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Investigation of Neutron Absorber Homogeneity in Gd-Containing Neutron Absorber Materials

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1. Introduction

Safe spent nuclear fuel (SNF) disposal requires the identification and development of neutron absorber materials (NAMs) for criticality control. These NAMs are used in plate or sheet forms as internal baskets that support SNF assemblies. The main functions of the baskets are SNF geometry control, structural support, and nuclear criticality safety. The baskets may include various NAMs, such as boron stainless steels, B-Al alloys, and Al-B_4C composites. Most of commercial NAMs contain B as a neutron absorber because ^{10}B has proven to be the efficient isotope for absorbing thermal neutrons. While there exist sufficient codes, standards and specifications that are applicable to boron NAMs, there is limited information on other NAMs containing non-B elements [1,2].

We have been developing Gd-containing NAMs (Gd-NAMs) with both mechanical strength and neutron-absorbing capability. Besides the structural integrity, these NAMs need to prove the acceptable requirements, including the neutron absorption capability and uniform distribution of neutron absorber. In this study, we first performed neutron attenuation testing and measured the attenuation coefficients of Gd-NAMs to investigate the neutron-absorption capability. Subsequently, a method was developed for evaluating the homogeneity in the Gd spatial distribution, which is applicable to qualification testing for new NAMs.

2. Methods

In order to investigate the effectiveness of neutron absorber of NAMs, we performed neutron transmission test for determining the neutron attenuation coefficients and analyzed the optical images for inspecting the homogeneity of Gd-particles. Each method is described briefly in this section.

2.1 Neutron Transmission Test

Ti-Gd binary alloys with Gd contents ranging from 1 to 10 wt.% were fabricated via plasma arc melting. Then, neutron attenuation tests were performed to measure the neutron attenuation coefficients (μ) of Ti-Gd NAMs in the HANARO reactor in Korea. A cold neutron beam from a 40-m small-angle neutron scattering instrument was employed, with a total neutron flux of ~7.9×10^8 n/cm^2 s. The mean wavelength of the neutron beam, which was monochromatized from the guide by a velocity selector, was ~6 Å (~2.3×10^{-3} eV) with a wavelength spread of 0.12. The measurement of neutron counts by using samples with different thicknesses makes it possible to derive the attenuation coefficient.

2.2 Microstructure Image Analysis

An attempt was made to evaluate quantitatively the homogeneity of neutron absorbers of Gd-NAMs. Firstly, microstructure images from optical microscopy were converted to 8-bit grayscale and the areal fraction of Gd-particles in NAMs was estimated using ImageJ [3], a Java-based image process program. Then, the relative positions of the particles were described by a radial distribution function (RDF) [4], which may be used as a parameter for determining the homogeneity of Gd-particles.

3. Results

3.1 Neutron Absorption Capability

We evaluated the coefficients μ from the results of neutron transmission test. With the measured count rates (I) and background ones (I_o), the coefficient was derived from Eq. (1). We have calculated total macroscopic cross sections (Σ_t) for Gd-NAMs from the ENDF/B-VIII library [5], which are listed in Table I for comparison with the measured μ. While the ratio of μ to Σ_t is approximately 80% for Ti-Gd alloys containing <5 wt.% Gd, the difference between the two parameters increases with the Gd content of the alloy. For strongly absorbing materials (Ti-10Gd), the experimental attenuation law deviates from the exponential behavior significantly.

$$I(x) = I_o exp(-\mu \cdot x) \quad (1)$$

Table I: Comparison of μ and Σ_t

	μ (cm^{-1}) [E_n=0.0023 eV]	Σ_t (cm^{-1}) [0.001~0.005 eV]	μ / Σ_t
Ti-**1**Gd	19.2	22.8	84.2%
Ti-**3**Gd	52.3	66.7	78.4%
Ti-**5**Gd	92.5	111.9	82.7%
Ti-**10**Gd	149.5	230.4	64.9%

3.2 Homogeneity of Neutron Absorbing Particles

In determining the homogeneity of Gd-particles, we applied a new method on the basis of image analysis. First, a microstructural optical image was converted to 8-bit grayscale, from which the coordinate of Gd-particles were measured in the region of interest (ROI). Then, we described the distribution of particles for a ROI using a RDF. Seen from the RDF, the degree of homogeneity of particles could be estimated quantitatively. A series of image analysis process is shown in Fig. 1.

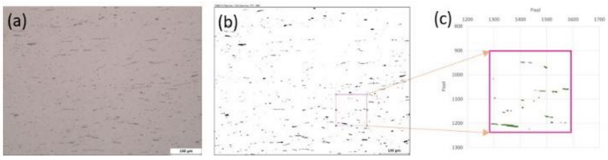

Fig. 1. Example of the image analysis procedure for Ti-3Gd alloy: (a) Optical image, (b) 8-bit grayscale, (c) Region of interest (ROI) for a RDF calculation

We measured the areal fractions of Gd-particles in Ti-xGd alloys from the grayscale images, which are listed in Table II. The fraction was calculated by the ratio of pixel numbers in black to total number of pixels for the ROI. The basic assumption in this analysis is that the black spot is a Gd particle while the white region is composed of Ti. This assumption is reasonable since all samples are binary alloys. To examine the homogeneity of Gd-particles for each sample, the ROIs were selected, as shown in Fig. 2. We carried out this process three times for each case and averaged the results.

TABLE II. Comparison of μ and Σ_t

	Ti-1Gd	Ti-3Gd	Ti-5Gd	Ti-10Gd
Gd atomic density (a/o)	0.31	0.93	1.58	3.27
Gd areal fraction (%) - *measured*	*0.33*	*1.11*	*1.64*	*3.44*

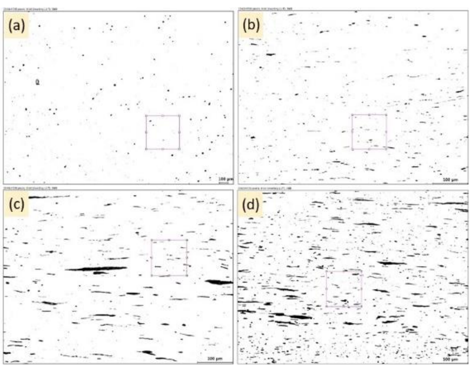

Fig. 2. Converted 8-bit grayscale images of Gd-NAMs; Regions of interest marked with a pink square. (a) Ti-1Gd, (b) Ti-3Gd, (c) Ti-5Gd, (d) Ti-10Gd

A RDF, g(r) describes the relative position of the objects and is a measure of the spatial distribution of a system of particles [4]. The g(r) curves are displayed in Fig. 3 for four kinds of Gd-NAMs, where a value of one for g(r) indicates a uniform distribution of particles. Values that differ from one indicate an enhanced or suppressed probability relative to the uniform distribution. In most cases, we see that g(r) approaches one as inter-particle distances become high while g(r) differs considerably from unity, especially for a low-Gd NAM. This trend is dominant as the amount of neutron poisons decreases.

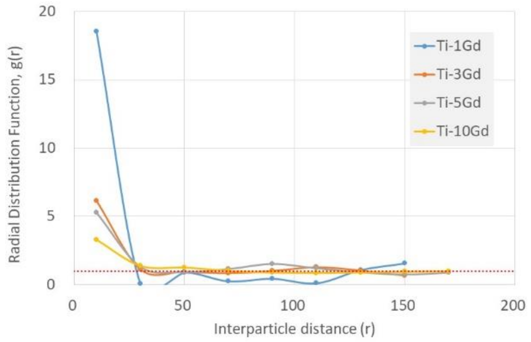

Fig. 3. The experimentally obtained RDFs for Gd-NAMs. The dashed line at g(r) = 1 represents a uniform distribution.

4. Conclusions

The RDF was applied to quantifying the degree of homogeneity of Gd-particles in Gd-NAMs. From the analysis of optical microscopic images, we evaluated the RDFs, from which it was verified that the g(r) differs significantly from one in the region of small inter-particle distances. A value of one for the RDF indicates a uniform and homogeneous distribution of objects. This RDF is believed to be used as a parameter for defining the homogeneity of neutron absorbing particles.

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