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X-RAY TRANSMISSION/SCATTERING TECHNIQUE
FOR THICKNESS-INDEPENDENT DENSITY
MEASUREMENT

E. J. Giacomelli

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X-RAY TRANSMISSION/SCATTERING TECHNIQUE FOR THICKNESS-INDEPENDENT DENSITY MEASUREMENT

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ABSTRACT

A nondestructive technique, using penetrating X radiation, has been developed to measure the density uniformity of low-Z, compressible materials that is independent of material thickness. Thickness independence is achieved by simultaneously monitoring the transmitted and scattered X rays. Results on samples of pressed carbon materials have demonstrated that there is the expected linear relationship between measured quantities and material density, independent of material thickness, and that this is a viable means of measuring density uniformity.

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SUMMARY

Penetrating X radiation is extensively used to obtain density information from a variety of different materials. Most commonly used methods involve monitoring X-ray transmission or scattering. A new technique which monitors both X-ray transmission and scattering has been developed to measure density uniformity of low-Z materials directly and independent of the material thickness. Samples of pressed carbon materials having a wide range of densities and thicknesses were used to evaluate this technique. Results have demonstrated that there is the expected linear relationship between measured quantities and density, independent of material thickness. Using this technique, density variations in pressed carbon materials have been established.

INTRODUCTION

The technique utilizing penetrating radiation was developed to solve the problem of nondestructively measuring density uniformity in a variety of low-Z, compressible materials. No existing technique could adequately make this measurement. The measurement concept is based on simultaneously monitoring transmitted and scattered X radiation. Samples of pressed carbon materials were used to evaluate this concept, and the viability of using this technique to measure density uniformity has been demonstrated. This technique offers greater precision and is more generally applicable to a wide variety of conditions than existing techniques that monitor scattering alone. This report describes the measurement concept and the method of evaluation.

X-RAY TRANSMISSION/SCATTERING TECHNIQUE FOR MEASURING DENSITY

THEORETICAL BACKGROUND

The technique for measuring material density involves the use of penetrating X radiation. A highly collimated X-ray beam is used to penetrate a sample material. The beam undergoes absorption and scattering in the sample, and is transmitted with reduced intensity. The amount of absorption and scattering that occurs depends on several variables, including the density of the sample. A scheme has been selected so that this measurement is insensitive to all variables but density, and the sample density can be determined directly and independently of sample thickness by measuring the ratio of scattered to transmitted X rays emitted from the sample.

Figure 1 is a diagram of the scheme that is being used. The expression for the ratio of scattered to transmitted X rays is:

$$I_s/I_t = C\rho e^{(\mu_t x_t - \mu_s x_s)}, \text{ with } C = \frac{N_A}{A} d\sigma \Delta x \Delta\omega.$$

In this expression, ρ represents the density of the scattering volume, ΔV , as defined by the detectors' collimations; N_A , Avogadro's number; A , the atomic weight of the material; $d\sigma$, the differential scattering cross section; Δx , the thickness of the scattering volume; and, $\Delta\omega$, the solid angle subtended by the scattered X-ray collimator slit. The quantities μ_t and μ_s and x_t and x_s are, respectively, the linear attenuation coefficients for the transmitted and scattered X rays and the path lengths of the transmitted and scattered X rays within the sample from the scattering volume to the sample surface. But, $\mu_s \approx \mu_t$ and the sample material can be easily positioned so that $\mu_t x_t = \mu_s x_s$. In this case:

$$I_s/I_t = C\rho,$$

Figure 1. SCHEME FOR THE DENSITY MEASUREMENT.

where, because the geometry and material are fixed, C is a constant. So, for the scheme just described, the ratio of scattered to transmitted X rays from a sample material is directly proportional to the density of that material. Therefore, the measurement is independent of thickness and the density is obtained directly. The value of C is found experimentally by using a set of standards having known densities. (Each different material requires its own set of standards.)

INSTRUMENTATION

Figure 2 provides a view of the entire measurement system; a block diagram of the principal components is presented in Figure 3. The X-ray source is a GE 75-kV X-ray machine with a

175665

Figure 2. OVERALL VIEW OF THE ENTIRE MEASUREMENT SYSTEM.

Figure 3. PRINCIPAL COMPONENTS OF THE DENSITY MEASUREMENT SYSTEM.

GE-75 X-ray tube having a tungsten target and a beryllium window. The source collimator with a builtin, remotely operated shutter is mounted to the X-ray tube and is situated below a remotely operated sample handler. Measurement of transmitted and scattered beam intensities is accomplished with two standard scintillation-type detector systems. Each detector, an NaI (TI) crystal optically coupled to a photomultiplier tube, is used in conjunction with a preamplifier, amplifier, scaler, and timer. The detectors are mounted to a collimator that is positioned above the sample handler. Two slits in the collimator, one for each detector, collimate the transmitted and scattered X rays to be counted. They form an angle of 45 degrees and focus at a point 3 cm below the bottom surface of the collimator. Figure 4 is a view of the detectors, collimators, and sample handler.

The bremsstrahlung radiation produced in an X-ray tube has a broad energy distribution. In order to narrow this distribution and form a peak-shaped incident beam spectrum, it was necessary to filter the incident beam. A tin/nickel combination is being used for this filter. This combination was chosen because L X rays from the tungsten target were interfering with the measurement. The tin filter shapes a 26-keV X-ray peak, and the nickel filter separates that peak from the tungsten L X-ray peak. Figure 5 shows the resulting spectra (for X-ray machine operating settings of 40 kV and 70 mA). Pulse-height discrimination is then used to select only X rays from the 26-keV peak for counting.

EVALUATION

Samples of pressed carbon materials were used to evaluate this measurement concept. Sample bulk densities ranged from 0.21 to 0.86 g/cm³, with thicknesses ranging from 1.9 to 4.4 cm. A series of measurements were taken on each sample at different positions, but maintaining a constant measurement depth (depth of the scattering volume within the sample) of 1 cm. A measurement consisted of monitoring the I_s and I_t simultaneously for a

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Figure 4. CLOSEUP VIEW OF THE DETECTORS, COLLIMATORS, AND SAMPLE HANDLER.

Figure 5. SPECTRUM OF THE INCIDENT X-RAY BEAM.

1000-second count time and then taking the I_s/I_t ratio. The average measurement for each sample was then plotted against the sample's bulk density. The result was the expected linear relationship between I_s/I_t and density. A straight-line fit to the data points is seen in Figure 6. Adjacent to each point is the sample thickness in centimeters. Clearly, the variations in sample thickness had no effect on the linearity of the fit. The maximum deviation from the fit was 0.8%, with a correlation coefficient of 0.9998. (A value of 0 means that no correlation exists and a value of 1 represents a perfect fit.) The measurement precision (1σ), based on counting statistics for a 1000-second count time, was better than 0.5%.

Figure 6. PLOT OF THE I_s/I_t RATIO AS A FUNCTION OF THE BULK DENSITY FOR PRESSED CARBON SAMPLES.

From the measurements taken on each sample, the variations in density were established. The maximum variation in density for each sample was then plotted against the bulk density. The results are reported in Figure 7. As seen, samples with the higher bulk densities have smaller density variations. This relationship is reasonable because, as the theoretical density of the material is approached the variations in density are expected to decrease.

CONCLUSIONS

The scope of this discussion has been limited to results obtained from work that was done at a constant measurement depth. It is appropriate here to point out that measurements taken

at various measurement depths have demonstrated that the measurement response changes with a changing measurement depth. However, the measurement concept has been verified and, with sufficient precision to be a useful tool, the technique can be calibrated to provide density measurements at any given sample depth, or simply used to determine relative variations in density at any given depth.

Figure 7. PLOT OF DENSITY VARIATIONS AS A FUNCTION OF THE BULK DENSITY FOR PRESSED CARBON SAMPLES.

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