Fabrication and Properties of Metal Matrix Composites as a Neutron Absorber Material of the Spent Nuclear Fuel Dry Storage System

Ji Won Mun, Tae Gyu Lee, Ho Jin Ryu*,
Department of Nuclear and Quantum Engineering, KAIST, Daehak-ro 291, Yuseong-gu, Daejeon, 34141, Korea
**Corresponding author: hojinryu@kaist.ac.kr*

1. Introduction

Dry storage systems have many advantages such as transportability, expandability of capacity, reduced management, and passive safety. To successfully manage the criticality and decay heat of spent fuel, neutron absorption and heat dissipation are important aspects. B_4C/Al metal matrix composites (MMC) are used as basket materials that contain SNF assembly [1]. Conventional B_4C/Al MMC is fabricated by Powder Metallurgy (P/M) [1-3]. In this study, a new technique is introduced to fabricate B_4C/Al MMC using compact melting & pressing. In addition, the feasibility of the new material, Gd_2O_3/Al MMC as a dry storage basket material, was investigated. Gd_2O_3 was selected because of its large neutron absorption cross section that can efficiently manage the criticality with a small amount of reinforcement.

2. Review of conventional basket materials

2.1. Cadmium

Cadmium is a good shielding material because it has large thermal neutron absorption cross section and good mechanical properties [4]. A comparison between the thermal absorption cross section of Cadmium and other neutron absorbers is listed in Table 1. Nevertheless, Cadmium, which is poisonous and dangerous for the health of workers during the fabrication, must be sealed to avoid leakage in use.

Table 1. Thermal absorption cross-section of isotopes

Isotopes	*Thermal absorption cross-section, δ [barn]*
B-10	200
Cd-113	30000
Gd-157	254000

2.2. Boron-containing plastics

Polyethylene and polypropylene are commonly used for the matrix of boron-containing plastics because they have good processability. However, boron-containing plastics have poor mechanical properties such as low toughness [5].

2.3. Bohler material (Boron-alloyed stainless steels)

Boron steel can hardly meet the demand of the practical applications due to the limitation of boron content [6].

2.4. Boral, Boralyn (B_4C/Al MMC)

B_4C can capture Helium that is produced by neutron absorption of boron nuclide because of its particular crystal structure [3] [7]. Therefore, B_4C is proper to be a neutron absorbing materials in the basket. In addition, heat dissipation is an important factor to choose the basket material. Aluminum has a high thermal conductivity therefore, B_4C/Al MMC is widely used as a basket material. When the mass fraction of B_4C is changed from 5% to 20% in B_4C/Al composites, its toughness decreases and its hardness increases [3]. Also, due to its lower neutron absorption cross-section when compared to Cd, a 5 mm B_4C/Al neutron absorber with high B_4C content (≥30%) achieves neutron shielding properties similar to a 0.5 mm Cd plate by neutron transmission testing results [3]. It is very inefficient in terms of storage capacity in a limited area.

3. Design and experimental preparation

3.1. Fabrication of B_4C/Al MMC with compact melting & pressing

Porosity is usually increased when fabricating MMC with a high volume fraction. Therefore, to reduce the porosity of MMC, a new technique, compact melting & pressing, was used to make a low porosity MMC even with small size reinforcement and a high volume fraction.

3.2. Design of Gd_2O_3/Al MMC

In this study, 5, 10, 15, 20, 30, and 40 vol. % Gd_2O_3 particle-reinforced aluminum MMCs were investigated. 7075Al powder was used as matrix, Gd_2O_3 particle size is around 10 μm. It was also fabricated by compact melting & pressing. Theoretical density of each sample is shown in Table 2 and the density can be calculated using equation (1).

$$\rho_c = \frac{1}{\frac{x\%}{\rho_p} + \frac{1-x\%}{\rho_m}} \quad (1)$$

where x% is the mass fraction of Gd_2O_3, ρ_c is the theoretical density of Gd_2O_3 composite, ρ_p and ρ_m are the densities of Gd_2O_3 and Al, respectively.

The absorption and attenuation relationship for Gd_2O_3/Al composite can be expressed in the following equation (equation (2)) [8].

$$I = I_0\, e^{-Nh\sigma_a} \quad (2)$$

Table 2. Composition and density of MMC

Specimen	*Gd [vol.%]*	*Al [vol.%]*	*Density [g/cm³]*
S01	5	95	3.02
S02	10	90	3.24
S03	15	85	3.45
S04	20	80	3.67
S05	30	70	4.09
S06	40	60	4.51
S07	50	50	4.94

where I_0 and I are the intensities of the incoming and outgoing neutrons, respectively, N is the atomic nuclear number per cubic centimeters, h is the thickness of the absorber, and σ_a is the neutron absorbing cross section. σ_a can be calculated by the volume percentage of each component and the thermal neutron absorbing cross sections of Gd and Al, which are 254,000 barns and 0.23 barn as shown in the following equations [3] [9] [10].

$$h = \frac{-lnI/I_0}{N\sigma_a} \quad (3)$$

$$N = 2 \times \frac{x\rho_c}{M_{Gd_2O_3}} \times N_A \times A_{157_{Gd}} \quad (4)$$

Where $M_{Gd_2O_3}$ is the molar mass of Gd_2O_3, N_A is Avogadro's number, and $A_{157_{Gd}}$ is the natural abundance of 157-Gd, which is 15.65% [10].

Neutron transmittance of the 0.5 mm Cd plate I/I_0= 0.004%, and 3.5 mm 20wt.% B_4C/Al MMC has the same effectiveness [3]. Using equations (2) (3), and (4), it is calculated that 0.0002 mm 5wt.% Gd_2O_3 / Al MMC has equivalent neutron absorbing property to a 0.5 mm Cd plate or 3.5 mm 20wt.% B_4C/Al MMC.

4. Results

4.1. Microstructure of MMC

Figure 1 shows the microstructure of Gd_2O_3 /Al MMC and B_4C/Al MMC with a volume fraction of 30vol.% and 40vol.%, respectively. Porosity was low despite of high volume fraction of reinforcement.

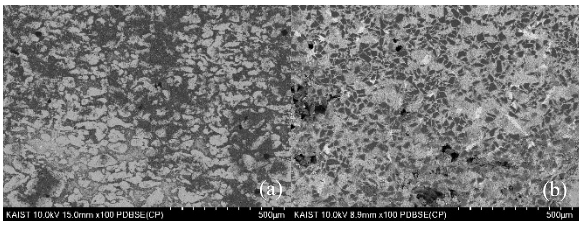

Figure 1 (a) Gd_2O_3 /Al MMC (30vol.%) and (b) B_4C/Al MMC (40vol.%)

4.2. Hardness test

The Rockwell hardness test was performed with a B scale and the three-point bending tests were performed using a universal testing machine (UTM, Instron 5583, Instron Corporation, USA). It was shown that the hardness decreases as volume fraction of Al increases. The hardness values of Gd_2O_3 and Aluminum 7075-T6 are 116.5 and 87, respectively [11] [12].

4.3. Strength and toughness

The tensile strength of Aluminum 7075 alloy is 220 MPa. By adding reinforcement, strength increases. If the reinforcement composition is too high, 40vol% for example, Gd_2O_3 particles contact with each other and high porosity is formed reduces the strength of the MMC. Impact energy of the Gd_2O_3/Al composite is determined by the Charpy impact test.

5. Conclusions

Gd_2O_3 reinforced Aluminum can achieve the same neutron absorbing material behavior with better mechanical properties than the conventional B_4C/Al MMC material. The application of Gd_2O_3/Al MMC in spent nuclear fuel dry storage system may lower the decay heat and the required minimum wet storage period before dry storage can be reduced.

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