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Determination of mass attenuation coefficients and effective atomic numbers for Inconel 738 alloy for different energies obtained from Compton scattering

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ABSTRACT

The mass attenuation coefficient of Inconel 738 superalloy has been measured at different gamma ray energies by using the Compton scattering technique. The theoretical values of mass attenuation coefficient of a glass sample were calculated using WinXCom program. The effective atomic number and electron density are also calculated. The results showed that the mass attenuation coefficients, effective atomic number and electron density increase with the decrease in gamma ray energies which is in good agreement with theoretical values (less than 2% error).

1. Introduction

With increasing use of gammas-ray active isotopes in industry, medicine and agriculture, it is necessary to study the absorption and interaction of gamma radiation in materials. The mass attenuation coefficient, effective atomic number and electron density are basic quantities required for determining the attenuation of X-ray and gammas-ray in matters and useful for understanding their physical properties.

Gerward et al. (2001, 2004) introduced the WinXCom program for calculating the mass attenuation coefficients of elements, compounds and mixture materials. With the development of theoretical tables and computer program for calculation, it has now become possible to make a meaningful comparison between theoretical and experimental results. From the mass attenuation coefficients, a number of related parameters can be derived, such as the mass energy absorption, total interaction cross-section, the effective atomic number and electron density.

In literature reviews, some or all of these parameters are determined for alloys (Kaewkhao et al., 2008; Han and Demir, 2009; Murty et al., 2000), minerals (Han et al., 2009; Smale et al., 2006), gemstones (Korkut et al., 2011; Kaewkhao et al., 2012), polymer (İçelli et al., 2008), amino acid (Manohara and Hanagodimath, 2007), semiconductor (Erzeneoğlu et al., 2006), superconductor (Cevik and Baltas, 2007), glasses (Singh et al., 2006; Sharma et al., 2006; Kaewkhao et al., 2010; Limkitjaroenporn et al., 2011), building materials (Bhandal and Singh, 1993; Yilmaz et al., 2011; Akkurt et al., 2010) and some of investigators tried to determine these parameters applying different methods (Naydenov et al., 2004; Athanassiadis; 2009).

Inconel 738 superalloy material is widely used for turbine blades in hot parts of gas-turbine engines due to its combination of superior high-temperature creep-rupture strength and corrosion resistance. The material is a nickel-based superalloy in which the outstanding mechanical properties at high temperature are obtained through precipitation strengthening. The major contribution of precipitation strengthening primarily comes from the precipitation of ordered L12 intermetallic Ni_3 (Al and Ti) 0° phase. The conventional manufacturing method to produce such excellent material is performed by vacuum casting, followed by precipitation hardening. Due to the very high density of Inconel 738 superalloy, there is a possibility that the material can be used as gammas ray shielding material. Therefore, it is interesting to examine this material in detail for its interaction in atomic scale.

In the present work, the radiation shielding properties and interaction parameters have been investigated for inconel 738 superalloy. The majority of gamma-ray emissions from Special Nuclear Materials (SNMs) are in the 100–600 keV range (Keyser et al., 0000). Therefore, the mass attenuation coefficients, effective atomic numbers and effective electron density of Inconel 738 superalloy were measured for eight different photon energies in

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range between 223 and 662 keV. The incident photon energies have been changed by the Compton scattering technique.

2. Theoretical backgrounds

2.1. Compton scattering

The inelastic scattering of X-ray and gamma ray from electrons had been known for a decade when the American researcher Compton (Trousfanidis, 1983) showed a mathematical relationship between incident and scattered gamma ray energies as follows:

$$E_{\gamma'} = \frac{E_\gamma}{1 + (1 - \cos\theta)E_\gamma/mc^2} \tag{1}$$

where $E_{\gamma'}$ is the scattered gamma ray energy, E_γ is the incident gamma ray energy, θ is the scattering angle, and m is the electron rest mass. This formula is easily derived by assuming a relativistic collision between the gamma ray and an electron initially at rest. Certainly, under normal circumstances, all the electrons in a medium are not free but bound. If the energy of the photon, however, is of the order of keV or more, while the binding energy of the electron is of the order of eV, the electron may be considered at rest. The collision is inelastic in the sense that one photon is absorbed and another of different frequency and momentum is emitted.

3. Mass attenuation coefficient and effective atomic number

The mass attenuation coefficient is written as follows (Limkitjaroenporn et al., 2011).

$$\mu_m = \frac{\ln(\frac{I_0}{I})}{\rho t} \tag{2}$$

where ρ is the density of material (g/cm^3), I_0 and I are the incident and transmitted intensities and t is the thickness of absorber (cm).

Theoretical values of the mass attenuation coefficients of mixture or compound have been calculated by WinXCom, based on the rule of mixture (Gerward et al., 2004).

$$\mu_m = \sum_i w_i(\mu_m)_i \tag{3}$$

where w_i is weight fraction of element in an alloy, $(\mu_m)_i$ is mass attenuation coefficient for individual element in alloy. The value of mass attenuation coefficients can be used to determine the total atomic cross-section ($\sigma_{t,a}$) by the following relation (Limkitjaroenporn et al., 2011).

$$\sigma_{t,a} = \frac{(\mu_m)_{alloy}}{N_A \sum_i^n (w_i/A_i)} \tag{4}$$

where N_A is Avogradro's number, A_i is atomic weight of constituent element of alloy. The total electronic cross-section ($\sigma_{t,el}$) for the element is also expressed by the following formula (Limkitjaroenporn et al., 2011)

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{Z_i} (\mu_m)_i \tag{5}$$

where f_i is the number of atoms of element i relative to the total number of atoms of all elements in alloy, Z_i is the atomic number of the ith element in alloy. Total atomic cross-section and total electronic cross-section are related to effective atomic number (Z_{eff}) of the compound through the formula (Limkitjaroenporn et al., 2011).

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \tag{6}$$

The electron density can be defined as the number of electrons per unit mass, and it can be mathematically written as follows (Kaewkhao et al., 2008).

$$N_{el} = \frac{\mu_m}{\sigma_{t,el}} \tag{7}$$

4. Experimental setup and procedure

The fabrication of Inconel 738 specimens was implemented by vacuum casting and annealing. The process started with the induction melting of ferritic stainless steel, followed by casting into a 10 cm diameter cylindrical bar. The annealing was performed at 1100 °C for 30 min to attain homogenization and then quenched into oil bath immediately.

The compositions of Inconel 738 superalloy were analyzed by energy dispersive X-rays fluorescence spectrometer (Panalytical Minipal-4). The density of the sample at room temperature is measured by the Archimedes's principle using a sensitive microbalance with xylene as the immersion liquid. The density is calculated according to the following formula:

$$\rho = \frac{W_a}{W_a - W_b} \times \rho_b \tag{8}$$

where W_a and W_b are the weights of samples in air and xylene, respectively, and ρ_b is the density of xylene (ρ_b = 0.863 g/cm^3). All weight measurements were used a sensitive microbalance.

The experimental arrangement is shown in Fig. 1. The source system was mounted on a composite of adjustable stands. This setup can move in the transverse direction for proper beam alignment. The ^{137}Cs radioactive source of 15 mCi (555 MBq) strength was obtained from the Office of Atom for Peace (OAP), Thailand. The aluminum rod was used as the scattering rod. The Compton scattered gamma-rays were measured on a rotatable scintillator detector in the scattering plane by using the 2″ × 2″ NaI(Tl) detector having an energy resolution of 8% at 662 keV (BICRON model 2M2/2), with CANBERRA photomultiplier tube base model 802-5. The optimum distance between the source and the scatterer was chosen to be 20 cm and that between the scatterer and detector, 20 cm. The spectra were recorded using a CANBERRA PC-based multi-channel analyzer (MCA).

The spectrum on the MCA of detector gave instance counts in each of 1024 bins divided by voltage. To measure the angular dependence of Compton scattering, we first perform a calibration relating the channel number of the MCA spectrum to the energy of known gamma-ray sources and vary the angle of the scatter detector and acquire measurements on the MCA. The different angles (θ) were used to produce the different gamma ray energies. Kaewkhao et al. (2012) first applied the Compton scattering technique to mass attenuation coefficient measurement, and the validity of Compton scattering system and energy calibration have been confirmed.

To measure mass attenuation coefficients, the sample was placed between the scattering rod and detector (Fig. 1). The intensities of scattered photon (before traveling through the sample) were detected as incident photon intensities (I_0). After the photon traveled through the sample, the attenuated photon intensities (I) were detected, and Eq. (2) was used to determine mass attenuation coefficients.

The statistical error of gamma ray energies in this experiment calculated from full width at half maximum (FWHM) of the full energy peak. The width of a Gaussian distribution is related to the standard deviation σ by (Trousfanidis, 1983).

$$FWHM = 2\sqrt{2\ln 2}\sigma \tag{9}$$

An optimum sample thickness ($0.5 \leqslant \mu x \leqslant 5.0$) was selected in this experiment on the basis of the Nordfors criteria. The statistical error in this experiment calculated from the standard error of 3 items (i) ray-sum measurement, which calculated from experiment,