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Design, fabrication, and properties of a continuous carbon-fiber reinforced Sm_2O_3/polyimide gamma ray/neutron shielding material

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HIGHLIGHTS

- Sm_2O_3 is used for neutron absorber instead of B_4C, and Sm_2O_3 has a good photon-shielding effect.
- Carbon-fiber cloth and polyimide were used to enhance shielding materials' mechanical behavior and thermal behavior.
- Both Monte Carlo method and shielding test were used to evaluate shielding performance of the novel shielding material.

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ABSTRACT

The design and fabrication of shielding materials with good heat-resistance and mechanical properties is a major problem in the radiation shielding field. In this paper, based on gamma ray and neutron shielding theory, a continuous carbon-fiber reinforced Sm_2O_3/polyimide gamma ray/neutron shielding material was fabricated by hot-pressing method. The material's application behavior was subsequently evaluated using neutron shielding, photon shielding, mechanical tensile, and thermogravimetric analysis–differential scanning calorimetry tests. The results show that the tensile strength of the novel shielding material exceeds 200 MPa, which makes it of similar strength to aluminum alloy. The material does not undergo crosslinking and decomposition reactions at 300 °C and it can be used in such environments for long periods of time. The continuous carbon-fiber reinforced Sm_2O_3/polyimide material has a good shielding performance with respect to gamma rays and neutrons. The material thus has good prospects for use in fusion reactor system and nuclear waste disposal applications.

1. Introduction

As nuclear technology develops, the demand for neutron shielding materials grows and the types of shielding materials required need to be diversified [1,2]. In practice, many situations need the support of high-performance shielding materials, e.g. for the safe disposal of nuclear waste and the safe operation of fusion reactors [3,4]. The domain of application of nuclear technology has been expanding rapidly. As a result, the environments in which shielding materials are used are becoming increasingly harsher [5]. The effectiveness of radiation shielding is subject to strict rules and standards, and there are corresponding requirements for the mechanical properties and heat resistance of the shielding material that must be met [6]. Traditional shielding materials cannot fulfill current development needs. Research and development of neutron shielding material (NSM) with high thermal durability and excellent mechanical properties is the best solution to this problem.

In order to satisfy the needs of different tasks, a series of research investigations on shielding materials were conducted. Pb-B polythene is one of the most widely used shielding materials in the radiation protection field. The Nuclear Power Institute of China manufactured various types of Pb-B polythene composites [7]. However, the maximum temperature for the use of polythene is limited to 100 °C. In addition, the tensile strength of Pb-B polythene composites is relatively low so they cannot satisfy the demands placed on them for most purposes under high temperature and pressure conditions. High density polyethylene has been used to reinforce the mechanical properties and heat resistance of shielding materials, but the increase in performance was limited and so it has not been widely adopted [8,9]. A boron–aluminum composite

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has been fabricated using powder metallurgy. The manufacturing process is, however, relatively complicated leading to high production costs [10]. In this paper, a novel type of shielding material is designed and fabricated for high-temperature and high-pressure environments based on new materials and methods.

During the 1960–1990s of the last century, polymer technology developed rapidly. Continuous carbon-fiber reinforced polyimide composites have high specific strength, high specific modulus, and excellent high temperature performance and corrosion resistance [11,12]. They are one of several high performance materials that have found wide application. In order to make the design method fit the philosophy of combining structure with function, the use of a continuous carbon-fiber reinforced polyimide resin as the matrix for the shielding material is the best way to improve the mechanical and thermal performance of the material.

2. Experimental methods

2.1. Design of the shielding material

Neutron shielding theory is different from gamma shielding theory [13]. The effectiveness of a neutron shield mainly depends on neutron-nucleus collisions and neutron absorption. As collision with a light nucleus can decrease the energy of neutrons better, resin is generally chosen as the neutron moderator. After moderation, neutrons are absorbed by nuclei with large neutron absorption cross-sections, e.g. ^{10}B and ^{6}Li. In contrast, gamma radiation shields depend on photon-matter interactions (e.g. the photoelectric, Compton, or electron-pair effects). As the cross-sections of photonic interactions increase with atomic number, heavy metals (e.g. Pb and Bi) are usually employed as gamma ray absorbers. When neutron and gamma ray shielding requirements are considered together, a type of heavy metal with large neutron-absorption cross-section clearly needs to be added into the polymer resin to improve the shielding effect for both neutrons and gamma rays.

Traditional shielding materials use boron carbide as the neutron absorber. However, the atomic number of boron is low and so it does not have a good shielding performance in respect of gamma rays [14]. Some rare earth elements have larger thermal-neutron absorption cross-sections and photon-reaction cross-sections than boron (e.g. Gd, Sm, Eu, and Er). Therefore, a rare earth element may be a good neutron absorber to use instead of boron (see, for example, the absorption cross-section for samarium shown in Fig. 1). Absorption of X-rays and neutrons by rare earth elements has been researched by Beijing University of Chemical Technology [15]. They pointed out that although boron reacts with neutrons to produce helium bubbles (which rapidly degrade the mechanical properties of the shielding material), the reaction with rare earth elements has little impact on the material's structure. Thus, using samarium (Sm) as a neutron absorber can ensure that the shielding material has a stable performance for long periods of time.

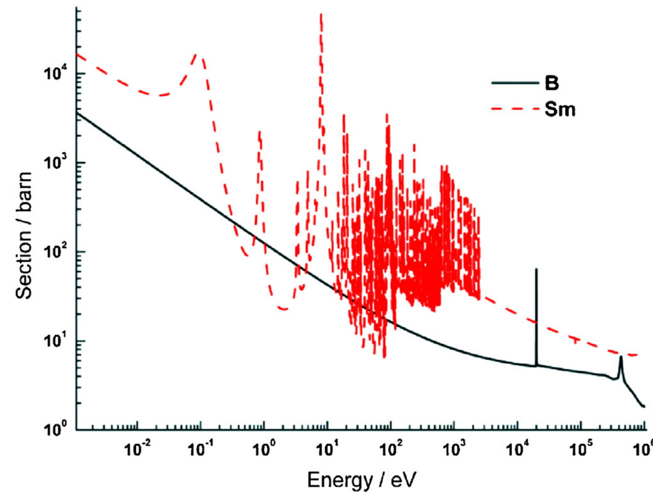

Fig. 1. The neutron absorption cross-sections of samarium and boron.

2.2. Raw materials

2.2.1. Sm_2O_3 powder (sub-micron)

Sm_2O_3 powder would ordinarily sink in the resin and thus be distributed non-uniformly. In order to avoid deposition of Sm_2O_3 powder and ensure that the shielding material has good mechanical and shielding properties, sub-micron powder was chosen to manufacture the NSM. The microstructure of the Sm_2O_3 powder is shown in Fig. 2.

2.2.2. Thermosetting polyimide resin (model: TY005-1)

Polyimide plastics are a kind of engineering plastic with some special properties. They have excellent thermal-stability, good chemical corrosion resistance, and great mechanical properties. In addition, they can prevent burning without the additional use of a flame retardant. Thermosetting polyimide was thus chosen for the matrix to effectively improve the heat resistance and mechanical properties of the shielding material.

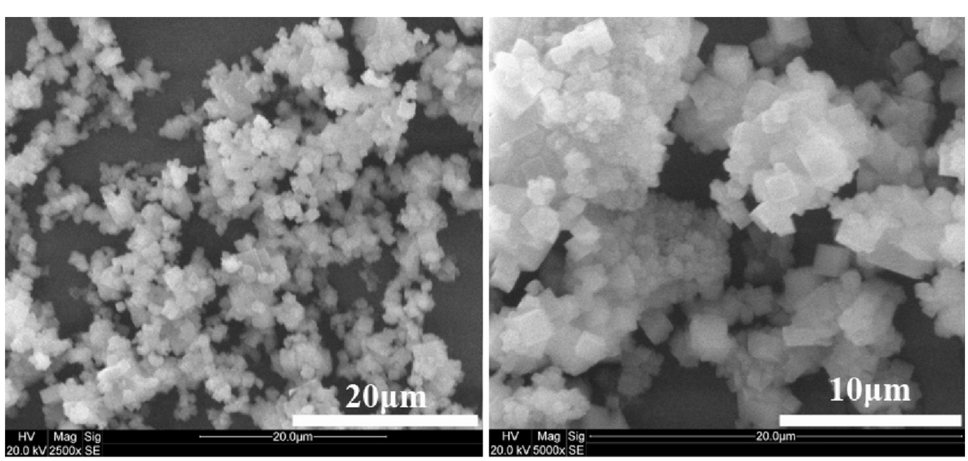

Fig. 2. The microstructure of Sm_2O_3 powder.