MONOCHROMATIC X-RAY BEAMS FOR NDT

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INTRODUCTION

The interaction of an x-ray beam from a conventional generator with an object containing more than one type of material is a very complicated process. The shape of the bremsstrahlung spectrum from the generator depends on the target material and orientation, as well as on the inherent filtration and any additional filters through which the beam passes. Absorption of the beam in the part under study varies dramatically with energy and depends critically on the atomic number and density of the material. Thus, interaction of x-rays in an object can provide a great deal of information about the elemental composition of the part. However, this information is difficult to extract from data obtained using a bremsstrahlung spectrum.

The use of a monochromatic beam would greatly simplify the interpretation of results from such studies. Radioisotopes have been used as monochromatic sources, but they have a number of drawbacks. Only a limited selection of energy values is available, and often more than one energy line is produced by a given isotope. To obtain intensities useful for inspection work, rather high activity sources are required, necessitating extra care in shielding during use and storage. An alternate method of obtaining monochromatic beams is to use diffraction from a crystal to select the desired energy from a bremsstrahlung spectrum. This technique has been used extensively to study phase transitions and the crystalline properties of matter[1].

For an x-ray beam incident at an angle $\theta$ on a crystal having lattice spacing $d_{hkl}$, constructive interference will occur in the reflected beam only for those energies (or wavelengths) which satisfy the Bragg condition,

$$2d_{hkl}\sin\theta = n\lambda$$

(1)

The lattice spacing depends on the crystal type and orientation. For example, graphite is a hexagonal crystal with possible lattice spacings given by

$$\frac{1}{d_{hkl}^2} = 4\frac{(h^2 + hk + k^2)}{3a^2} + \frac{l^2}{c^2},$$

(2)

where $a = 2.461$ Å and $c = 6.708$ Å are the lattice constants for graphite. The orientation of the crystal is specified by the Miller indices, $hkl$, which can take integral values.
In this report we present preliminary results from studies of monochromatic x-ray beams generated using a graphite crystal. In the following section we describe the experimental apparatus and the properties of the monochromatic beam. We follow that with examples of applications of this technique in characterization of detectors, measurement of attenuation coefficients, and computed tomography.

EXPERIMENTAL SETUP

A diagram of the apparatus used in our studies is shown in Fig. 1. The crystal is highly oriented pyrolitic graphite (HOPG)\(^2\), which is not a single crystal, but rather a collection of small crystals with their planes oriented in approximately the same direction. This mosaic spread leads to a slight broadening of the energy spectrum of the diffracted beam, but this is acceptable for most applications. The crystal is 25mm high by 15mm wide, and is 1.3mm thick. It is mounted on a goniometer to allow for orientation in the beam to select reflection from the 002 planes.

Any source of x-rays can be used for this technique. We have used a microfocus generator (IRT HOMX 160) with a tungsten target operated in the range 0-100 kVp and 0-2 mA. The incident beam is defined by a set of lead collimators and a lead beam stop is placed behind the crystal to intercept the portion of the beam which is not diffracted. The size and angular divergence of the diffracted beam are determined by the geometry of the collimators and the crystal. A radiograph of the diffracted beam produced at an angle of 4.2° is shown in Fig. 2. The angular divergence of this
beam is $-0.5^\circ$ and the energy dispersion is $-2$ keV. The energy dispersion is due to the finite angular divergence of the beam as well as the mosaic spread ($-0.2^\circ$) of the crystal. The energy spectrum for this diffracted beam as observed with a germanium detector is displayed in Fig. 3a). The prominent peak at 25 keV corresponds to the principle wavelength ($n=1$ in Eq. 1), whereas the secondary peak ($n=2$ in Eq. 1) appears at 50 keV. Higher order peaks would be present if the incident bremsstrahlung source were operated at higher energies. The small peak at 15 keV is an artifact of the detector and will be explained in the following section. The intensity of this diffracted beam is $3 \times 10^7$ photons/cm$^2$ sec at a distance of 1m from the crystal. A graphite crystal is very efficient$[2,3]$, reflecting approximately 50% of the photons which satisfy Eq. 1. In principle, intensities 100 times greater could be achieved through careful selection of the generator, collimators, and crystal. The maximum energy attainable with this setup is determined by geometry. At higher energies it becomes more difficult to separate the diffracted beam from the primary beam. Tighter collimation and smaller crystals are required. By using a filter to suppress low energies it is feasible with the present system to produce a useful 120 keV beam from the secondary diffraction peak.

CHARACTERIZATION OF DETECTORS

When making a quantitative measure of x-ray interaction in a material it is very important to have a good calibration of the response of the detector used in the measurement. Diffractively produced x-ray beams are ideally suited for these calibrations. We have applied this technique to germanium and cadmium telluride semiconductor detectors and to a sodium iodide scintillation detector.

The response of a 10mm thick by 25mm diameter germanium detector at three different energies is shown in Fig. 3a-c). In all cases there appears a small peak about 10 keV below the primary peak. This is due to the escape of characteristic $K\alpha$ and $K\beta$ x-rays from the front surface of the germanium detector. As the energy of the incident x-ray increases, the average depth of interaction in the detector increases and it is less likely that a 10 keV x-ray can escape back through the surface. The relative area of the escape peak compared to the principle peak varies from 5.4% at 25 keV to 2.2% at 38 keV. These results are in good agreement with previous results obtained at lower energies$[4]$. Figure 3d-f) displays the response of a 2mm cubic CdTe detector, and Fig. 3g) and 3h) shows the response of a 25mm thick by 25mm diameter sodium iodide detector. Both of these detectors have a much stronger K-escape peak than does Ge. This is because the characteristic x-rays from Cd, Te, and I are in the range 27-30 keV, and thus have a higher probability of escaping from the detector than does a 10 keV x-ray from Ge. For NaI at 49 keV 14% of the counts appear in the escape peak. Another peak is seen at 22 keV in the spectra obtained using the CdTe detector. As this peak does not shift with incident energy it cannot be due to an escape x-ray. It was determined that this peak results from fluorescence of silver in a conductive epoxy used to attach the leads to the CdTe crystal.

These spectra were obtained for an ideal geometry with the monochromatic beam collimated so as to strike the center of the detector perpendicular to its face. For x-rays incident at an angle or near an edge of the crystal the escape peaks would be more pronounced. Also, as seen above, the presence of inert materials in the vicinity of the crystal can lead to prominent fluorescence peaks in the observed spectra. When using a bremsstrahlung source to make quantitative measurements of material properties, the observed spectra must be corrected to avoid bias from these effects.
Fig. 3 Response of different detectors to monochromatic beams at the energies indicated. Results are presented for a germanium detector, a-c), a cadmium-telluride detector, d-f), and a sodium-iodide detector, g) and h). Interpretation of the spectra is given in the text.
The energy resolution of these detectors can be deduced from the widths of the spectra. When doing this calculation it is important to take into account the inherent energy spread of the beam (~2 keV in our studies). Thus, the widths of the spectra obtained using the Ge detector are dominated by the spread of the beam. It would be necessary to collimate the beam to <0.1° in order to measure the resolution of the Ge detector. The present beam is adequate for measuring the resolution of the other detectors. From Figs. 3e) and 3h) we determine the resolution (FWHM) of the CdTe detector to be 6.4 keV at 47 keV, and the resolution of the NaI detector to be 8.2 keV at 49 keV.

MEASUREMENT OF ATTENUATION COEFFICIENTS

The rate of transmission of x-rays through an object depends on the thickness, $x$, and linear attenuation coefficient, $\mu$, according to the formula

$$I = I_0 \exp(-\mu x),$$

where $I_0$ is the incident flux and $I$ is the transmitted flux. By measuring $I_0$ and $I$ and the thickness one can determine the attenuation coefficient as follows:

$$\mu = \frac{1}{x} \ln \left( \frac{I_0}{I} \right).$$

This coefficient exhibits a strong energy dependence. Hence, precise measurement requires a monochromatic beam.

Using the apparatus of Fig. 1 we measure the transmitted intensity by placing a sample in the beam between the crystal and the detector. The incident flux is measured by removing the sample and counting for an equal length of time. Very good statistical accuracy is attainable using this method. The more difficult task is to limit systematic errors introduced by instabilities in the generator or detector. To demonstrate this technique we have used samples of aluminum and mylar ($C_5H_4O_2$) of varying thickness. Looking at Eq. 4 we see that if we plot $\ln(I_0/I)$ versus thickness the result should be a straight line whose slope is the linear attenuation coefficient. The data is plotted in Fig. 4 for the two samples at an energy of 30.5 keV. The results are in good agreement with tabulated values[5].

![Fig. 4](image-url)

Fig. 4: Attenuation of a 30.5 keV x-ray beam by different thicknesses of aluminum and mylar. A linear least-squares fit to the data yields the attenuation coefficients indicated. Both vertical and horizontal error bars are smaller than the data points.
One problem which can limit the usefulness of computed tomography is beam hardening(6,7). When a conventional bremsstrahlung x-ray source is used, the preferential absorption of lower energy photons will harden the spectrum as the beam passes through thicker sections of an object. Distortions in the reconstructed image will result as it is not possible to associate a unique linear attenuation coefficient with each point in the object. Corrections can be made to minimize this effect, but this requires careful calibrations. The use of a monochromatic source eliminates this problem.

We have made a preliminary study of the application of a diffractively produced monochromatic beam to computed tomography. We use a Ge detector with a 200μm diameter pinhole collimator to define the scan beam. The sample is translated and rotated through the beam using a computer controlled positioner to produce an image with 100μm pixel size. We have imaged a 1/4" diameter ceramic disk which contains several 300μm diameter voids. The Donner algorithms(7) are used for reconstructing the images.

Figure 5a) shows the results of a CT scan taken with a conventional generator at 70 kVp. The halo seen around the edge of the disk is a manifestation of beam hardening. The image obtained using a monochromatic beam of energy 28 keV is displayed in Fig. 5b). In this case the density across the disk is much more uniform. This is quantified in Fig. 5c) which shows the intensity across a slice of each image.

The time required to complete this scan was about 12 hours, so this is not yet a technique for mass production. As mentioned above, it should be possible to increase the intensity by a factor of 100, and one could also use an array of detectors to speed up data acquisition.

![Computed tomography images of a 1/4" diameter ceramic disk obtained using a) 70 kVp bremsstrahlung beam, and b) 28 keV monochromatic beam. A cross section through each image is shown in c).](image-url)
CONCLUSION

The increased use of composite materials in manufacturing means that it will become increasingly important to develop methods for nondestructively discriminating among different elements in an object. Techniques for accomplishing this task can be developed based on the energy- and material-dependent absorption of x-rays. A monochromatic source is very useful for investigating these processes. We have demonstrated a method using x-ray diffraction to produce a tuneable monochromatic beam from a conventional x-ray generator. Applications of such a source include characterization of detectors, measurement of attenuation coefficients, and computed tomography.

ACKNOWLEDGEMENT

This work was sponsored by NIST under cooperative agreement #70NANB9H0916 and was performed at the Center for NDE, Iowa State University.

REFERENCES