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# AN EFFICIENT METHOD THAT PRECISELY CHARACTERIZES LASER-TARGET DEFECTS MORE COMPLEX THAN NONCONCENTRICITY*

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ABSTRACT

An expansion of an efficient, fast Fourier technique[1,2] for precisely characterizing complex laser target defects is described. The defects characterized are the traditional nonconcentricities and the more complex ellipticities and higher-order wall nonuniformities in single-layered targets. This characterization method uses experimentally derived molybdenum step-wedge data. The molybdenum steps (12.5 μm) were exposed to a 45-kV tungsten-bremsstrahlung source and were recorded on holographic plate emulsion. Using the step-wedge data, targets with 6.25-μm-wall thickness and diameters of 150 and 300 μm were modeled with nonconcentricities and ellipticities. Sensitivities of ± 1/2 to 1% for nonconcentric defects and ± 1.4 to 2.8% for elliptic defects were calculated for target diameters between 300 and 150 μm, respectively. In addition, modeled targets with a combination of nonconcentric and elliptic defects were easily characterized in the presence of film noise.

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## I. INTRODUCTION

Laser fusion experiments require highly symmetric and uniform spheres often incorporating optically opaque multilayered targets. In our previous work, x-ray contact microradiography, combined with computer analysis, has proved to be a sensitive technique for detecting and quantifying defects in targets.[1-9] With these techniques we can measure the global uniformity to submicrometer accuracy and identify local defects and quantify their spatial extent in the internal structure. These nonuniformities are not observable with optical or scanning-electron-microscope techniques.

Previously, we were able to detect nonconcentricities of inner and outer walls of targets (Type I defects) of $\pm$ 95 Å ($\sim\pm$ 1% for 1-$\mu$m-wall thickness) using an efficient fast Fourier technique.[1] This sensitivity was better than that of interferometry, $\pm$ 300 Å[12,13] ($\sim\pm$3%), and comparable to phase-sensitive interferometry, $\pm$ 100 Å[12,13] ($\sim\pm$1%). We will describe in Sec. II an expansion of this Fourier technique. This technique can characterize the traditional inner-wall nonconcentricity, the more complex inner-wall ellipticity (lower-order Type II defects), and higher-order wall nonuniformities in single-layered targets. Sensitivities of $\pm$ 1/2 to 1% for nonconcentric defects and $\pm$ 1.4 to 2.8% for elliptic defects were calculated for target diameters between 300 and 150 $\mu$m, respectively.

In Sec. II we will also show the utility and sensitivity of this refined method on eight simulated molybdenum target images and eleven glass target images.

## II. REFINED TYPE I AND TYPE II DEFECT DETECTION

In Ref. 8 three classes of defects in thin-walled laser targets are described. Briefly, Type I defects are nonconcentricities of the inner and outer walls of a target; Type II defects are nonsphericities of one or both walls; and Type III defects are local wall-thickness variations. In this section we will define the refined Fourier techniques that are very sensitive and efficient in detecting and quantifying only Type I and Type II defects in contact microradiographic images.

### A. Computational Procedure

Detecting and quantifying Type I and Type II defects requires measuring the global symmetry of the target images. An expansion of an efficient fast Fourier technique[1,2] for precisely characterizing complex laser target defects is described. This expanded characterization technique requires the interplay of several pieces of information. This information includes experimental x-ray radiographic step-wedge data, computer-modeled single-layered laser targets using the step-wedge data, and measurements such as the estimated power spectrum and standard deviation. The estimated power spectrum and standard deviation are calculated from the sampled optical densities of an annular region in the modeled and real contact x-ray radiographic images. The following five steps show how this characterization and detection technique are orchestrated.

1. Expose a precisely fabricated step wedge to a known bremsstrahlung or monochromatic x-ray source. Record the optical film density vs material thickness on an x-ray energy compatible

emulsion such as holographic plate or high-resolution plate. Convert the optical film density for each step to computer-compatible digital information using a microdensitometer. From the digitized optical densities, a film noise model $\sigma_n$, described by a power law,[6,14] can be constructed.

$$\sigma_n = \alpha D^{\gamma} \quad , \tag{1}$$

where $\alpha = 0.036$, $\gamma = 0.3$, and D is film density.

2. Using Step 1, computer model the contact radiographic image densities of a single-layered target of interest. The following parameters have to be known: x-ray geometry, object diameter and wall thickness, amount of ellipticity and nonconcentricity, aperture size of the digital-image scanner, and a model of the film noise.

3. Determine the characterization parameters from the computer-modeled and real single-layered targets using the following steps:

a. Calculate a precise center and approximate radius.[8]

b. Obtain N (where $N = 2^n$) statistically independent and equally spaced azimuthal samples of the average optical densities between 50 and 90% of the target's radius (assuming a thin-walled target) using bilinear interpolation.

c. Calculate the standard deviation, $\sigma_T$, of the N statistically independent samples. This is a measure of the amount of nonconcentricity, ellipicity, and higher-order nonuniformities.

d. Calculate the average single-point noise, $\hat{\sigma}_N$, of the film after bilinear interpolation and independent annuli averaging.

$$\hat{\sigma}_N = R * \sigma_N/\sqrt{N} * \sqrt{M} \quad , \tag{2}$$

where N - number of averaged independent annular samples,

M - number of averaged independent annuli,

R - constant of 2/3 for bilinear interpolation,

$\sigma_N$ - film-noise model.

e. Normalize the N statistically independent samples of Step 3b by dividing by the computed standard deviation, $\sigma_T$, of Step 3c.

f. Compute the estimated power spectrum of the N normalized samples of Step 3e. The total power of the estimated power spectrum between the first and Nyquist spatial frequencies is N/2.

g. Compute the portion of the standard deviation, $\sigma_T$, that is contributed by nonconcentricity, ellipticity, and higher-order nonuniformities. This is experimentally derived by dividing the estimated power, $\hat{P}_i$, at each spatial frequency by the total power, N/2, taking the square of this ratio and multiplying by the standard deviation, $\sigma_T$.

$$\sigma_i = \sigma_T \sqrt{\frac{\hat{P}_i}{N/2}} \quad , \text{ where } i = 1, \ldots N/2 \quad . \tag{3}$$

The resulting $\sigma_i$ is a measure of nonconcentricity for i = 1, and a measure of ellipticity for i = 2 (see Appendix A). The higher-order measures of nonuniformity, $\sigma_i$, for i > 2 can be calculated but not currently calibrated to a measure (i.e., μm). The phase angles for i = 1 and 2 denote the polar orientation of the major axis of the nonconcentricity and ellipticity defects.

4. To calibrate the $\sigma_i$s of a real laser target, a known amount of nonconcentricity, NC (units of μm) and ellipicity, EP, would be computer-modeled based on Steps 1 and 2. The corresponding $\sigma_1$ and $\sigma_2$ for the amount of nonconcentricity, NC, and ellipticity, EP, would be calculated using Step 3. Given a digitized contact microradiograph of a real target, exposed under the same radiographic conditions as modeled images, the amounts $\hat{\sigma}_1$ and $\hat{\sigma}_2$ using Step 3 can be calculated. $\hat{\sigma}_1$ and $\hat{\sigma}_2$ are then calibrated using Eqs. (4) and (5).

$$\text{Nonconcentricity} = \frac{\hat{\sigma}_1}{\sigma_1} * \text{NC} \tag{4}$$

$$\text{Ellipticity} = \frac{\hat{\sigma}_2}{\sigma_2} * \text{EP} \tag{5}$$

B. Type I and Type II Defect Detection Sensitivities

To determine the sensitivity in detecting Type I and Type II defects, the estimated power spectrum values, $\hat{P}_i$s of Step 3f of Sec. II.A (i.e., $\hat{P}_1$ and $\hat{P}_2$ for nonconcentricity and ellipticity, respectively), must be greater than a constant, K. The constant K is defined by the estimated power spectrum being Chi-square distributed with two degrees of freedom for a 99% confidence. Thus, if any $\hat{P}_i$ is greater than K, a 99% confidence interval can be placed on that type of defect being present. Then its magnitude and orientation can be calculated by Eqs. (4) and (5) for nonconcentric and elliptic defects. For the higher-order Type II defects only the knowledge that the defect is statistically significant will be known. We can then determine the sensitivity of this technique and a noise error window about the calculated magnitude. The noise error arises from the film-grain-digitizing system, Eq. (2), and from the uncertainty in determining the target image's geometric center (Step 3a, Sec II.A). The 99% confidence window of the noise error for nonconcentricity is defined to be three times $\hat{\sigma}_N$ of Eq. (2) added in quadrature with the uncertainty in determining the target image's geometric center. The 99% confidence window of the noise error for ellipticity is defined to three times $\sigma_n$ times a constant of approximately $\sqrt{8}$.

To establish the sensitivity based on the noise error of Type I and Type II defect detection, we simulated microradiographic images of nonconcentric, elliptic, and perfect molybdenum targets. These images of molybdenum targets have 6.25-μm-wall thickness and diameters of 150 and 300 μm. To computer simulate these targets experimentally derived molybdenum step-wedge data were needed. The step-wedge data were six molybdenum steps increasing in 12.5-μm increments, exposed to a 45-kV-tungsten-bremsstrahlung source and recorded on holographic plate emulsion. From this an optical density-to-material thickness transformation was established per Step 1 of Sec. II.A. This was used with a previously described method[8] to computer-simulate the microradiographic images.

During the analysis of a perfect simulated image we intentionally displaced the image's center from its true geometric center. We have verified that the microsphere's center can be determined to better than 5% of the sampling interval. Thus, the error introduced in nonconcentricity by uncertainty in determining the target image's center is the value of Eq. (4) for a 5% shift in the center of a perfect target. An error in centering does not introduce an error in ellipticity. The noise error due to the film-grain-digitizing system affects sensitivity to both nonconcentric and elliptic defects. To obtain the effect we computed the amount of nonconcentricity using Eq. (4) for 20 random noise patterns added to a target having nonconcentricities of 2.5% and 10%. The same was done for a target containing similar sized elliptic defects. It was found that the noise error at the 99% confidence limit for nonconcentricity, Eq. (6), was three times $\hat{\sigma}_N$ of Eq. (2). Also, the noise error for ellipticity was three times $\hat{\sigma}_N$ times approximately $\sqrt{8}$, Eq. (7) (see Appendix A). The $\sqrt{8}$ constant will change depending on Eqs. (A-2), (A-3), and (A-4).

$$\text{Nonconcentricity noise error window} = \pm 3\ \hat{\sigma}_N . \qquad (6)$$

$$\text{Ellipticity noise error window} = \pm 3 * \sqrt{9} * \hat{\sigma}_N \ . \qquad (7)$$

In the cases examined the noise error dominates over the centering error. Thus, the sensitivity to nonconcentric and elliptic defects is defined by Eqs. (6) and (7). The sensitivities to simulated molybdenum targets of diameters between 300 and 150 μm, respectively, are ± 1/2 - 1% for nonconcentric defects, and ± 1.4 - 2.8% for elliptic defects.

C. Experimental Results

We have simulated and analyzed a set of eight molybdenum targets for Type I and Type II defects. The targets of Table I all have wall thicknesses of 6.25 μm and diameters of 150 μm for Mo0 thru Mo5 and 300 μm for Mo6 and Mo7. Table I compares the sizes of the simulated Type I and Type II defects with those measured by the refined algorithm. Both Type I and Type II defects are a measure in percent of nonconcentricity and ellipticity. The nonconcentricity is measured by the shift in centers on the inner and outer walls divided by the wall thickness and multiplied by 100. The elliptic defects are a measure in percent of the difference of the radii of the minor and major axes divided by the wall thickness and multiplied by 100.

In a second set of 11 glass targets, we analyzed for Type I and Type II elliptic defects. These targets have diameters ranging from 150 to 330 μm. They were radiographed using the contact microradiographic techniques of Ref. 8. Table II compares the sizes of Type I and Type II defects using the refined FFT algorithm and the old FFT algorithm of Ref. 1. For comparison we have also included the results of optical interferometric measurements made on these targets. The new and old methods agree quite favorably. Only LB6's nonconcentricity measurement is not within the range of the two older methods. This can be explained by the statistically significant higher-order nonuniformity found in the third spatial frequency of the estimated power spectrum.

## III. CONCLUSIONS

This refined method demonstrates added capability of detecting and quantifying both Type I and Type II elliptical defects. It also gives the capability of defining a noise error window and defect sensitivity based on the film-digitizing system noise and centering error noise. Our limits of detecting nonconcentricity of the inner and outer walls is ± 1/2 to 1% for molybdenum targets with 6.25-μm-wall thickness and diameters of 300 and 150 μm, respectively. Also, our sensitivity to detecting ellipticity of the major and minor axes of the inner wall is ± 1.4 to 2.8% for similar molybdenum targets. Furthermore, the global defect analysis time has not been lengthened with the inclusion of Type II defect detection.

## Appendix A

Using a development similar to Ref. 2, it will be shown that the first and second Fourier coefficients are good indicators of nonconcentricity and ellipticity, respectively. Assume the film density at a point is linearly related to the total length of material traversed by the x-ray source over a limited film-density range. Because of this linear relation, we will equate density and path length.[2]

Given the geometry as shown in Fig. 1, points $C_i$ and $C_o$ are the centers of the inner ellipse wall and outer circular wall. The inner elliptical wall has major and minor axes of a and b, and the outer circular wall has a radius of $r_o$. The ellipticity and nonconcentricity have been exaggerated. Consider a circular path of radius R, which must lie totally within the inner wall of the minor ellipse axis. This implies 50 to 90% limits on the annular average of Step 3b of Sec. II. The densities, $d_R(\theta)$, along this path can be derived by taking a slice through the sphere of Fig. 1 at y = Rcos$\theta$, denoted by the dashed line. This defines an annulus and the path length of $d_R(\theta)$. By simple substitutions and using a binomial expansion, $d_R(\theta)$ can be approximated by Eq. (A-1).

$$d_R(\theta) \approx 2\left(K_o - K_1^{1/2}\right) + \frac{R^2}{2K_1^{1/2}}\left(\frac{a^2}{b^2} - 1\right)\cos 2\theta - \frac{2a^2 R\, C_i}{K_1^{1/2} b^2}\cos\theta \quad ,$$

$$\text{where } K_o = \left(r_o^2 - R^2\right)^{1/2} \text{ and } K_1 = a^2 - \frac{a^2 C_i^2}{b^2} - \frac{R^2}{2} - \frac{a^2 R^2}{2b^2} \quad . \qquad \text{(A-1)}$$

It is easy to see from Eq. (A-1) why the first and second Fourier coefficients are a good measure for the nonconcentricity and ellipticity when both or either are present in a target.

Another interesting fact is the relative power in the first and second Fourier coefficients for a typical laser target, where

$$K_2 = \frac{2a^2 \ RC_i}{K_1^{1/2} b^2} \text{ , first coefficient,} \tag{A-2}$$

$$K_3 = \frac{R^2}{2 \ K_1^{1/2}} \left( \frac{a^2}{b^2} - 1 \right) \text{ , second coefficient,} \tag{A-3}$$

$$\text{Power Ratio} = K_2^2 / K_3^2 \ . \tag{A-4}$$

Example:

$a$ = 143.75 μm, $b$ = 143.125 μm, $C_i$ = 0.625 μm, and $R$ = 105.0 μm.

Then from Eq. (A-4) the ratio is approximately 7.5. This ratio is typically in the range of 7 to 9 for the same size nonconcentricity to ellipticity defects. This implies that the sensitivity to elliptic defects is approximately $1/\sqrt{7}$ to 1/3 that of nonconcentric defects of the same size.

Table 1. Simulated Type I and II Defects Measured

| | Simulated | | Actual | |
|---|---|---|---|---|
| Sample | Nonconcentricity | Ellipticity | Nonconcentricity | Ellipticity |
| Mo0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Mo1 | 1.6 | 0.0 | 1.6 | 0.0 |
| Mo2 | 10.0 | 0.0 | 10.0 | 0.0 |
| Mo3 | 0.0 | 5.0 | 0.0 | 5.0 |
| Mo4 | 2.5 | 10.0 | 2.4 | 10.0 |
| Mo5 | 2.5 | 5.0 | 2.4 | 5.0 |
| Mo6 | 1.6 | 0.0 | 1.6 | 0.0 |
| Mo7 | 10.0 | 0.0 | 10.0 | 0.0 |

Table 2. Type I and II Defects Measured Three Ways

| | Percent Nonconcentricity | | | Percent Ellipticity |
|---|---|---|---|---|
| Sample and Exposure Date | Old FFT | Optical Interferometry | New FFT | New FFT |
| LB1-7-15-77 | 4 | 3 | 3 | 0 |
| LB2-7-15-77 | 5 | 8 | 4 | 0 |
| LB3-7-15-77 | 17 | 11 | 13 | 0 |
| LB4-7-15-77 | 12 | 10 | 10 | 0 |
| LB5-7-15-77 | 5 | 3 | 5 | 0 |
| LB6-7-15-77 | 7 | 9 | 5[a] | 0 |
| LB8-7-15-77 | 1 | 5 | 1[a] | 2[a] |
| LB9-7-15-77 | 11 | 10 | 10 | 0 |
| LB10-7-15-77 | 5 | 5 | 5 | 0 |
| LB11-10-13-77 | 2 | <3 | 2 | 0 |

[a] Has a statistically significant higher-order nonuniformity at the third spatial frequency of the estimated power spectrum.

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Figure

Fig. 1. Single-layered target with nonconcentric walls and elliptic inner wall.

Figure

Fig. 1. Single-layered target with nonconcentric walls and elliptic inner wall.