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Measurements of diamond turned copper mirrors at glancing incidence*

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Abstract

The results of glancing incidence absorptance measurements performed on diamond turned copper mirrors are presented. A photoacoustic calorimetry technique is used in which the output from a low power, chopped cw Nd:YAG laser ($1.06 \mu\text{m}$) is incident upon the mirror at angles of incidence from 0 to 87° , for both s and p-polarizations. Measurements are obtained as a function of the diamond turning groove orientation with respect to the plane of incidence. Minimum absorptance at high angles of incidence is achieved with s-polarized light and with the grooves aligned parallel to the plane of incidence. The effects on the absorptance of a large scratch at glancing incidence are also described.

Introduction

In certain high power laser applications, glancing or grazing incidence mirrors may be needed because of their high reflectivity. The glancing incidence properties of bare metal¹ and dielectric overcoated metal² mirrors have been recently measured. This paper presents the results of glancing

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incidence measurements performed on diamond turned copper mirrors. Of obvious interest in these measurements is the dependence on the diamond turning groove orientation with respect to the plane of incidence and the polarization of the laser beam.

Description of experiment

The apparatus used to measure the absorptance characteristics of the mirrors has been described elsewhere.³ It uses photoacoustic calorimetry in which the piezoelectric transducer is attached directly to the back of the mirror substrate. The laser used during this work is a cw Nd:YAG (1.06 μm) which delivers <150 mW of laser power in a 0.8 mm $1/e^2$ diameter spot on the mirror surface. The output from the laser is chopped, travels through a collimating telescope and polarizing elements, and reflects off the copper mirror mounted on a rotation stage. A high signal-to-noise ratio is achieved by using a phase sensitive lock-in amplifier to detect the output from the piezoelectric transducer.

Absolute absorptance is determined using either a Carey Spectrometer Model 2390 or a laser energy ratiometer. The spectrometer gives typical absolute absorptance values for the diamond turned copper mirrors tested of 1.2% at 1.06 μm .

The mirrors were fabricated at Lawrence Livermore National Laboratory on the PERL (Precision Engineering Research Lathe) machine. Two mirrors were tested during this program; each was from a different set of four identical ones that were diamond turned off-center. The inside edges of the four mirrors were on a 2.41 cm diameter circle centered on the spindle.

The mirrors consist of copper electroplated (UBAC) onto a 3.81 cm diameter x 0.635 cm thick stainless steel substrate. Table 1 lists the diamond turning parameters for the mirrors. From the RPM and feed rate, the groove spacing is calculated to be 1.27 μm (50 μinch). Measurements by a Rank Taylor Hobson Talystep profilometer indicate a 26 Å rms roughness over a

0.1 mm scan length.

Experimental results

The absorbance characteristics for s-polarized light of the first of the two mirrors are given in Fig. 1. The small diameter of the mirror limited the largest angle which could be tested to 87° . Figure 1(a) is with the grooves parallel to the plane of incidence, and Fig. 1(b) is with the grooves perpendicular to the plane of incidence. Error bars on the data points represent the reproducibility of the photoacoustic calorimetry measurement; when the error bars are absent, it is because they are smaller than the size of the dot used to plot the data.

The actual values for the absorbances plotted in Fig. 1 are tabulated in Table 2. Examining the value of the absorbance at 87° , it is clear that the absorbance is significantly smaller when the grooves are oriented parallel to the plane of incidence (0.050% absorbance) rather than perpendicular to the plane (0.078% absorbance).

The experimental results can be compared with the theoretical absorbance for a bare metal mirror as predicted by the Fresnel equations.⁴ Values for the index of refraction, n , and the extinction coefficient, k , for copper at $1.06 \mu\text{m}$ must be substituted into the Fresnel equations. There are many sources in the literature for these values;⁵⁻⁹ in this paper the values of n (0.362) and k (7.078) measured by Hagemann, *et al.*⁵ are used. Other sources in the literature have quoted Hagemann's values;^{10,11} however, it should be noted that these values may not be necessarily appropriate for UBAC copper. Although there may be some disagreement regarding the best values of n and k to use in the theoretical equations, the data on the diamond turned copper mirrors stand alone by themselves and do not rely on knowing the values of n or k .

The Fresnel equation prediction is given as the solid curve in Fig. 1. Although there is good agreement between the data and the theory in overall

curve shape, there is significant differences in absolute magnitude. Again, this difference may be because the values of n and k used are not valid for UBAC copper.

Figure 2 shows the absorptance characteristics of the first mirror for p-polarized light. Figure 2(a) is for the grooves oriented parallel to the plane of incidence and Fig. 2(b) is for the grooves aligned perpendicular. Besides good overall agreement in curve shape between the data and theory, there is essentially no difference in the data between the two different groove orientations. This can be seen clearly in Table 3 which is a tabulation of the data plotted in Fig. 2.

Absorptance measurements of the second diamond turned mirror give results very similar to the first mirror. The first mirror had some very small spots on its surface which did not interfere with the glancing incidence measurements. The second mirror had a clean surface, but unfortunately it was accidentally scratched before being tested. A screwdriver fell onto the mirror surface; the shaft of the screwdriver dropped nearly parallel to the mirror surface, bounced once, and landed off the mirror. The shaft of the screwdriver has a square cross-section; evidently the corner edge of the shaft struck the mirror surface since only a single, well-defined scratch was left after the accident.

Although an unfortunate accident, the presence of the scratch did provide an opportunity to examine the affects of a scratch on the absorptance characteristics of a mirror at glancing incidence. Figure 3 is a sketch of the surface of the second mirror showing the approximate location of the scratch with respect to the groove orientation. During the absorptance measurements, the laser spot on the mirror becomes very elongated as the angle of incidence becomes large. The measurements normally begin at the center of the mirror and, at the highest angle, the laser footprint extends across the full diameter of the mirror. As can be seen in Fig. 3, the laser footprint misses the scratch when the plane of incidence is parallel to the groove direction. The laser footprint does intersect the scratch when the plane of

incidence is perpendicular to the groove direction; however, the intersection only occurs for angles of incidence greater than 86° .

Figure 4 plots the absorptance characteristics of s-polarized light for the second mirror. The absorptance characteristics with the grooves oriented parallel to the plane of incidence [Fig. 4(a)] looks essentially the same as for the first mirror [Fig. 1(a)]. This is also true when the grooves are oriented perpendicular to the plane of incidence [Fig. 4(b)], except, of course, at 87° . The data in Fig. 4 are tabulated in Table 4. Comparing the absorptance at 87° for the unscratched and scratched mirrors, the scratch apparently causes a 26% increase in absorptance.

For completeness, Fig. 5 shows the absorptance characteristics of the second mirror for p-polarized light, and Table 5 lists the values of the data. Apparently the scratch has minimal effect on the absorptance at this polarization, probably because the absolute absorptance is higher.

Conclusion

Analysis¹² shows that the increase in absorptance at glancing incidence, for s-polarized light when the grooves are oriented perpendicular to the plane of incidence, is due to the fact that the walls of the grooves are not parallel to the surface of the mirror. The angle of incidence of the laser beam with respect to the mirror surface is, on a microscopic level, actually smaller than measured. Hence, the absorptance tends to be higher than expected.

Although the area of the laser beam footprint on the mirror which overlaps the scratch at 87° , is a small fraction of the total area of the elongated laser spot, it still contributes a significant absorption loss. This seems to imply that the absorptance characteristics of the mirrors are more sensitive to surface imperfections at glancing incidence.

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FIGURE CAPTIONS

- Figure 1. Absorptance characteristics of the first diamond turned copper mirror at $1.06\ \mu\text{m}$ for s-polarized light. (a) is for the diamond turned grooves oriented parallel to the plane of incidence; (b) is for the grooves oriented perpendicular to the plane of incidence. The bare metal theoretical curves use values for n and k given by Hagemann *et al.*⁵
- Figure 2. Absorptance characteristics of the first diamond turned copper mirror at $1.06\ \mu\text{m}$ for p-polarized light. (a) is for the diamond turned grooves oriented parallel to the plane of incidence; (b) is for the grooves oriented perpendicular to the plane of incidence. The bare metal theoretical curves use values for n and k given by Hagemann *et al.*⁵
- Figure 3. Sketch depicting the approximate location of the scratch on the surface of the second diamond turned copper mirror.
- Figure 4. Absorptance characteristics of the second diamond turned copper mirror at $1.06\ \mu\text{m}$ for s-polarized light. The laser beam footprint does not overlap the scratch. (a) is for the diamond turned grooves oriented parallel to the plane of incidence; (b) is for the grooves oriented perpendicular to the plane of incidence. The bare metal theoretical curves use values for n and k given by Hagemann *et al.*⁵
- Figure 5. Absorptance characteristics of the second diamond turned copper mirror at $1.06\ \mu\text{m}$ for p-polarized light. The laser beam footprint

overlaps the scratch at 887° . (a) is for the diamond turned grooves oriented parallel to the plane of incidence; (b) is for the grooves oriented perpendicular to the plane of incidence. The bare metal theoretical curves use values for n and k given by Hagemann *et al.*⁵

Table 1. Diamond Turning Parameters for Copper Mirrors

RPM	1000
Rake Angle	0°
Feed	0.050 inch/minute
Tool Nose Radius	0.030 inch
Cutting Fluid	Flood with Shell DIALLA-X
Depths of Cut	0.001 in.; 500 μ in.; 200 μ in.; 50 μ in.; 20 μ in.
Z Slide Control	Mechanically locked during facing cuts

Table 2. Data Plotted in Fig. 1 for s-Polarization

Angle (°)	Groove orientation with respect to plane of incidence	
	<u>Parallel</u>	<u>Perpendicular</u>
	Absorptance (%)	Absorptance (%)
0	1.20 ±0.017	1.20 ±0.046
10	1.17 ±0.016	1.18 ±0.046
20	1.10 ±0.021	1.11 ±0.026
30	1.01 ±0.015	1.02 ±0.027
40	0.888 ±0.015	0.899 ±0.015
50	0.743 ±0.010	0.755 ±0.015
60	0.574 ±0.008	0.596 ±0.013
70	0.388 ±0.007	0.411 ±0.006
75	0.294 ±0.004	0.315 ±0.004
80	0.195 ±0.005	0.220 ±0.005
81	0.176 ±0.007	0.197 ±0.003
82	0.155 ±0.003	0.177 ±0.006
83	0.135 ±0.002	0.159 ±0.002
84	0.114 ±0.003	0.138 ±0.001
85	0.095 ±0.003	0.120 ±0.003
86	0.073 ±0.003	0.101 ±0.002
87	0.050 ±0.001	0.078 ±0.002

Table 3. Data Plotted in Fig. 2 for p-Polarization

Groove orientation with respect to plane of incidence		
Angle (°)	<u>Parallel</u>	<u>Perpendicular</u>
	Absorptance (%)	Absorptance (%)
0	1.20 ±0.018	1.20 ±0.031
10	1.20 ±0.019	1.17 ±0.029
20	1.28 ±0.018	1.22 ±0.031
30	1.40 ±0.027	1.33 ±0.020
40	1.56 ±0.031	1.52 ±0.047
50	1.83 ±0.031	1.79 ±0.041
60	2.26 ±0.036	2.25 ±0.063
70	2.96 ±0.056	2.95 ±0.068
75	3.39 ±0.065	3.42 ±0.091
80	3.71 ±0.069	3.72 ±0.037
81	3.70 ±0.061	3.72 ±0.037
82	3.66 ±0.049	3.66 ±0.040
83	3.56 ±0.058	3.56 ±0.106
84	3.34 ±0.063	3.44 ±0.094
85	3.05 ±0.034	3.18 ±0.064
86	2.72 ±0.069	2.74 ±0.038
87	2.21 ±0.038	2.21 ±0.082

Table 4. Data Plotted in Fig. 4 for s-Polarisation

Angle (°)	Groove orientation with respect to plane of incidence	
	<u>Parallel</u>	<u>Perpendicular</u>
	Absorptance (%)	Absorptance (%)
0	1.20 ±0.017	1.20 ±0.023
10	1.17 ±0.014	1.17 ±0.012
20	1.10 ±0.018	1.12 ±0.015
30	1.02 ±0.016	1.03 ±0.012
40	0.889 ±0.014	0.908 ±0.010
50	0.746 ±0.011	0.770 ±0.014
60	0.580 ±0.008	0.604 ±0.007
70	0.389 ±0.006	0.423 ±0.006
75	0.296 ±0.005	0.325 ±0.003
80	0.198 ±0.005	0.224 ±0.002
81	0.178 ±0.006	0.198 ±0.003
82	0.157 ±0.002	0.180 ±0.002
83	0.137 ±0.002	0.158 ±0.003
84	0.117 ±0.002	0.137 ±0.003
85	0.097 ±0.001	0.119 ±0.002
86	0.077 ±0.004	0.105 ±0.004
87	0.056 ±0.001	0.098 ±0.002

Table 5. Data Plotted in Fig. 5 for p-Polarisation

Angle (°)	Groove orientation with respect to plane of incidence	
	<u>Parallel</u>	<u>Perpendicular</u>
	Absorptance (%)	Absorptance (%)
0	1.20 ±0.012	1.20 ±0.017
10	1.20 ±0.012	1.18 ±0.015
20	1.27 ±0.019	1.19 ±0.013
30	1.39 ±0.022	1.33 ±0.019
40	1.54 ±0.034	1.48 ±0.015
50	1.82 ±0.044	1.71 ±0.020
60	2.22 ±0.048	2.19 ±0.023
70	2.91 ±0.054	2.85 ±0.029
75	3.32 ±0.081	3.30 ±0.033
80	3.62 ±0.050	3.64 ±0.035
81	3.60 ±0.054	3.64 ±0.034
82	3.57 ±0.045	3.58 ±0.034
83	3.47 ±0.057	3.51 ±0.034
84	3.26 ±0.074	3.28 ±0.032
85	2.98 ±0.029	3.01 ±0.025
86	2.65 ±0.070	2.76 ±0.038
87	2.17 ±0.022	2.17 ±0.054

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

Fig. 5