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PHYSICAL MEASUREMENTS OF INERTIAL
FUSION TARGETS*

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ABSTRACT

Measurement of inertial-fusion targets has stimulated the development of many new techniques and instruments. This paper reviews the basis for selected target measurement requirement and the development of optical interferometry, optical scattering, microradiography and scanning electron microscopy as applied to target measurement. We summarize the resolution and speed which have been achieved to date, and describe several systems in which these are traded off to fill specific measurement applications. We point out the extent to which present capabilities meet the requirements for target measurement and the key problems which remain to be solved.

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I. Introduction

Targets for unclassified inertial fusion (IF) experiments must meet stringent fabrication criteria for dimensions and uniformity. Development of measurement techniques to assess whether targets meet these unique requirements has been an important element of IF research. This paper reviews the basis for the requirements, the development of the methods presently used for IF target measurement, and some of the plans for future improvements.

A representative unclassified inertial fusion target sphere consists of an inner fuel region surrounded by a hollow shell of high density "pusher" and an outer "ablator" layer. The overall size and thickness must be controlled within a few percent, but the most precise tolerances are on the thickness uniformity and smoothness of the pusher and ablator layers.

Three somewhat independent criteria determine the uniformity and smoothness tolerances. These are implosion symmetry, pusher stability during the implosion, and mixing of pusher material with the DT fuel.^{1, 2} If one side of the pusher or ablator wall is thicker than the other, the implosion will not proceed symmetrically. Also, the imploding pellet is subject to fluid instabilities. Small thickness variations or pertur-

bations on the target surfaces or at interfaces between layers of different density grow exponentially in amplitude as the target is compressed and can cause breakup of the imploding snell. Growth of small perturbations on the inner surface of the pusher can cause mixing of pusher material with the fuel, quenching the thermonuclear burn and reducing target yield even though the pusher remains basically intact and the implosion proceeds to high density.

The net result of these factors is a set of strict requirements on the initial smoothness and uniformity of each layer, surface and interface of the target wall. Since the growth rate of a perturbation depends on its lateral dimensions or "wavelength," these requirements specify the maximum allowable initial amplitude for a defect of given lateral dimensions.

Figure 1 shows these requirements for a 600 μm diameter target with a 40 μm thick wall. A target of approximately this size would be appropriate for a 100 kJ laser. While the actual allowable defect amplitudes depend on the specifics of the pellet construction and the implosion process, the general shape of the curve will apply to all targets of roughly the same size, and will apply to each shell of a double-shell target.

Curves such as these are very useful in deciding which characterization techniques should be pursued for fusion targets. Generally in considering the "resolution" of a measurement technique, one thinks only of the spatial resolution. In evaluating techniques for measuring IF targets, however, we must also consider the sensitivity to small aspect ratio defects--those with a small amplitude and a relatively long wavelength. Near the "worst wavelength," the minimum in the curves of Fig. 1, we must detect defects with aspect ratios as small as 0.001. Such defects are generally invisible to measurements which look only at the surface contour. To properly characterize IF targets, we must develop a set of techniques with a combination of spatial and amplitude resolution which covers the entire relevant "defect space" shown in Fig. 1.³

Measurement techniques are used in a variety of ways, allowing many different trade-offs between speed, accuracy and comprehensiveness. Measurements to provide feedback on the fabrication process must be accurate, but not necessarily rapid or nondestructive. Sorting the output of a low yield production process requires high speed, nondestructive measurements, but need only measure a few commonly occurring defects. Final target measurement for correlation with the results of implosion experiments must be accurate, comprehensive and nonde-

structive, but need not be faster than an hour or so per sphere. As no single technique or instrument meets all of these requirements, many different approaches are needed.

Presently the primary techniques used to measure these inertial fusion targets are optical interference microscopy, optical scattering, microradiography, and scanning electron microscopy. Each of these techniques has unique advantages and drawbacks. In this article we review the development of each technique as applied to inertial fusion targets, summarize the present capabilities for resolution and speed, and describe planned developments.

11. Optical Interference Measurements

Optical interference microscopy has been one of the most useful methods for measuring IF targets. One reason for this success is the high sensitivity of interferometry to small aspect ratio defects. Height and thickness are deduced by measuring an optical phase shift. The sensitivity of these measurements (5-50 nm) greatly exceeds the spatial resolution (≈ 500 nm).

For transparent targets, such as hollow glass and polymer microspheres, optical interferometry has become the primary

measurement technique. Measurements can be made rapidly, sample preparation and handling are quite simple, and a wide variety of useful techniques have been developed. Optical interferometry is also very useful for measuring the surface structure of opaque targets. Measurement techniques are more cumbersome than for transparent targets, but the methods have excellent accuracy.

Scientists at Lawrence Livermore National Laboratory first applied interferometry to inertial fusion targets, using a Twyman-Green interferometer to measure thickness and uniformity of hollow glass microspheres.⁴ Thickness was determined by measuring the spacing between adjacent (concentric) fringes. Fringe spacing was modeled with a complex ray tracing program.⁵ Nonconcentricity was estimated from the offset between the fringe pattern center and the geometric center of the microballoon. Other defects were judged qualitatively from the fringe pattern uniformity. To facilitate these measurements, a computer code was developed to simulate the interference pattern seen on a microsphere with a specified defect.⁶

These early methods were somewhat cumbersome and, while quite sensitive to wall thickness variations, were mostly used for qualitative comparison and for sorting the "best" micro-

spheres from a large batch. Also little or no attention was paid to examining a sphere in several orientations to assure that all defects had been seen.

Important steps in quantitative measurement were the use of white light fringes to make rapid, accurate measurement of wall thickness,⁷ and simple methods for quantifying thickness variation.⁸ Further refinements took into account the role of dispersion and the effect of the actual optical system.^{8,9} Techniques were developed for measuring a variety of targets, including flat slabs, layered structures, and hemispheres used to construct double shell targets.¹⁰

Another major step was the development of a microsphere rotator coupled to an interference microscope.^{10,11,12} This allowed the first systematic examination of an entire target, assuring that all defects had been seen and accurately measured.

The next advancement in sensitivity was achieved by the use of AC interferometry. This technique allows automated measurement of optical phase shifts and provides greatly improved accuracy. Measurements by eye alone are typically accurate to $\lambda/10$, or about 20-50 nm. With AC interferometry the accuracy can easily be extended by a factor of 5-10.

The first AC interferometer applied to inertial fusion target measurement was constructed at the University of Rochester.¹³ This instrument maps the phase pattern seen on the face of a target. In parallel with this development, workers at Livermore constructed a fully automated system for rotating and mapping a transparent target.^{14,15} Optics for this system were based on a phase measuring microscope developed by Smith.¹⁶

A more advanced AC interferometer which will also map the surface of opaque targets is being assembled and tested at Livermore.^{17,18} A similar system is under construction at Los Alamos.¹⁹ These instruments will provide approximately 10 nm amplitude resolution, 1-2 μ m spatial resolution, and mapping speeds of 50,000 points/second, requiring several minutes to map a typical target.

In addition to detailed, high resolution measurements of individual targets, interference measurements are useful for rapidly characterizing the average parameters of a batch of spheres and for sorting for spheres to meet specific requirements. For transparent targets, a skilled interference microscope operator can make rapid measurements of thickness, concentricity and surface contamination. Measurement rates of 50-100 spheres per hour are typical, and scanning for a sphere

with specified parameters can be done at rates of 500-1000 spheres per hour. To aid in making these rapid measurements, workers at Livermore have developed a computer controlled system for scanning a large number of transparent microspheres, rapidly measuring the thickness and diameter of any selected spheres, and automatically storing the data for later analysis.²⁰ With this system measurement rates are several hundred spheres per hour.

Other applications of interferometry have also been explored. Several groups have used interferometric measurements to characterize cryogenic DT fuel layers in glass microspheres.^{21,22,23} A recent development is the use of holographic interferometry to eliminate the fringe pattern caused by the glass microsphere and allow more accurate measurement of the fringe pattern caused by the fuel itself.²⁴ Researchers at the University of Illinois are developing an AC interferometer to measure the fringe pattern on a free falling microsphere.²⁵ They plan to use this instrument to measure and control freezing of the DT fuel during free fall.

Interferometry can also be used to measure the fuel density in targets pressurized through a hollow support stalk. An interesting side effect of these measurements is an increased sensitivity to concentricity defects. The gas fill

increases the offset of the interference rings from the geometric center of the spheres.²⁶

In yet another application, interferometry is used to measure the density distribution in a gas jet target.²⁷

The diversity of applications which have been found for interferometry is a reflection of the good match between the characteristics of the measurement method itself and the demands of inertial fusion target measurement. This match seems certain to assure that interferometry will continue to play an important role in target measurement.

III. Optical Scattering Measurements

Another class of techniques which have played a role in inertial fusion target measurements are those based on optical scattering. In general the appeal of these techniques is their speed and simplicity. The drawbacks are that the data is often difficult to interpret quantitatively.

One of the earliest methods used to detect wall thickness variations in glass microspheres is in this category.²⁸ The microsphere is observed with an ordinary light microscope, slightly out of focus. In this configuration refraction causes

a dark band to be seen around the rim of the microsphere. The width of this band correlates with the thickness of the microsphere wall. The method is quite sensitive to thickness variations, but it is difficult to make quantitative measurements. The technique is useful for rapid, qualitative measurement of the average uniformity of a microsphere batch without using an interference microscope.

Another measurement method based on optical scattering uses a tuneable dye laser to illuminate a microsphere and measure the intensity of the backscattered light as a function of wavelength.²⁹ The modulation pattern is very intense and can be interpreted to find the target wall thickness. This method might be the basis for accurate wall thickness measurements without the need for accurately positioning the target in the focal plane of an interference microscope.

An optical scattering method developed to measure roughness of machined surfaces was investigated briefly for its applicability to inertial fusion targets. In this method, the intensity of diffracted light is measured as a function of angle. From this one can deduce the amplitude of any periodic structure of the surface.³⁰ This measurement was not very successful when applied to IF targets because of the steep curvature of the wall. A further problem is one common to other

scattering measurements: the technique measures only average surface characteristics whereas target performance may be affected by a few isolated defects which are either aperiodic or which have high individual but low "average" amplitude.

Analysis of the Fraunhofer diffraction pattern from transparent microspheres is another possible source of information. Researchers at McDonnell Douglas conducted a brief study empirically correlating target parameters with the intensity structure of the diffraction pattern.³¹ More recently detailed calculations have been made of scattering from transparent microspheres with various defects.³² Significant changes in the amplitude, polarization and phase pattern are predicted. Modeling the scattering requires large computer codes and is quite expensive and time consuming. However, it may prove possible to identify some simple characteristic features which could be measured rapidly to provide useful information.

IV. Microradiography

While optical and scanning electron microscope measurements provide excellent data for transparent targets and for target surfaces, microradiography is the primary technique for measuring thickness and uniformity of opaque targets. As

almost all more advanced target designs contain one or more opaque layers, the importance of accurate radiographic measurements will continue to increase.

As with optical interference techniques, the advantage of microradiography for measuring inertial fusion targets is that measurements of thickness are independent of the spatial resolution. Spatial resolution is obtained either by projection imaging with a very small source or by contact imaging on a high resolution detector (presently film). Thickness information is obtained from the amount of x-ray absorption. Unfortunately, this also means that microradiography is inherently less sensitive to thickness variations than is optical interferometry--accurate absorption measurements are more difficult than accurate interferometric phase measurements.

Multi keV x rays are the most appropriate "probe" for IF target measurement. To get the maximum information about thickness from a given exposure level, the absorption length of the radiation should be comparable to the thickness of the material being examined. If the absorption length is too short, all of the radiation is stopped in the sample. If it is too long, the radiation passes through unattenuated. In either case no thickness information is obtained. The optimum absorption length depends on the specifics of the measurements, but

it is generally 50 to 100% of the material thickness. Most target material layers are from a few micrometers to a few hundred micrometers thick, and absorption lengths of this magnitude are obtained with x rays from a few keV to several hundred keV. Fortunately, this is within the normal operating range of many x ray generating systems.

The first quantitative development of microradiography for measuring inertial fusion targets was done by researchers at KMS Fusion.³³ They recognized the value of absorption information in determining thickness and developed a scanning slit microdensitometer and peak height analysis for measuring contact microradiographs of targets. This system measured wall thickness within 0.08 μm and thickness uniformity within about 5% for thin ($\approx 1 \mu\text{m}$) glass microspheres. Researchers at Los Alamos developed techniques for radiographing large numbers of targets simultaneously and used an image analyzer to do rapid, semi-quantitative sorting of the images.³⁴

Another Los Alamos group has developed an extensive computer code for two-dimensional analysis of digitized radiograph images.^{35,36} Their program, written for a CDC-7600 computer, divides the image into sectors and compares the average density of the sectors to detect differences caused by thickness variations. This method provides very sensitive

radiographic analysis. For thin ($1\text{ }\mu\text{m}$) microspheres, sensitivity to concentricity defects is $10 - 20\text{ nm}$ ($1 - 2\%$). For shorter wavelength defects, the sensitivity ranges from 30 to 100 nm ($3 - 10\%$). The sensitivity of these techniques for detecting defects on thicker targets has not yet been explored experimentally, but one would expect it to remain about the same fraction of the wall thickness. Recently a streamlined version of this program was adapted to a mini computer.³⁷

While very complete and accurate, these measurements are time consuming. The microsphere must be radiographed in at least three orientations, and each of these images must be carefully digitized, presently done with a scanning microdensitometer. A day or more is required to analyze several spheres.

To fill the need for less comprehensive, more rapid measurements, Livermore researchers have developed a simplified method for rapidly measuring thickness and concentricity using least squares fitting to a trace across the microsphere image.³⁸ They have also developed a system for rapid digitization of a radiograph image and implemented the combined digitization and analysis on a microcomputer.³⁹ The system requires only a few minutes to digitize an image and measure thickness within $0.3\text{ }\mu\text{m}$ and concentricity within $1 - 3\%$. A similar system is also under construction at Los Alamos.⁴⁰

In parallel with development of radiographic analysis has come the development of improved x-ray sources for making the radiographs themselves. High brightness, monochromatic sources shorten the required exposure time, provide better images, and simplify the computational analysis.^{39,41} Present sources typically produce a few hundred watts with less than a 1 mm spot size. Electron energies up to 40 keV are available, and filtered k_{α} emission is used to provide monochromatic x-rays.

There are a number of ideas for more advanced radiography which may lead to much faster and more accurate measurement of IF targets. One proposal is to do point-by-point mapping with x-rays analogous to the automated interferometric mapping described earlier. The incident x-ray flux is apertured to a small spot and the absorption through the target sphere is measured as the target is rotated in the x-ray beam. Photon counting of the transmitted flux provides the most accurate possible thickness measurement for a given exposure. A simplified version of this concept is being used at C.E.A. Limeil to measure target thickness. A stalk-mounted target is placed in an apertured x-ray beam to measure absorption through a 20 μ m diameter spot on the sphere.⁴²

Another concept for advanced radiography is using a micron sized x-ray source to project an enlarged image of a target. Scientists at Exxon Research used a SEM beam to generate a microscopic x-ray source for radiographing microspheres and then examined the developed radiographs with a SEM to obtain maximum spatial resolution.⁴³ Researchers at Rutherford Laboratories have developed a novel technique in which they place target spheres on a thin foil, raster a focused electron beam across the back side of the foil, and use the intensity of the transmitted x-ray signal to control the intensity modulation of the SEM display.⁴⁴ This produces a high resolution microradiograph of the targets, displayed on the SEM screen.

If the image generated by a microscopic x-ray source is projected onto a 2-dimensional detector, such as a CCD array,^{45,46} an image of the target could be produced in real time as it is rotated in the x-ray beam. The primary appeal of this concept is the capability for rapid manipulation and examination of a sphere. However this technique could also be used to make point-by-point measurements by counting photons with a detector placed at the center of the projected image.

V. Scanning Electron Microscopy

Scanning electron microscopy provides higher spatial resolution than can be achieved with either optical or radiographic methods. Spatial resolution of less than 10 nm can be readily obtained with a good instrument. The limitations on SEM measurements of IF targets are that small aspect ratio defects (less than about 1:20) are difficult to detect, and sample mounting and handling procedures are time consuming and usually destructive to the targets.

Because of these factors, the best application of scanning electron microscopy to IF target measurement is diagnosing problems with the fabrication processes, rather than non-destructive sorting or final inspection of a target. The SEM provides rapid, high resolution measurements of the surface structure and surface contamination of glass microspheres and coatings and of the thickness and internal structure of fractured or cross-sectioned samples. High resolution surface measurements are particularly important because small surface defects can nucleate the growth of large "cone" defects in a coating.⁴⁷ Because of the natural combination of electron microscopy with x-ray spectroscopy, the SEM is also heavily used for composition and microstructure analysis, a separate and equally important area of IF target fabrication. These

measurements are all vital to developing target fabrication processes. SEM measurements are also used to cross check and calibrate interferometry and radiography measurements.⁴⁸ For thin, opaque layers, these measurements are presently the most accurate thickness diagnostic.

Several significant developments have been made applying the SEM to measuring IF targets. One is a target manipulation system for the SEM similar to those described earlier for use with optical systems.^{49,50} This allows systematic inspection of an entire target and recording of the sequence of images on video disc. The process of target rotation, SEM scan and image recording is fully automated and controlled by a microcomputer.

Another development is the differential detection of back-scattered electrons to measure surface topography.⁵¹ These measurements are quite sensitive to low aspect ratio defects, improving the detection limit to about 1:50. It is also possible to make automated, quantitative measurements of surface roughness by this means.

VI. Summary and Conclusions

Measurement of inertial fusion targets has stimulated the development of many new techniques and instruments. These

measurements cover a variety of applications, from complete, high accuracy measurement of individual targets to rapid survey and sorting measurements. To date the most extensive development has been of optical techniques. This is a natural result of the relative ease and accuracy of these measurements and their being very well suited to present transparent targets. As targets become more complex, and more frequently include opaque layers, microradiography will undoubtedly receive more emphasis.

The present techniques are close to satisfying the measurement requirements for transparent targets, both for resolution and speed. For opaque targets, on the other hand, much development work remains. Figure 2 shows the composite resolution presently available for an opaque target. Measurements of surface structures are adequate, but measurements of the thickness and density uniformity are not. Present microradiography measurements have good resolution for concentricity and other "long wavelength" defects, but are not able to measure short and intermediate wavelength defects with sufficient amplitude resolution. Analysis also must be extended to measure each layer of a multilayer target. Extending microradiography resolution and versatility or developing alternative methods such as acoustic probing⁵² will be one of the main challenges in target measurement.

Also, methods for sorting opaque targets are not very well developed. We do not yet have fast, accurate techniques for scanning large numbers of opaque spheres, rapidly measuring the key parameters and selecting the acceptable targets. In this respect the future of opaque target measurement may lie in a somewhat different direction from that taken with transparent targets. Because of the greater difficulty of rapid measurements and of sorting, it may prove more attractive to concentrate on improving the yield of the fabrication processes rather than combining low yield fabrication with rapid sorting.

The trade-off between production improvements and sorting is of long term importance. In a power reactor, a set of high yield processes would mean better utilization of production equipment and target materials and would eliminate the need for rapid, nondestructive sorting measurements. There are, of course many intermediate possibilities, with sorting used where perfecting the production process is either impossible or not cost effective. These trade-offs cannot (and need not) be made at this time, but the issue should be kept firmly in mind, as it will have an important impact on the ultimate direction of IF target measurement development.

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FIGURE CAPTIONS

Fig. 1. Wall uniformity requirements for a typical inertial fusion target 600 μm in diameter and 40 μm thick. The considerations of implosion symmetry, pusher stability, and pusher-fuel mixing dominate the requirements for defects of different spatial dimensions as shown.

Fig. 2. Present resolution limits versus requirements for an opaque inertial fusion target. Horizontal hatching indicates a capability for surface contour measurement. Vertical hatching indicates a thickness uniformity measurement. One of the major remaining challenges for opaque targets is to measure small aspect ratio thickness variations near the most critical spatial wavelength.

Figure 1

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Figure 2.

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