2	E_{th} j/cm2
Aluminum	0.06	0.86	2.70	635	0.899	0.26	396	0.18	0.44
Copper	0.011	1.18	8.97	1058	0.384	3.9	212	2.0	5.9
Gold	0.016	1.14	19.3	1038	0.13	1.9	67.5	0.94	2.8
Silver	0.011	1.71	10.5	936	0.23	2.9	104	1.4	4.3

RESULTS AND DISCUSSION

Figure 4 is a dark field photograph of the Spawr copper. The damage sites are clearly visible along the edge of the mirror. Figure 5a is a regular micrograph of a damage site illuminated at 2 j/cm² on the Spawr mirror. Figure 5b and 5c are dark-field illumination photomicrographs at the same magnification as 5a at the center and edge respectively, demonstrating the laser enhanced scratches in the damaged area. Figure 5d is a Nomarski photomicrograph taken at about twice the magnification of 5a demonstrating that many small laser enhanced scratches are evident, as well as some pitting. These scratches are very similar in appearance to what Brown reported observing laser damage of an anti-reflection coated cylindrical lens.[11]

The effect of scratches on damage threshold is further demonstrated in Fig. 6 for sample LLL-Ag-5. LLL-Ag-5,6, and 7' were all diamond turned simultaneously in a fixture which can hold eighteen mirrors. Sample 5 was cleaned with alcohol and optical tissue by lightly wiping the surface. Fig. 6a is the dark field illumination photograph of the mirror which shows the (mainly) uni-directional scratches from the cleaning. Fig. 6b and 6c are Nomarski photomicrographs taken at the same magnification of the same place but by rotating the part so as to emphasize the diamond turning marks in 6b and show the background in 6c. The damage of site 793 has clearly been initiated along the scratches of the cleaning process and at one-half the threshold for just diamond turned silver as discussed below.

Electroplating defects can effect the laser damage threshold as shown in Fig. 7. The pox marks are evident across all the surface but are more pronounced in the area where the laser damage occurs. This Nomarski photomicrograph was taken with the background contrast such that only the laser effected pox marks showed.

Diamond turning marks and electroplating defects in silver are shown in Fig. 8. Fig. 8a is the dark field illumination of the mirror taken at about the same time as 6a and with identical illumination and camera settings. Attempts were made to rinse the mirror clean with acetone and alcohol, blowing off the residual solvent with canned methane or freon. The residual film on LLL-Ag-7' has been removed in some spots by the laser without damaging the surface. We inspected the surface with the light scattering technique and with the Nomarski microscope without finding damage. Site 837 shown in Fig. 9 on LLL-Ag-7', illuminated at 3.9 j/cm^2, demonstrates damage along the diamond turning lines. I translated the sample and followed one of the heavier damage lines into an undamaged region where I could see that the diamond turning mark was one of the darker lines in the field of view. Light scattering may offer a quantitative measure of the important parameters of the particular diamond turning marks which seem to create damage at a lower threshold. Fig. 9 shows damage similar to that of the copper mirror in Fig. 7. These small marks are felt to be due to electroplating defects.

Table 2 summarizes our findings. We have listed the lowest level energy density, E_d, which caused damage and the highest level at which laser damage was not observed, E_{nd}. Due to inhomogeneities in the laser damage threshold across the surface E_d can be less than E_{nd} as for the LtL-Cu-78 The 1 μm absorption is estimated from the 1 μm reflectivity which we measured [12] and estimating the scattering as 0.001-0.002 for the diamond turned mirrors and for as much as 0.004 for the polished mirrors. Qualitatively we know the diamond turned mirrors scatter much less than the polished mirrors because during the reflectivity measurements an S-1 diode "sniperscope" was used to view the 1 μm 0.5 cm diameter, 100 mw, cw laser beam. The scattering from the polished sample was readily observable but we could see no 1 μm scattering from the diamond turned samples. Diamond turned samples have given some of the lowest light scattering of metal mirrors with the exception of one super-polished piece of kanigen. [3,13]

One of the most encouraging results is the 4.0 j/cm^2 damage threshold for diamond turned silver which is 80% of the theoretical damage threshold. Higher damage thresholds possibly may be achieved by better cleaning procedures as well as improvements in electroplating surface defects. Goldstein and co-workers have demonstrated that with 1 μm 11 ns pulses the damage thresholds appear to follow absoprtion.[10]

The results for copper are especially disappointing. The damage threshold of about 2.5 j/cm^2 is only about 40% of the theoretical value. We do not know why the threshold is proportionally so much lower than for the case of silver. Studies of optical properties at 10.6 μm have indicated that Cubath[a] has given the highest reflectivity by as much as 0.004. We plan to test Selrex Cubath in the future.

(a) Produced by Sel-Rex Corporation, Nutley, N.J.

TABLE 2

SUMMARY OF LASER DAMAGE THRESHOLD

Sample	A	E_{dam} j/cm^2	$E_{no\ dam}$ j/cm^2	E_{theory} j/cm^2	Comments
			SILVER		
LLL-Ag-7'	0.010	4.0^c	4.0^c	4.8	EP/HT/DT/R
		3.9^b	1.6^b		45° P polarization
		5.4^a	4.8^b		45° S polarization
LLL-Ag-5	0.009	2.2^b	2.2^b	5.3	EP/HT/DT/R/cleaned
LLL-Ag-6	0.020	0.43^b	0.24^b	2.4	EP/HT/DT/R/P/cleaned
			COPPER		
LLL-Cu-78	0.01	2.0^c	2.6^c	6.5	EP/HT/DT/R
		2.0^b	1.6^b		45° P polarization
		5.9^b	4.9^b		45° S polarization
LLL-Cu-44	0.042	0.16^b	None	1.5	EP/DT/R/C/P/cleaned
Baker 10	0.026	0.7^b	0.4^b	2.5	P
Spawr Cu	0.018	0.39^b	0.41^b	3.6	P

a = ±5%　　EP = Electroplate　　P - Polished

b = ±10%　　DT = Diamond Turned　　c = Coated

c = ±20%　　R = Rinsed

We have not optimized our polishing parameters and hope to improve laser damage threshold for polished samples. LLL-Ag-6 and LLL-Cu-44 were both polished with suspended carbon particles. The especially high absorption for LLL-Cu-44 coupled with its damage threshold so low that we could not determine it with this experimental arrangement has led us to conclude that our technique with carbon particles will not yield good high power metal laser components. The results for Baker 10, polished with diamond and silicon oil, compare favorably with damage data on other polished copper.

Based on the work of Goldstein, et al [10], we tested some samples at 45° angle of incidence using first p and then s polarization. Similar to Goldstein we found an improvement in the damage threshold for s polarization. This improvement is due to the decreased absorption as well as the increased area of illumination. The values given in Table 2 are the energy density in the beam measured in a plane perpendicular to the laser propagation direction. We concur with Goldstein's findings that use of metal turning mirrors may be very competitive with dielectrics in terms of laser damage. In the case of diamond turning, the initial fabrication cost and especially the refinishing cost would be better than for dielectrics.

It may be possible to take advantage of the periodic nature of the surface finish of a diamond turned mirror. Although the total amount of scattering is low (less than 0.002) the mirror may serve as a low efficiency diffraction grating and the diffracted beam be used for beam diagnostics.

Comparisons of laser damage thresholds at different wavelengths and pulse lengths can be compared to our results using equation 3. Table 3 normalizes results for other polished copper reported mainly by Spawr and Pierce[14] and one from Stewart[15] of 10.6μm, 470 ns pulsed study. The values have been normalized to our values of 0.018 absorption and 150 psec. Our results seem to be consistent with others except for the pulses longer than 500 ns. There is a possibility that at the longer pulse length, a different mechanism is associated with the damage than with the shorter pulse lengths.

It is now tempting to speculate on the cause of the lower damage threshold around micro-scratches. Bloembergen has discussed the effects of pits and scratches enhancing the electric field and lowering laser damage.(16) It may be possible that scratches have a higher absorption to pulses than is measured by low power cw methods, and therefore the scratches have lower damage thresholds than the theoretical value.

TABLE 3

POLISHED COPPER LASER DAMAGE DATA NORMALIZED TO A = 0.018 t - 150 psec

Testor	λ μm	t nsec	A %	E_{exp} j/cm2	$E_{normalized}$ j/cm2	Ref.
Our Data	1.06	0.15	1.8	0.4 - 0.6	0.4 - 0.6	-
Cincannati Electronics	1.06	17	∿ 2	2 - 4	0.3	13
Raytheon	1.06	11	1.4	2.9	0.3	8
Los Alamos	1.06	0.05	∿ 2	0.4	0.7	13
Los Alamos	3	50	∿1.8	10	0.6	13
Northrop	5	10^5	∿1.5	1000	1	13
Los Alamos	10.6	1	∿0.9	> 4	> 0.3	13
Battelle NW	10.6	470	1.7	35	0.6	14
Hughes Research	10.6	600	∿0.9	260	2.1	13

CONCLUSIONS

Diamond turned metals have the highest laser damage threshold for metal mirrors which we have tested. Diamond turned silver competes favorably with dielectric mirrors especially for turning S polarized beams.

Our work has demonstrated that various fabrication effects degrade the laser damage of silver. The degradation factor, D, is estimated and presented in Table 4. One can estimate the damage threshold due to the effect by multiplying the theoretical damage threshold by D.

TABLE 4

FABRICATION DEGRADATION FACTOR FOR SILVER

Fabrication Effect	D
Slight Electroplating Defects	0.8
Diamond Turning Marks	0.7
Scratches During Cleaning	0.5
Polishing	0.1 - 0.2

In contrast to Stewart [14] we were unsuccessful in polishing with suspended carbon particles in that although we achieved smooth surfaces low damage threshold resulted.

ACKNOWLEDGMENTS

We are grateful for the donation of a sample and helpful discussions with Mr. Walter Spawr, the advanced use of the data of Dr. Irv Goldstein, and the assistance of our colleague Mr. Wayne Whistler in making the reflectivity measurements.

Appendix

(The following information has been added because we felt it would be of interest to those receiving the report version of our paper, but its inclusion would unduly extend the proceedings version.)

For those planning to use diamond turned optics in a laser fusion experiment, great care should be made in extrapolating our results for operational size optics. It is important to note that most samples were small 3.86 cm diameter and that obtaining similar performance or optics 30-50 cm diameter involves more than simply making the part larger. Furthermore these parts were turned with a single degree of freedom. Our study demonstrates the importance of surface finish effecting laser damage threshold. Contoured parts have an inferior surface finish because of additional errors in the diamond turning process.

It is interesting to note that 4-6 repeated laser illuminations at 2 j/cm^2 on the same site of LLL-Cu-78 did not produce laser damage. Unfortunately we did not find any evidence that repeated shots at say 70-90% of the laser damage threshold would significantly alter (increase or decrease) the threshold for the spot. Enhancement of cw laser damage threshold by conditioning the surface with illuminations lower than the damage threshold have been reported earlier by one of us (TTS) and most recently by Huguley at Boulder.

After our paper was presented, Dr. Dale Miller of LLL and I performed some scanning electron microscopy (SEM) of LLL-Cu-78 which indicates a possible explanation for the lower laser damage threshold is imperfections in the electroplating. Figure 10 shows a 1000x photomicrograph of defects which cover the surface.

Plans for future laser damage experiments with the LLL ILS laser will investigate the lower damage threshold of copper and different types of silver as well as polished samples. Our test plans are still being developed but some of the anticipated samples are summarized in Table 5.

Table 5. Anticipated Laser Damage Samples

Type	Fabricated	Comments
Cu	Y-12	OFHC CDA 101, interrupted cut
Cu	Y-12	OFHC ASTM 187, interrupted cut
Cu	Y-12	Electroplated Sel-Rec Cu Bath interrupted cut
Cu	LLL-Rocky Flats	Pyrophosphate Cu; ion polished by Commonwealth Scientific
Cu	LLL	OFHC, interrupted cut
Ag	Rocky Flats/Y-12	Lea Ronal Electroplate, center cut
Ag	Rocky Flats/Y-12	Lea Ronal Electroplate pulse plating, center cut.
Cu	LLL/polished	diamond abrasive and silicon oil
Ag	LLL/polished	diamond abrasive and silicon oil

Reduction of the energy density data is a very time consuming process. These experiments were started on April 22 and the reduced data was not available until June. An approximation of the energy density can be obtained from burns on polaroid film. The wedge formed by the mirrors described in Figure 1 form a series of burn spots on the polaroid film depending on the intensity of the laser pulse. The more intense the laser, the more spots burned. Furthermore, we differentiate three levels of exposure (burn) of one spot, threshold, weak, and strong (increasing energy density respectively). More than 50 laser shots were reduced using photocal and the corresponding identification from the polaroid film was made. This data was taken over many different rolls of polaroid film. We calculated the average and standard deviation of the energy density for each spot as reported in Table 6. The results of Table 6 is our basis for estimating the energy approximation using the polaroid technique as ± 20% of the energy value. This technique may prove valuable in obtaining answers quickly when one is willing to sacrifice or wait for the more accurate data reduction. We feel that it is imperative to continue to use photocal to prevent any gross differences in polaroid film sensitivity to burns and other experimental uncertainties giving large errors. Increasing the data base to many hundreds of shots will increase our confidence in this technique.

Table 6. Energy Density Estimates from Polaroid Burns

Spot Identification	Average Energy and Standard Deviation j/cm^2
T2	0.17 ± 0.06
W2	0.22 ± 0.03
S2	0.25 ± 0.02
T3	0.35 only one datum
W3	0.41 ± 0.07
S3	0.60 ± 0.1
T4	0.84 ± 0.2
W4	1.05 ± 0.2
S4	1.6 ± 0.2
T5	2.0 ± 0.3
W5	2.6 ± 0.2
S5	4
T6	4.3 ± 0.6

REFERENCES

1. T. T. Saito, "Machining of Optics: An Introduction" to be published in Appl Opt 14: 1773 (1975)
2. J. Weaver, G. Sommargren, and E. Bliss "Self Calibration and Analysis of Image Formation in the Sub-nanosecond Domain" Proceedings of the Society of Photo-Optical Engineers, 18th Annual Technical Meeting 48: p-63.
3. T. T. Saito "Characterizations of Diamond Turned Optics" to be published AF Weapons Laboratory Technical Report.
4. P. Baker, J. Sonderman, and T. T. Saito "Finishing of Precision Generated Optical Components" to be presented to the Soc. Photo-Optical Instrumentation Eng. Symposium on the "Design, Manufacture, and Application of Metal Optics" San Diego, Aug 1975.
5. F. Twyman,"Prism and Lens Making", 2nd Edition, Hilger & Watts Ltd., London p-46.
6. R. W. Stewart "Investigate Materials Systems for Mirrors Used in High Power CO & CO_2 Lasers," Technical Report ARPA Order No. 2175, Battelle Pacific Northwest Laboratories, Richland, Washington (Dec. 1972).
7. B. E. Newnam "Damage Resistance of Dielectric Reflectors for Picosecond Pulses" in Laser Induced Damage in Optical Materials 1974, A. Glass and A. H. Guenther Editors, National Bureau of Standards Special Publication 414, 1974.
8. J. Hizny "Characterization of Low Scatter Optics" given at ASTM Mini-Symposium "The Possibility of Using Light Scattering to Establish a Surface Characterization Standard" Dallas, Tex Jan 1975.
9. J. Z. Hizny "Substrate Throughprint in Low Scatter Mirrors" Society of Photo-Optical Instrumentation Engineers symposium "The Design,Manufacture, and Application of Metal Optics" at San Diego August 1975.
10. I. Goldstein, D. Bua, and F. A. Horrigan "Pulsed Laser Damage to Uncoated Metallic Reflectors" 7th Annual Laser Induced Damage in Optical Materials, 1975.
11. N. J. Brown "Fabrication of Laser Optics at Lawrence Livermore Laboratory" 7th Laser Induced Damage in Optical Materials Symposium, 1975.

12. T. T. Saito "1.06 μm Reflectivity Measurements of Metal Optics" UCID 16815, Lawrence Livermore Laboratory, Livermore, CA 1975.

13. H. E. Bennett "High Energy Laser Mirrors and Windows" Semi-Annual Report No. 6, ARPA Order 2175, Michelson Laboratory, Naval Weapons Center, China Lake, CA March 1975.

14. W. J. Spawr and R. L. Pierce, Metal Mirror Selection Guide, SOR Report #74-004, 30 Dec 74, published in part as "Guide to Metal Mirrors" Laser Focus, March 1975, p-37 (1975)

15. R. W. Stewart, "Investigate Material Systems for Mirrors Used in High Power CO and CO_2 Lasers" Semiannual Technical Report, August 1973, ARPA Order No. 2175, Battelle Pacific Northwest Laboratories, Richland, Washington

16. N. Bloembergen, "Role of Cracks, Pores, and Absorbing Inclusions on Laser Damage Threshold at Surfaces of Transparent Dielectrics" Appl Opt 12:661 (1973)

FIGURE CAPTIONS

Figure 1: Schematic of experimental apparatus showing the mode locked oscillator which generates the 150 psec pulse. Diagnostics include calorimeters, 1-Z photographic plates, and polaroid pictures.

Figure 2: Schematic for the dark field photographic scheme for investigating laser damage specimen.

Figure 3: The dark field photographs were taken of a diamond turned copper mirror (a) as received from our diamond turning laboratory, and (b,c,d) after 90 seconds of cleaning in a vapor degreaser using TF freon at 50° C. Figure a and b were taken at the same photographic conditions. Figure c and d were taken at longer exposure times to demonstrate the residue on the mirror which still has not been removed.

Figure 4: Dark field photograph of the Spawr copper demonstrating the rows of laser damage spots along the bottom.

Figure 5: Site 793 on the Spawr copper was illuminated at 2 j/cm^2. The laser damage is manifested by the enhanced scratches shown in (a) which is a regular photomicrograph and (b) which is taken using dark field illumination. (c) shows the edge of the damage area and the background smoothness of the undamaged area. (d) is a Nomarski photomicrograph of site 793.

Figure 6: The scratches caused by the cleaning are visible in the dark field photograph of LLL-Ag-5 which is a dimaond turned silver sample. The laser damage along the scratches is shown in (b) and (c) which are Nomarski micrographs of the same place with the sample oriented to show the diamond turning marks (b) and to show the background smoothness (c).

Figure 7: The damage on the diamond turned copper is due to electroplating artifacts which appear as pox marks in this Nomarski photomicrograph.

Figure 8: The removal without any apparent damage of the residual film from the diamond turned silver LLL-Ag-7 sample is shown in the dark field photograph (a). The damage in the slight electroplating defects is shown in (b).

Figure 9: Laser damage along the diamond turning marks of the silver sample LLL-Ag-7' is shown in the Nomarski photomicrograph.

Figure 10: LLL-Cu-78 observed with a scanning electron microscope at 1000X using 450 ev electrons at 45° angle of incidence. The many defects explain the damage threshold being only 40% of theoretical.

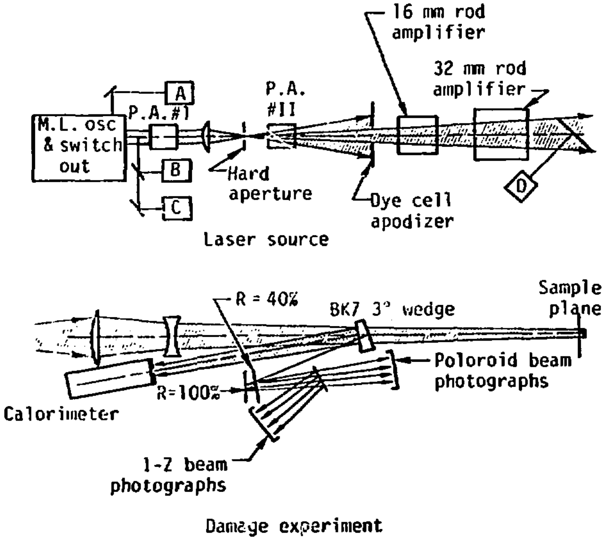

16 mm rod
amplifier
32 mm rod
amplifier
A
P.A.
#II
P.A.#1
M.L. osc
& switch
out
B
C
Hard
aperture
Dye cell
apodizer
D
Laser source
R = 40%
BK7 3° wedge
Sample
plane
Poloroid beam
photographs
R=100%
Calorimeter
1-Z beam
photographs
Damage experiment

FIGURE 1

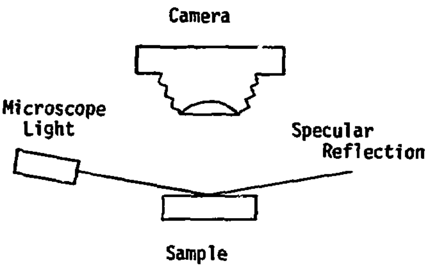
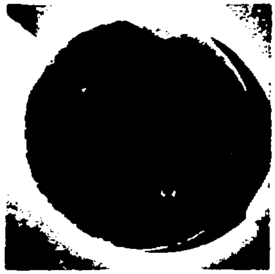


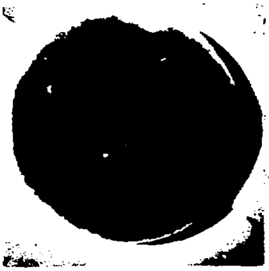
FIGURE 2

Vapor degreaser cleaning of
LLL-CU

a. No cleaning
(t = 1/8 sec)



b. 90 sec cleaning
(t = 1/8 sec)



c. 90 sec cleaning
(t = 1/4 sec)

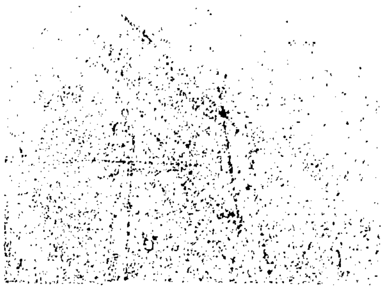
d. 90 sec cleaning
(t = 1/2 sec)

FIGURE 3

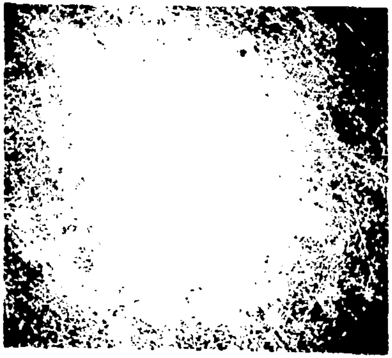

SPAWR COPPER

SPAWR COPPER

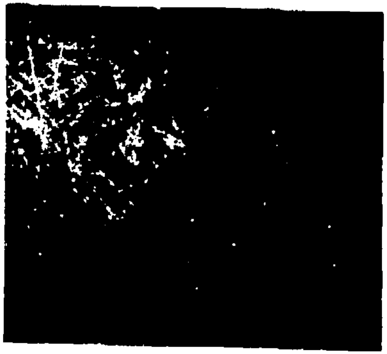
SITE 793



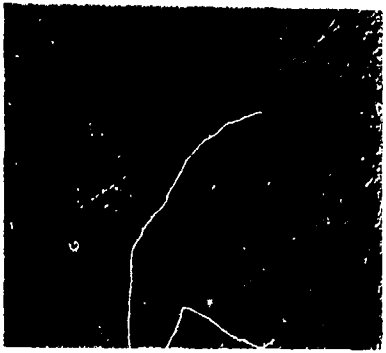
A 100 µm



B 100 µm



C 100 µm



D µ

FIGURE 5

LLL-Ag-5

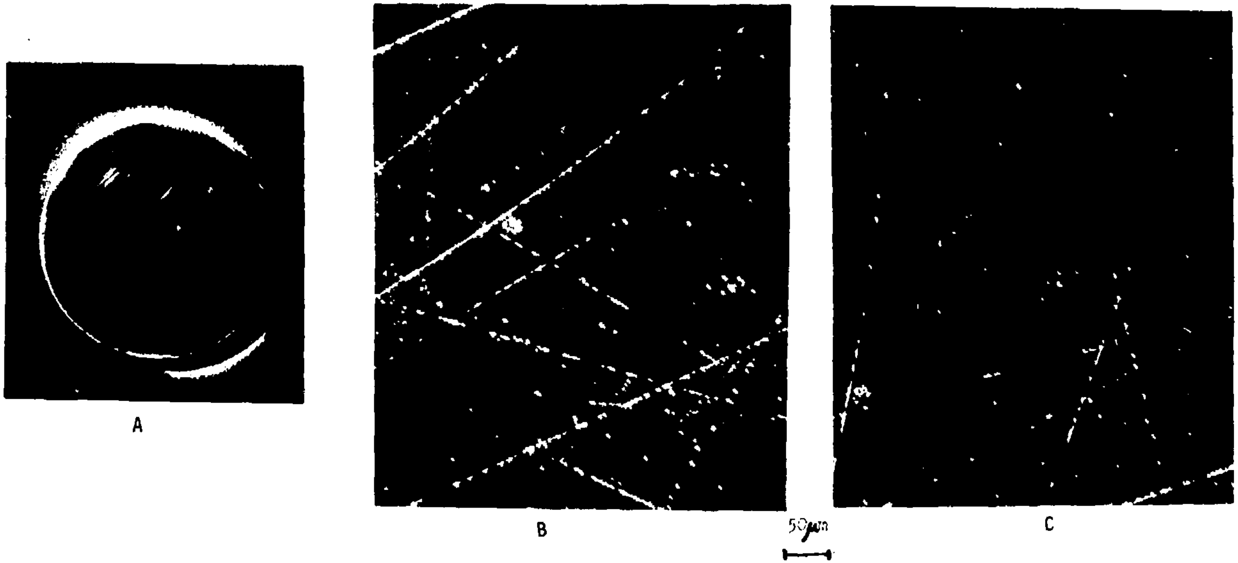


FIGURE 6

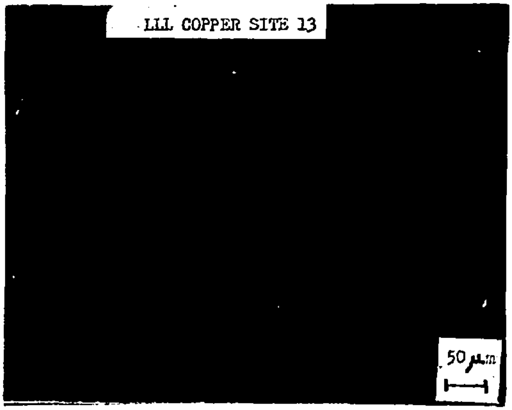


FIGURE 7

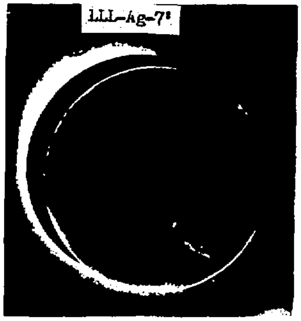


FIGURE 8a

FIGURE 8b

FIGURE 9