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**MECHANICAL DEFLECTION ANALYSIS
OF DIAMOND-TURNED
REFLECTIVE OPTICS**

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OAK RIDGE, TENNESSEE**

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MECHANICAL DEFLECTION ANALYSIS OF DIAMOND-TURNED REFLECTIVE OPTICS

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ABSTRACT

An analytical technique has been developed that predicts the amount of warpage that metal reflective mirrors sustain due to various support and load conditions. The finite-element method is used to compute mirror-surface displacements that result from support or load conditions. Surface warpage is then determined by a best-fit comparison of these data to the desired surface contour.

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SUMMARY

An analytical technique has been developed that predicts the amount of warpage that metal reflective mirrors sustain due to various support and load conditions. The laser fusion project being conducted at LASL requires that metal reflective optics be fabricated by diamond turning. The diamond-turning process imposes some unusual loading conditions which result in mirror warpage. The finite-element method is used to compute mirror surface displacements resulting from these support and load conditions. Surface warpage is then determined by a best-fit comparison of these data to the desired surface contour. The technique is not limited to diamond turning, but can be used to predict warpage from a variety of loading conditions placed on the mirrors.

INTRODUCTION

The Los Alamos Scientific Laboratory (LASL) is performing research into energy production by laser-induced fusion. As seen in Figure 1, their experiments require highly reflective metal mirrors to direct and focus the high-energy laser beams onto the target containing fusionable materials. Mirrors for these experiments require ultra-precise contours. Contour tolerances on the order of 40 microinches are essential for proper functioning of the experiment. The surface finish must be highly reflective and should scatter a minimum amount of energy. Maintenance of local and global geometrical configuration of the mirror is required.

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Figure 1. LOS ALAMOS SCIENTIFIC LABORATORY LASER FUSION FACILITY. (Under Construction)

The mirrors are to be manufactured by single-crystal diamond machining. This process produces a highly reflective surface and provides precision contours. However, as with most machining processes, some contour errors are inherent. Errors in the mirror profile can arise from several sources. Of primary concern are deformations introduced during the machining process which cause unwanted perturbations in the geometrical configuration of the mirror. These perturbations result, primarily, from centrifugal force, from internal forces created when the mirror is fixtured to the diamond-turning machine, and from gravity and temperature variations encountered during the machining process. Characterization and minimization of these potential sources of errors are necessary to produce the required optical quality of the mirrors. LASL, the Oak Ridge Y-12 Plant,^(a) and The University of

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

Tennessee - Knoxville have initiated a development program to determine the appropriate machining, analytical, and experimental techniques that are necessary to make possible the characterization and minimization of errors of the type just described. The purpose of this report is to describe some of the accomplishments that have been made to date in the development program.

ANALYSIS OF DIAMOND-TURNED REFLECTIVE OPTICS

THE DIAMOND TURNING PROCESS—MACHINING AND ANALYSIS TECHNIQUES

A single-crystal diamond cutting tool and a turning machine, modified to eliminate vibration and improve tool-path control, have been combined to produce the highly reflective and accurate mirror surfaces needed for the fusion experiment. Figure 2 shows a 16-inch-diameter, parabolic-contoured, segmented mirror after machining. The center of the mirror is approximately 19 inches from the parabola axis and the focal length is about 30 inches. This particular mirror has a contour accuracy of 70 microinches and a surface finish of 3.5 microinches, peak to valley. Lapping and polishing a mirror of this size to those accuracies would be prohibitively expensive to produce in quantity. A brief polishing operation improves the surface finish without destroying the contour accuracy.

Successful diamond turning is dependent upon having a vibration-free machining system and absolute control over the tool path in relation to the mirror surface. A view of such a machine, as developed at Y-12, is presented in Figure 3. Vibration-free operation was achieved through the use of air-bearing spindles and slide, air-bag isolation supports, and a direct-drive electric spindle motor. Precision tool-path control is achieved by using numerical control. Machine-slide positioning is achieved through the use of laser interferometry, air-bearing slide bearings, and thermal control. These features are explained by Gerth, et al.^{1,2}

Time and economic schedules do not permit the luxury of fabricating and testing a wide variety of candidate designs for the mirror-fixturing system which is required in the diamond-turning process. Therefore, analytical tools must be developed to facilitate the selection of only the most promising candidate designs for preliminary testing. The method of analysis must have the capability of predicting mirror-surface displacement perturbations caused by centrifugal forces, fixturing forces, gravity loads, and temperature variations encountered during the diamond-turning process. Furthermore, information generated from the analysis should be in a form which can be readily interpreted for tool-path compensation.

Because of the varied geometry and loading conditions of the mirror-fixturing systems under consideration, closed-form elasticity solutions of the type necessary to yield the desired results are not practicable. Therefore, these investigators have turned to the finite-element method³ to solve the problem. Some of the results obtained through the use of this method are illustrated in this report.

One of the potential mirror designs investigated was a light-weight mirror and an associated fixturing device. Figure 4 gives the approximate dimensions and shape of the undeformed structure. The diamond-turning process at the Y-12 Plant often requires that the fixture and mirror blank be rotated at speeds up to 200 rpm. The resulting centrifugal forces cause distortions in the mirror face being machined. This result suggests, for example, that if a rotating mirror surface were machined to a flat contour; then, when the mirror was no

Figure 2. A SIXTEEN-INCH-OUTSIDE-DIAMETER, OFF-AXIS PARABOLIC MIRROR.

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Figure 3. LARGE-COMPONENT, DIAMOND-TURNING MACHINE WITH AN OPTICAL INSPECTION TABLE.

longer rotating, its surface contour would no longer be flat. To efficiently correct for this undesirable distortion, it must be known, *a priori*, the effect of centrifugal forces on the mirror surface geometry and this information must be used to correct for distortion during the machining process.

A finite-element discretization of the mirror and fixture, shown in Figure 4, is shown in Figure 5. Triangular and quadrilateral axisymmetric finite elements³ were used in the model, and the SAP IV computer program⁴ was implemented to determine the deformations of the structure. To illustrate an example for centrifugal force, Figure 6 provides a computer plot of the deformed structure where the displacements have been magnified 10^6 times. Displacements of Points 1, 2, 3, and 4 relative to the undeformed geometry are shown. The numbers in parentheses represent the displacements in microinches of these points in the Z and X directions, respectively. Warpage of the mirror surface can be determined from the displacement of Points 2, 3, and 4. The desired tool path is then altered to provide numerical-control compensation for the centrifugal-force-induced warpage.

The manner in which a mirror blank is attached to its machine fixture determines how the mirror surface responds during the machining process. At the Y-12 Plant, two techniques

Figure 4. CROSS-SECTION VIEW OF A LIGHT-WEIGHT MIRROR AND FIXTURE.

Figure 5. UNDEFORMED FINITE-ELEMENT GRID OF A LIGHT-WEIGHT MIRROR AND FIXTURE.

commonly used to fasten the mirror to its support fixture are: (1) insertion of a rubber-like potting material between the mirror blank and machine fixture, and (2) direct attachment of the mirror blank to the fixture, using specially designed studs. The potting procedure, seemingly, has an advantage over the stud procedure because the rubber-like potting material isolates the fixture distortions from the mirror blank. A reduction of point loads is

Figure 6. DEFORMED FINITE-ELEMENT GRID OF A LIGHT-WEIGHT MIRROR AND FIXTURE.

also accomplished. A potting material is included in the finite-element model of Figure 5. Figure 6 shows this structure under the influence of a centrifugal force. Note that the potting material permits the mirror blank to deform independent of the fixture.

Figures 7 through 13 illustrate the warpage that might be encountered when using the stud-mounting procedure. With this type of mounting scheme, the mirror blank is subjected

Figure 7. TRAPEZOID-SHAPED MIRROR. (Finite-Element Grid Used to Compute Displacement Contours; All Supports are on the Back of the Mirror; Letters Indicate Support Locations)

Figure 8. MIRROR-SURFACE DISPLACEMENT CONTOURS. (In Microinches; Gravity Load with Supports at A, B, and C)

Figure 9. MIRROR-SURFACE DISPLACEMENT CONTOURS. (In Microinches; Gravity Load with Supports at D, E, and F)

Displacements in Microinches

Figure 10. MIRROR-SURFACE DISPLACEMENT CONTOURS. (100-Microinch Specified Z Displacement at Support C)

Displacements in Microinches

Figure 11. MIRROR-SURFACE DISPLACEMENT CONTOURS RELATIVE TO THE "BEST-FIT" PLANE. (Gravity Load with Supports at A, B, and C)

Figure 12. MIRROR-SURFACE DISPLACEMENT CONTOURS RELATIVE TO THE "BEST-FIT" PLANE. (Gravity Load with Supports at D, E, and F)

Figure 13. MIRROR-SURFACE DISPLACEMENT CONTOURS RELATIVE TO THE "BEST-FIT" PLANE. (Specified Z Displacement at Support C)

to various force and displacement perturbations initiated at the stud/mirror interface. These perturbations could, for example, be caused by thermal expansion, gravity, and centrifugal loads or bolting forces.

For illustrative purposes, the finite-element method was used to assess the effect of a gravity-type load and the effect of a specified displacement perturbation of a flat, solid mirror blank with a trapezoid-shaped boundary configuration. Figure 7 illustrates typical geometry and finite-element discretizations used in the analysis. For this analysis, an 8 to 21-variable-node, isoparametric, three-dimensional element was used.⁵ The solution was carried out by using the SAP IV computer program. For all cases illustrated, the mirror blank is supported by a three-point support on the back of the solid mirror blank. Each support is restrained against translation and rotation. Figures 8 through 10 show displacement-contour results for two load cases considered. Figure 8 illustrates the normal displacements of the mirror subject to a gravity load in the $-Z$ direction. The mirror is supported at Locations A, B, and C on the back surface of the mirror. The curvature of the contour lines results from the interaction of the gravity load and stud reactions. Figure 9 shows the displacement contours for the same loading conditions, but with the supports moved to Locations D, E, and F. Figure 10 shows the normal-displacement contours for the mirror, subject to a specified displacement of 100 microinches in the $-Z$ direction at Location F.

The displacement-contour plots of the type presented are useful in determining how a particular mirror geometry, supported in a specific manner, reacts to various loading conditions. However, from an optical standpoint, this information is of little help in its present form since the displacements are plotted relative to the undeformed geometry of the structure. The rigid-body component of the displacement often masks the actual warpage of the mirror surface. To make the data more useful to the opticians, a least-squares, best-fit plane was matched to the deformed geometry. New displacement contours were plotted relative to the best-fit plane. This method, in effect, eliminates the rigid-body motion of the mirror surface and results in what are called an "analytical interferogram". An interferogram of this form can be used to quantify the quality of a mirror. To illustrate the analytical interferogram, Figures 11 through 13 show the normal displacement contours for a trapezoid mirror with the same loading and support conditions as shown in Figures 8 through 10, except that the displacements are plotted relative to the best-fit plane. These figures clearly indicate the actual warpage of the mirror surface. A comparison of Figures 11 and 12 reveals that, for the gravity-load case, the support of the mirror at Locations D, E, and F is more desirable than at Locations A, B, and C. The distortion pattern in Figure 12 is more suitable to tool-path compensation. Figure 13 shows that the 100-microinch displacement of a support on the back of the mirror did not warp the mirror surface. It can be concluded from the example that if a support stud were inadvertently displaced a small amount in a direction normal to the mirror surface during the fixturing process, then the mirror surface would not warp and the quality of the mirror would not be compromised.

Conclusions

An analytical technique has been developed for predicting the warpage effects on metal reflective mirrors caused by various load and support conditions. By computing an analytical interferogram for a particular mirror geometry, an efficient determination can be made of the acceptable fixturing configurations to use in the diamond-turning process.

Analytical interferograms may also have other important applications. For example, by comparing an analytical interferogram of a mirror subject to a known load or displacement perturbation to an experimental interferogram of a machined mirror, it may be possible by a pattern-recognition process to determine the causes of certain distortions found in the machined mirror.

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