# Basis Material Decomposition – a Quantitative X-ray Imaging Method and its Application in Industrial Sorting

Markus FIRSCHING<sup>\*</sup>, Jörg MÜHLBAUER<sup>\*</sup>, Frank NACHTRAB<sup>\*,\*\*</sup> Andreas JOBST<sup>\*\*\*</sup> <sup>\*</sup> Fraunhofer Development Center X-ray Technology EZRT, Dr.-Mack-Str. 81, 90762 Fürth <sup>\*\*</sup> Cluster of Excellence »Engineering of Advanced Materials«, Friedrich-Alexander University Erlangen-Nuremberg, Dr.-Mack-Str. 81, 90762 Fürth

\*\* Fraunhofer Institute for Integrated Circuits IIS, Am Wolfsmantel 33, 91058 Erlangen

Abstract. Dual Energy techniques have been known since the mid-70's and are well established in medical imaging and security applications, but have not yet been commonly used in NDT. Dual energy allows obtaining quantitative information of the object under investigation. This could either be the proportion of photo absorption (corresponding to the effective atomic number Z) and Compton scattering (corresponding to the density) or the respective projected densities for a given set of basis materials. The latter one is called basis material decomposition. The underlying method of basis material decomposition will be introduced. We present both synthetic setups to evaluate the method, and real examples from mineral sorting to demonstrate the benefits this approach can provide.

## Introduction

In X-ray imaging, three quantities of the object define the attenuation of X-rays: The atomic number, the density and the thickness of the object to be penetrated. In radiographic images the attenuation coefficient, density and thickness are integrated along the X-ray path through the object. Thus the areal density and the attenuation coefficient cannot be distinguished in a projection image without further knowledge. However, the attenuation coefficient depends on the energy of the X-rays. Therefore information on the type of material becomes available, if an object is imaged using different X-ray spectra or using an energy resolving detector. Those Dual Energy techniques have been known since the mid-70's [1] and are well established in medical imaging and security applications, but have not yet been commonly used in NDT.

While it seems possible to distinguish different materials by their X-ray attenuation, these are only special cases. Generally it is not possible, especially if the irradiated path length varies and/or is unknown. But even if the irradiated path length is known, the attenuation can be equal for two different materials. Diamond, for example, has the low atomic number of Carbon (Z=6) but a relatively high density of 3.6 g/cm<sup>3</sup> while kimberlite, the host mineral for diamonds, has a higher effective atomic number (effective Z approx. 13) and a lower density of approx.  $1.6 - 3 \text{ g/cm}^3$  resulting in very similar overall X-ray attenuation.

In such a case, basis material decomposition by dual energy imaging is a very powerful tool to overcome the limitations of standard radioscopy. As it can provide the areal density of the constituents, it implicitly contains a beam-hardening correction that



reduces the artifacts resulting from the thickness dependence of other dual energy techniques.

### The Method of Basis Material Decomposition (BMD)

Considering a compound material, the energy-dependent total attenuation coefficient  $\mu(E)$  with respect to the energy is a linear combination of the attenuation coefficients  $\mu_j(E)$  of the constituents (basis materials) weighted with their respective concentration. Given that the spectral characteristics of the imaging system are known, it is feasible to obtain areal densities of the corresponding basis materials by either energy resolved measurement or two measurements with different X-ray spectra [2].

According to Lambert-Beers law the intensity *I* behind an object with the mass attenuation coefficient  $\mu'(\mu'=\mu/\rho)$  and an areal density *a* (*a*= $\rho d$ , with mass density  $\rho$  and thickness *d*) for a single photon energy is:

$$I = I_0 \cdot \exp(-\mu'a)$$
$$K = \ln \frac{I_0}{I} = \mu'a,$$

where  $I_0$  is the unattenuated intensity and K is the extinction. If several materials (indexed by j) are present, the total attenuation coefficient is the sum of the components. Measurements at different energies (indicated by i) give a set of equations:

$$I_i = I_{0i} \cdot \exp(-\mu'_{ij}a_j),$$
$$K_i = \mu'_{ij}a_j$$

This linear system of equations can be solved under certain conditions and provides the areal densities  $a_j$  of the basis materials (which are assumed to be known). Since the access to mono-energetic X-ray sources is expensive and either not possible in a laboratory (synchrotron) and restricted by law in practice (radioactive sources), the method was adapted to X-ray sources with broad energy spectra S(E).

If the spectrum S(E) and the detector efficiency D(E) are known as functions of energy (from measurements or simulations), one can calculate the intensity which is determined by the detector:

$$I_0 = \int dE \, S(E) \, D(E)$$

The measured intensity behind an attenuating object can be expressed as:

$$I = \int dE \exp(\mu'(E) a) S(E) D(E)$$

For different spectra S(E) and/or detector efficiencies D(E) it can be used to calculate an effective attenuation coefficient in dependence of the areal density *a* via the extinction *K*:

$$K = K(S(E), D(E), a) = \ln \frac{I_0}{I},$$
$$\Rightarrow \mu'_{eff} = \mu'_{eff}(S(E), D(E), a) = \frac{K(S(E), D(E), a)}{a}$$

These effective mass attenuation coefficients are calculated for each spectrum and for each basis material. However they are dependent on the areal densities  $a_i$  which are not a priori

known but follow from the basis material decomposition. Therefore the areal densities are determined iteratively.

## **Experimental Setup and Results**

#### Setup

A conventional NDT X-ray source with a maximum acceleration voltage 225 kV and different filtering were used. At a focus detector distance of 1 meter, the applied power was between 70 and 300 W. The imaging was carried out using an indirect converting flat panel X-ray detector with 1k x 1k pixels and a pixel size of 200  $\mu$ m.

The simple example contains a titanium foil (thickness 0.25 mm, areal density  $0.11 \text{ g/cm}^2$ ) and an graphite rod with a diameter of 13 mm (areal density 2.1 g/cm<sup>2</sup> at the center). A sketch of the setup is shown in Figure 1.



Figure 1. Sketch of the arrangement used for the test measurements

As a real example, a diamond embedded in granulated kimberlite (the host material for natural diamonds) was used. For that purpose an aluminum tube (32 mm diameter) was filled with granulated kimberlite and one diamond. The diamond was completely covered with kimberlite. The setup can be seen in Figure 2, the diamond is put on top for demonstration only.



Figure 2. Exemplary preparation of a diamond containing kimberlite phantom (Al-tube, 32 mm diameter, filled with kimberlite granulate). Diamond size: approx. 2.5 mm.

## Results

Figure 3 shows the images of the simple setup acquired at 40 kVp (LE) and 100 kVp (HE) respectively. The images result in different grey values, but neither the type of material nor the amount can be recognized. The resulting BMD images with the basis material carbon and titanium can be seen in Figure 4.



**Figure 3.** low energy (LE) image of the two overlapping materials (graphite and titanium foil) at 40 kVp, filter 1 mm Al. Right: the corresponding high energy (HE) image at 100 kVp, filter 1 mm Al



**Figure 4.** top left: Carbon (graphite) image resulting from BMD. Top right: corresponding line scan bottom left: Titanium image resulting from BMD. Bottom right: corresponding line scan

For the graphite rod the maximum areal density is measured to approx. 2.1 g/cm<sup>2</sup>, which is in very good agreement with the expected value of 2.1 g/cm<sup>2</sup>. The titanium foil vanishes in the carbon image. For the titanium foil the maximum areal density is measured to  $0.95 \text{ g/cm}^2$ , which is in good agreement with the expected value of  $1.1 \text{ g/cm}^2$ . The graphite rod almost vanishes in the titanium image. On the right side of Figure 4, a line scan through the image is shown. The absolute values for the areal density can be read there as well as in the color map of the images on the left.

The realistic example containing the diamond embedded in granulated kimberlite can be seen in Figure 5. : On top the two images at two different spectra are shown (80 kVp and 120 kVp). On the bottom the resulting BMD images are shown in color. Black and blue denote no or low material, green indicates high content of the respective basis material. The left image represents the carbon content and the diamond can be seen clearly.



**Figure 5.** The two images on top show the images at two different spectra (80 kVp and 120 kVp). Below the resulting BMD images are shown in color. The left image represents the carbon content and the diamond can be seen clearly

### **Conclusion and Outlook**

The method of Basis Material Decomposition is demonstrated to be a powerful method in quantitative X-ray imaging. Areas of application include, but are not limited to: mining, recycling, sorting etc.

This method can also be applied to computed tomography (CT), where it can be used as a method to correct beam hardening in CT and thus can improve image quality. Currently an evaluation and comparison with other dual energy methods are being done. A setup of a demonstrator for industrial applications will be built. The software will be trimmed for sorting application needs regarding processing speed and real time capabilities and will provide the flexibility for adaption to other materials as food or plastics.

#### References

[1] R. Alvarez, A. Macovski, Phys. Med. Biol. Vol. 21, No. 5 (1976), 733-744

[2] M. Firsching, F. Nachtrab, N. Uhlmann, R. Hanke, Adv. Mater., Wiley-VCH, 2011, issn 1521-4095, doi 10.1002/adma.201004111