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Instruments

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COMPTON SCATTERING TECHNIQUE FOR
MEASURING THE AREAL DENSITY OF
GLASS-REINFORCED STRUCTURES

J. D. White

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the ATOMIC ENERGY COMMISSION under U. S. GOVERNMENT Contract W-7405 eng 26

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ABSTRACT

An investigation has shown the applicability of a new technique for the one-sided nondestructive measurement of the mass uniformity of glass-reinforced laminates. The number of gammas scattered into a detector through 135 degrees by Compton interactions was found to be a smooth function of the mass per unit area of the specimen over a wide range (0.27 - 2.07 gms/cm²).

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SUMMARY

An investigation has shown the applicability of a new technique for the one-sided nondestructive measurement of the mass uniformity of glass-reinforced laminates. A beam of monoenergetic photons from a radioisotope source is collimated and directed into the specimen to be examined. The number of gammas scattered into a detector through 135 degrees by Compton interactions was found to be a smooth function of the mass per unit area of the specimen over a wide range (0.27 - 2.07 gms/cm²). An analytical expression has been derived that describes approximately the dependence of the scattered intensity on the areal density. For a particular type of resin and glass, a calibration curve can be produced that relates scattering intensity variations to variations in the mass per unit area. This technique can then be, and has been, used for a routine evaluation of the mass uniformity of various structures.

INTRODUCTION

STATEMENT OF THE PROBLEM

The need for performance reliability in filament-wound, reinforced plastic composite structures has resulted in the initiation of a program to study the applicability of nondestructive testing (NDT) to glass-reinforced laminates. There are several material parameters which determine the integrity and strength of composite structures, namely: glass-to-resin ratio, porosity, delaminations, and areas of nonbond at a bladder/laminate interface.

The strength of composite structures is largely dependent upon mass uniformity, a characteristic that is dependent, in turn, upon the glass-to-resin ratio and porosity. Since the strength of a structure is an important design parameter, it was decided that an NDT technique for the measurement of mass concentration should be sought.

One of the most commonly used methods of measuring mass concentration is through-transmission radiation attenuation gaging.⁽¹⁾ In this technique, the attenuation of a beam of X rays between a source and detector by a material placed between them is related to the mass per unit area of the material. This method requires, however, that the material be placed between the source and detector. For parts which have closed surfaces, such as a cylindrical or spherical shell, and for parts which have a geometry such that it is not feasible to put material between the source and detector, this technique is impractical.

Another conventional NDT method for measuring mass concentration is the beta-backscatter technique in which betas from a radioisotope source strike the surface of the material to be investigated. Betas are then scattered through an angle of 170 degrees or greater into a detector. The number of betas scattered from the material is a function of the mass concentration of the material as long as the thickness of the material is considerably less than the beta range. The penetration depth of 2.18-mev betas in typical plastic materials, however, is on the order of only 0.04 inch.⁽²⁾ For materials thicker than about 0.01 inch, therefore, this technique loses its value.

Since even low-energy gammas penetrate materials more easily than high-energy betas, it seemed possible that the beta-backscatter technique could be converted to use gammas as the form of incident energy. Analytical calculations (shown in the Appendix) predict that, if a beam of monoenergetic gammas is directed such that it penetrates a section of the material, the

portion of the beam that undergoes one Compton scattering collision and exits from the material in a designated direction is proportional to the mass per unit area (or areal density) of the material.

An investigation was undertaken to experimentally find such a relationship for a filament-wound, reinforced plastic material. Samples of this material with a range of areal densities from 0.27 to 2.07 gms/cm² were examined using Am-241 and Gd-153 sources. This report is concerned with a description of the experimental procedure and a discussion of the results.

COMPTON SCATTERING

In theory, there are twelve different processes by which photons can be absorbed or scattered. Many of these processes occur quite infrequently, while some others, although predicted, have not yet been observed. In the energy domain met most frequently in nuclear transitions (ie, 0.01 to 10 mev), all but a very few of the effects are explainable in terms of three processes: the Compton effect, the photoelectric effect, and pair production.(3, 4)

In the photoelectric effect, the energy of the photon is completely transferred to an electron that is bound to the nucleus of an atom. For an incident energy of 1.02 mev or greater, a photon may interact with the intense field surrounding the nucleus and be converted into a positron-electron pair in the process called "pair production". In Compton, or incoherent scattering, the photon acts like a particle and undergoes a collision with a loosely bound electron. The collision can be effectively treated as the interaction between an electromagnetic quantum (photon) and a free electron. While the electron recoils with a momentum supplied by the photon, the photon is scattered through some angle and has an energy given by:

$$E = \frac{E_o}{\left[1 + \frac{E_o}{M_o C^2} (1 - \cos \theta) \right]}, \quad (1)$$

where:

E represents the energy of the scattered photon (mev),

E_o the energy of the incident photon (mev),

$M_o C^2 = 0.511$ mev, the rest mass of an electron, and

θ the angle through which the photon is scattered.

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COMPTON SCATTERING TECHNIQUE

EXPERIMENTAL STUDY

It was theoretically predicted that the number of photons scattered from a quantity of material should be a smooth function of the mass per unit area of the material. The experiments conducted during this study were performed to test this hypothesis.

In each experiment, a beam of photons from a radioisotope source was directed so that it intersected a 0.5-inch-diameter area on the surface of the specimen to be examined, as indicated in Figure 1. The photons scattered through an angle of 135 degrees strike a sodium iodide crystal and are counted with associated electronics, as outlined in Figure 2. A multichannel analyzer was used for the initial spectra characterization while the single-channel analyzer was used for the routine work. A characteristic energy spectrum of the scattered photons is given in Figure 3 for a Gd-153 source. In this figure, the scattered intensity is shown as a function of energy (in arbitrary units). The two peaks correspond to the 42-kev conversion X ray and the 100-kev gamma.

Figure 1. COMPTON SCATTERING APPARATUS.

Figure 2. PRINCIPAL COMPONENTS OF THE GAMMA COUNTING SYSTEM.

Figure 3. SCATTERED PHOTON SPECTRUM FOR A Gd-153 SOURCE.

Five filament-wound, reinforced plastic cylinders of known densities and thicknesses⁽⁵⁾ were examined in the manner just described. The resin and glass types were the same for each cylinder. An Am-241 radioisotope was used to supply 60-kev photons. The yield of photons scattered through 135 degrees was found to be directly proportional to density times thickness (ρt) in the range from 0.80 to 1.03 gms/cm², as seen in Figure 4. It was found that a one-percent change in the value of ρt leads to an 0.8 percent change in the scattered gamma intensity.

Figure 4. INTENSITY OF THE COMPTON-SCATTERED PHOTONS AS A FUNCTION OF THE DENSITY AND THICKNESS.

The values of density and thickness given for the cylinders are averages of measurements taken at various locations. An estimated uncertainty of two percent was assigned to the value of ρt for each cylinder. Compton scattering measurements were taken at four places (90 degrees apart) on each cylinder. The standard deviation of the mean of these measurements was calculated to be on the order of 0.5 percent for each cylinder, and the uncertainty in any individual measurement due to counting statistics was on the order of 0.1 percent.

Sixteen filament-wound cylinders were examined using the Gd-153 source. The range of their areal densities was from 0.27 to 2.07 gms/cm². There

were three groups of thicknesses—0.060, 0.180, and 0.360 inch. The number of 100-kev and 42-kev photons scattered from the cylinders into the detector was found to be a smooth function of the mass per unit area, as Figures 5 and 6 show. The same uncertainties apply to these figures as to those which were stated for Figure 4. Relationships between scattered photon intensity and mass per unit area of the target for a limited range of ρt is derived in the Appendix. This relationship is expressed as:

$$Y = K' (\rho t) \exp \left[-K'' (\rho t) \right], \quad (2)$$

where:

Y represents the photon intensity at the detector,

ρ the density of the target, and

Figure 5. NUMBER OF SCATTERED 100-KEV PHOTONS AS A FUNCTION OF THE MASS PER UNIT AREA.

Figure 6. NUMBER OF SCATTERED 42-KEV PHOTONS AS A FUNCTION OF THE MASS PER UNIT AREA.

t the thickness of the target.

K' and K'' are constants.

The curves in Figures 5 and 6 were produced by fitting this equation to the data points. In the range of areal densities exhibited by the cylinders and for the energy range included (42 through 100 kev), this relationship seems to hold. As the thickness of the laminate increases beyond two or three mean free paths of the photons, however, it is expected that either the equation should be modified or more energetic photons used.

In the mathematical treatment (Appendix), K'' is used to replace μ_p/ρ in the equation:

$$Y = K' (\rho t) \exp \left[- (\mu_p/\rho) (\rho t) \right], \quad (3)$$

where μ_r represents the linear removal cross section. The product, $K'(\rho t)$, is used to approximate the portion of the incident beam which undergoes one Compton scattering interaction that changes its direction into the proper solid angle to strike the detector. The exponential function approximates the attenuation of both the incident and scattered photons. Since the beams may be attenuated by absorption and scattering of the photons, the linear removal cross section, μ_r , is used rather than only one of the macroscopic absorption or scattering cross sections. A more sophisticated approach to the problem would include an integration of the product of scattering and beam-attenuation probabilities over the thickness of the material. It was assumed that μ_r was not a strong function of energy so that its value would be the same for the incident photon as that for the lower-energy scattered photon. For the purpose of completeness, values of μ_r/ρ were determined for 42 and 100-keV photons and were compared with the values of K'' that were obtained by fitting Equation 2 to the data in Figures 5 and 6. These values of μ_r/ρ were obtained by a through-transmission technique in which the attenuation of a narrow collimated beam passing through a cylinder wall of density ρ and thickness t was measured experimentally and compared to the equation:

$$I = I_0 \exp \left[-\mu_r/\rho (\rho t) \right], \quad (4)$$

where I and I_0 represent the transmitted and incident photon intensities, respectively.

The Gd-153 source was used to supply the 42 and 100-keV photons. For the case of the cylinder with the highest value of ρt (2.07 gms/cm²), a beam of 42-keV photons was reduced by 48 percent, while a beam of 100-keV photons was reduced 25 percent. The average calculated values of μ_r/ρ were 0.294 cm²/gm for 42-keV photons and 0.135 cm²/gm for 100-keV photons. Using the data of Figures 5 and 6 and Equation 2, the values of K'' were found to be 0.325 and 0.180 cm²/gm for the lower and higher-energy photons, respectively. The assumption that μ_r/ρ is the same for the incident and scattered photons is not valid in this energy range as is evidenced by the change in μ_r/ρ for the 42 and 100-keV photons obtained by the through-transmission method. By the use of Equation 1, it may be shown that for a scattering angle of 135 degrees, an incident photon of 100 keV yields a scattered photon of 75 keV, while a 42-keV incident photon results in a 38-keV photon. The much larger energy change for the 100-keV photon, therefore, is probably the reason that the difference between K'' and μ_r/ρ for that energy is greater than for the 42-keV photon.

DISCUSSION

A smooth, well-behaved relationship between the yield of photons that were Compton scattered from glass laminates into a detector and the areal densities of the laminates was found to exist over a wide range—0.27 to 2.07 gms/cm². With suitable calibration standards, this technique can be, and has been, used to evaluate the areal density uniformity of composite structures. Such a relationship should exist for all types of glasses and resins using almost any low-energy photons. As the thickness of the specimen becomes large with respect to the mean free path of the photons in the specimen, however, the sensitivity of the technique decreases. As the incident photon energy increases, the scattering cross sections decrease. The presence of high-Z elements in a low-Z specimen would complicate the situation if the incident photon energy or the once-scattered photon energy were near the K-absorption edge of the high-Z elements.

Future objectives should include: (1) an investigation to see if the weight percent of glass in a specimen can be determined by using a Compton scattering technique, (2) work with other types of materials, and (3) study of numerical methods of system optimization.

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APPENDIX

ANALYTICAL RELATION BETWEEN AREAL DENSITY AND SCATTERED PHOTON INTENSITY

The following is an approximate analytical development of the variation in the yield of photons that have been Compton scattered by the laminate into the solid angle subtended by the detector, Y , due to a variation in the areal density, ρt , of a material. It is assumed that the material is not of infinite thickness and that the intersection of the solid angles of the source and detector includes the entire thickness of the material. If "r" is defined as the average distance from the source to the point in the specimen at which a photon undergoes a scattering collision, then:

$$Y = \frac{S}{4\pi r^2} P_1 P_2 P_3, \quad (A-1)$$

where:

Y represents the intensity of the scattered photons that reach the detector, and

S the source strength (photons/sec).

P_1 represents the probability that the photon reaches the scattering center,

P_2 the probability that the photon is scattered into the solid angle subtended by the detector, and

P_3 the probability that the scattered photon escapes the laminate.

The probability, P_1 , that the photon reaches the scattering center may be written:

$$P_1 = e^{-\mu_r t'}, \quad (A-2)$$

where:

μ_r represents the linear removal cross section of the laminate (cm^{-1}), and

t' the thickness of traversed laminate (cm).

The probability, P_2 , that the photon is scattered into the solid angle subtended by the detector is:

$$P_2 = \frac{N_o Z \rho}{A} \frac{d\sigma}{d\Omega} \cdot \frac{\pi d^2/4}{h^2}, \quad (A-3)$$

where:

N_o has the value of Avogadro's number (6.02×10^{23} atoms/gm mole),

Z the atomic number (electrons/atom),

ρ the density of the laminate (gms/cm³),

A the atomic weight (gm/gm mole),

$\frac{d\sigma}{d\Omega}$ the differential scattering cross section (cm²/electron),

d the diameter of the detector (cm),

h the average distance from the point of scattering to the detector (cm), and

t the total thickness of the laminate (cm).

The probability that the scattered photon escapes the laminate without further interaction, P_3 , may be written:

$$P_3 = e^{-\mu_{r1} t''}, \quad (A-4)$$

where:

μ_{r1} represents the linear removal cross section for the scattered photons, and

t'' the thickness of the laminate to be traversed for escape.

Combining Equations A-1 through A-4 yields:

$$Y = \frac{SN_o Z \rho t}{4\pi r^2 A} \frac{\pi d^2}{4h^2} \frac{d\sigma}{d\Omega} \exp \left[(-\mu_r t' - \mu_{r1} t'') \right]. \quad (A-5)$$

In Equation A-5: S , d , N_o , π , and $\frac{d\sigma}{d\Omega}$ are constants so that Equation A-5 may be written:

$$Y = K \frac{Z}{A} \frac{1}{r^2} \frac{1}{h^2} (\rho t) \exp \left[- (\mu_r t' + \mu_{r_1} t'') \right]. \quad (A-6)$$

Now Z and A are the effective atomic number and atomic weight of the laminate. If only small changes of ρ are allowed, it may be assumed that Z/A is constant. Notice also that r and h are the distances from the source and detector to the location of the effective scattering center. For a change in ρt , the location of the effective center will also change. But, for small changes in ρt , the fractional changes in r and h should be negligible. With these arguments, Equation A-6 may be reduced to:

$$Y = K' (\rho t) \exp \left[- (\mu_r t' + \mu_{r_1} t'') \right]. \quad (A-7)$$

In Figure 1, it can be seen that t'' is approximately $0.707t'$; and, therefore, Equation A-7 becomes:

$$Y = K' (\rho t) \exp \left[- (\mu_r t' + 0.707 \mu_{r_1} t') \right]. \quad (A-8)$$

If it is assumed that $\mu_{r_1} \approx \mu_r$ (which may be the case if μ_r is not a strong function of energy) Equation A-7 may be written:

$$Y = K' (\rho t) \exp \left[- (1.707 \mu_r t') \right]. \quad (A-9)$$

Since t' is the thickness of material traversed to the average scattering center, it is certainly a function of t as long as t is not thicker than two or three mean free paths of the photons. If this limit is assumed, Equation A-9 can be approximated to:

$$Y = K' (\rho t) \exp \left[- \frac{\mu_r}{\rho} \rho t \right]. \quad (A-10)$$

For most materials, however, μ_r/ρ is not a strong function of density. Thus, if this further assumption is made, Equation A-10 reduces to:

$$Y = K' (\rho t) \exp \left[- K'' (\rho t) \right]. \quad (A-11)$$

From Equation A-11 it is seen that the yield of photons scattered from a specimen should be a smooth function of density and thickness. Therefore, it should be possible to produce a calibration curve of scattered yield versus areal density, ρt , and to use such a curve to measure the areal density of various materials.