

Study on Performance Optimization of Radiation Protection Materials Based on Nanotechnology

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Abstract: With the continuous development of nuclear energy development, medical treatment and aerospace, radiation protection materials are developing towards light weight, high efficiency and high stability. In the past, traditional protective materials have been difficult to adapt to the needs of complex working conditions. Based on the application of nano-technology radiation protection materials, this paper discusses the preparation technology and engineering regulation of nano-radiation protection materials, and explores the optimization path of the performance of radiation protection materials based on nano-technology, which provides a reference for R&D and application of high-performance nano-radiation protection materials.

Keywords: Nanotechnology; Radiation protection materials; Performance optimization

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1. Introduction

Traditional radiation protection materials are mainly lead-based materials, conventional concrete, and common polymer substrates. Although they can achieve the basic radiation shielding effect, they cannot meet the core requirements of modern engineering for lightweight, multifunctional integration and long service life due to their common defects such as high density, poor flexibility and biological toxicity of some components. Nano-materials have ultra-high specific surface area, rich interface defect structure and special electronic configuration characteristics, which can effectively improve the interaction probability between materials and radiation particles, strengthen the attenuation and dissipation efficiency of radiation energy, and at the same time, through the precise design of microstructure, the mechanical properties and thermal properties of materials can be simultaneously optimized^[1]. Compared with traditional micron-sized fillers, nano-sized functional components can achieve the same benefits with a lower doping amount, and even show better shielding effect, which can effectively improve the stability of the structure while ensuring the light weight of the material. This feature can make it a core technical direction to break through the performance bottleneck of traditional protective materials. Based on this, it is of great practical significance to systematically sort out the preparation process of nano-radiation protection materials and explore the optimization path of radiation protection materials based on nanotechnology.

2. Preparation process and engineering control of nano radiation protection materials

In the application of materials engineering, the preparation technology of nano-radiation protection materials can be divided into three categories: controllable synthesis of nano-functional fillers, modification of matrix materials and molding of composite systems. Different processes correspond to different performance control objectives, and suitable preparation paths can be selected according to actual application requirements. The preparation process of engineering protective materials not only needs to focus on the material properties of experimental scale, but also needs to take into account the stability of large-scale production, effective control of economic costs and adaptability of processing and application, so as to avoid the excellent laboratory performance, but it is difficult to achieve efficient landing production.

2.1. Controllable synthesis technology of nano-functional fillers

Liquid-phase precipitation method is a common method to prepare metal oxide nano-fillers, which can be suitable for the synthesis of lead oxide, ferro-ferric oxide, titanium dioxide and other nano-particles. By accurately adjusting the temperature and pH value of the reaction system and the relative ratio of reactant feeding, the particle size can be effectively controlled at 5–50nm, and nano-particles with good dispersibility, high purity and industrial mass production can be prepared. The practical application of this process can effectively inhibit the agglomeration effect of particles by adding dispersant, and can significantly improve the uniformity of products, making this preparation technology more suitable for large-scale preparation of basic nano-shielding fillers, and can be widely used in the production of industrial-grade radiation protection plates.

Hydrothermal and solvothermal methods are mostly used in the preparation of high crystallinity nano-materials, which can synthesize rare earth nanoparticles such as samarium oxide and cerium oxide and special structural materials such as boron nitride nanotubes. The products have regular crystals, low internal defects and excellent radiation shielding performance, which is suitable for the material preparation requirements of high-end radiation protection scenes. Rare earth nanoparticles can play a unique role in the protection of mixed radiation sites due to their high atomic number and moderate neutron capture cross section, but owing to their high cost of synthesis and production, they are mostly used in aerospace, nuclear medicine and other fields with high performance requirements.

Electrospinning technology can be used to prepare nanofiber protective materials, such as boron-doped polyvinyl alcohol nanofibers, carbon-based nanofibers, etc. The fiber diameter can be controlled at 100–500nm, forming a continuous three-dimensional network structure, which makes the materials have high-efficiency radiation shielding ability and good flexibility^[2]. This three-dimensional network structure can provide more scattering and absorption sites for radiation particles, and at the same time, it can significantly improve the flexibility and tear resistance of the material, making it more suitable for the production and application of wearable radiation protection equipment.

2.2. Forming and processing technology of nano-composite materials

Solution blending method can obtain flexible composite protective materials by dispersing nano-functional fillers in polymer solution and curing. This process is simple and low in production cost, and can realize uniform dispersion of nano-fillers, which is more suitable for composite modification of rubber, epoxy resin and other substrates. In practical production application, this process can effectively combine the ultrasonic dispersion with

high-speed stirring technology to further reduce the agglomeration probability of nanoparticles, thus effectively improving the uniformity of the overall properties of composites.

Melt extrusion is mainly aimed at thermoplastic substrates such as polypropylene and polyethylene. With the help of twin-screw extrusion equipment, nano-fillers can be uniformly dispersed in the substrate, and shaped components such as plates and pipes can be continuously produced to meet the large-scale production requirements of industrial radiation protection components. In practical application, this technology is more suitable for the application scene of automatic production line. With the support of this technology, the dispersion effect of filler can be further optimized by adjusting the rotation speed and extrusion temperature of the screw, and it is also the mainstream technology for industrial mass production of nano-composite protective materials at present.

In-situ synthesis method can effectively avoid the agglomeration problem in the process of early dispersion of filler by directly synthesizing nanoparticles in the matrix. For example, in-situ synthesis of cerium-tungsten composite nanoparticles in the matrix of regenerated collagen fibers can significantly improve the interfacial bonding force between filler and matrix and ensure the uniformity of radiation shielding performance. The practical application of in-situ synthesis method can further promote the chemical bonding between nanoparticles and matrix, help to greatly improve the transmission efficiency of interfacial stress, and effectively solve the problems of easy delamination and poor mechanical properties of traditional composites.

2.3. Engineering design and control of nanostructures

Gradient nanostructures, layered nanostructures and porous nanostructures are important structural design ideas to optimize the comprehensive properties of materials. Gradient nano-metallic materials can build a high-density stacking fault and dislocation network through surface nano-crystallization, and with the help of adaptive martensite transformation, the rapid annihilation of irradiation defects can be realized. At a high irradiation dose of 155 dpa, the internal defect density is only 3.8% of that of traditional coarse-grained materials. This structural design can make the surface layer of nano-materials have more excellent radiation resistance, further maintain the good mechanical strength of the core, and promote the synergy between the function and structure of materials.

Layered nanocomposites are designed with “brick-mortar” structure, and combined with the radiation shielding effect of nano-lamellae and the energy dissipation characteristics of the interface, the mechanical properties and shielding properties of the materials are improved synergistically. By adjusting the thickness and component ratio of each layer, the graded shielding of different energy rays can be realized through customization, which enables the material adapt to a more complicated radiation environment.

Porous nanostructures can not only reduce the overall density of materials, but also increase the scattering sites of radiation particles, thus achieving efficient radiation protection under the premise of lightweight. The design and application of porous structure can also significantly improve the thermal insulation and permeability of materials, which has significant application advantages in the preparation of wearable protective equipment.

3. Optimization path of radiation protection materials based on nanotechnology

3.1. Optimization strategy of radiation shielding performance

Doping nano-sized components with high atomic number is the core way to improve γ -ray shielding ability. Doping nano-sized particles such as lead oxide, bismuth oxide and tungsten trioxide into polymer or glass matrix can effectively improve the effective atomic number and linear attenuation coefficient of materials. Relevant

experimental data show that the linear attenuation coefficient of 0.059 keV γ -ray doped with 25 wt% nano-lead oxide in polystyrene matrix is increased by 26.7% and the half-value layer thickness is decreased by 37% compared with that of micron-sized lead oxide composites with the same proportion. The small size effect of nanoparticles can greatly increase the interaction frequency with γ photons, which makes them significantly improve the radiation shielding efficiency under the same doping amount, and even much higher than micron-sized fillers. At the same time, they can effectively reduce the material density.

The optimization of neutron shielding performance depends on boron-based and rare-earth-based nano-materials. Materials such as boron nitride nanotubes and nano-samarium oxide have high neutron capture cross sections. Nano-treatment can improve the dispersion uniformity of functional elements and enhance neutron absorption efficiency. Compared with traditional materials, the orderly arrangement of boron nitride nanotube films significantly increases the density by 3 times, and the neutron shielding performance can be effectively improved by 3.7 times, which is more suitable for the lightweight protection requirements in the aerospace field. Among them, boron has a strong ability to capture thermal neutrons. When it is applied to the optimization of radiation shielding performance of materials, nano-crystallization can significantly avoid the segregation of components and effectively ensure the uniformity of neutron shielding performance, which makes it more suitable for spacecraft cabins, nuclear reactor peripheral protection and other scenes.

Multi-component nano-composite system integrates the advantages of high atomic number nanoparticles, neutron absorbing nano-components and carbon-based nano-materials, which can simultaneously achieve high-efficiency shielding of gamma rays and neutrons, make up for the shortcomings of radiation absorption of a single material, and is suitable for the protection scene of mixed radiation field of nuclear facilities. By using the collaborative design of multi-elements, the integrated protection against wide-spectrum radiation can be further realized, and the limitation of single shielding of traditional materials can be effectively solved.

3.2. Optimization method of mechanical properties

One-dimensional and two-dimensional nano-materials can be used as reinforcing phases to improve the mechanical properties of composites. Carbon nanofibers, graphene and boron nitride nano-materials can form a continuous stress transfer network in the collective, effectively improving the tensile strength and impact toughness of materials. Relevant experiments show that adding 0.5 wt% carbon nanofibers to samarium oxide/epoxy resin composites can improve the tensile strength of the materials by 18% and the impact toughness by 22%. The length-diameter ratio advantage of one-dimensional nano-materials can effectively transmit external stress, and the lamellar structure of two-dimensional nano-materials can effectively hinder the crack propagation. The cooperative application of the two materials can significantly improve the structural stability of materials.

Interface modification is an important means to improve the bonding state between filler and matrix. Surface treatment of nano-filler with silane coupling agent, oleic acid and other reagents can reduce the surface energy of particles, improve wettability with matrix, reduce interface defects and avoid material cracking caused by stress concentration. The optimized way of interface modification can effectively eliminate the gap between filler and matrix, significantly improve the bonding strength of interface structure, and make composite materials less prone to performance attenuation under long-term irradiation and mechanical load, further ensuring the performance stability.

Gradient and layered nanostructures improve the radiation deformation resistance of materials through the interface slip and energy dissipation mechanism, and solve the problems of high brittleness and easy fracture of

traditional protective materials ^[3]. The optimal design of mechanical properties of this structure can make the material dissipate energy through the slip between layers when it is impacted, and at the same time effectively guarantee the integrity of the whole material.

3.3. Optimization of thermal stability and radiation aging resistance

Modification of nano-ceramic particles can effectively improve the thermal stability of polymer matrix. Nano-alumina, silica and other particles can effectively improve the thermal decomposition temperature and thermal oxygen stability of matrix, further inhibit the fracture and degradation of polymer molecular chains under irradiation environment, and promote the extension of service life of materials. Nano-ceramic particles can be used as a physical barrier of protective materials, which can effectively hinder the heat transfer and the diffusion of oxygen molecules, thus reducing the aging rate of polymers under high temperature irradiation.

The design of defect annihilation structure is the key link to improve the radiation resistance of metal-based nano-materials. The high-density stacking faults and dislocation networks in nano-metals can quickly annihilate defects such as vacancies and interstitial atoms during irradiation, effectively avoiding the problems of swelling and embrittlement of materials during irradiation. The design and application of high-density defect network can further realize the self-repair of irradiation damage, so that metal materials can still maintain good plasticity and strength in extreme irradiation environment.

The core-shell structure nanoparticles protect the functional components of the inner core through the thermal resistance and radiation resistance of the outer shell, and improve the stability of the material in the dual extreme environment of high temperature and high radiation. The application of this structure in the optimization of thermal stability and radiation aging resistance can realize the precise protection of functional components, effectively avoid the inactivation of core barrier elements in complex environments, and significantly improve the environmental adaptability of materials.

4. Environmental adaptability and optimization of green engineering application

In addition to the performance optimization system, the environmental adaptability and green development of nano-radiation protection materials are also crucial to its engineering development. At present, most of the related research focuses on the performance test in the laboratory standard environment, and the research on the complex scene of practical application is shallow. In addition to the laboratory variables, the actual scene is often accompanied by complex environments such as low temperature alternation, high humidity, salt spray and mechanical vibration. At this time, the long-term stability of materials still needs systematic verification and consideration. By introducing weather-resistant modified components and interface stabilization treatment, nano-composite materials can maintain stable shielding effectiveness and mechanical properties in the range of -40°C to 120°C, and further reduce the performance attenuation caused by environmental factors.

At the same time, green and non-toxic is also an important direction of industry development, and the traditional nano-fillers with lead components have potential biological toxicity and environmental risks. In order to solve this safety dedication, lead-free components such as nano-tungsten, nano-bismuth and rare earth oxides can be used to replace lead-based fillers. In this optimization design, shielding efficiency can be guaranteed, and biosafety targets in medical and wearing scenes can be better met, which is more in line with the industry orientation of environmental protection and sustainable development. With the application of industrialization, the

evaluation of the whole life cycle of materials and cost control cannot be ignored. The preparation cost of high-end nano-fillers is high, and the dispersion uniformity in large-scale production is difficult to control effectively, which is a realistic bottleneck hindering the development of the industry. Developing low-energy synthesis technology and high-efficiency dispersion technology can effectively promote the nano-recycling of waste protective materials and further reduce production costs and resource consumption.

5. Conclusion

To sum up, nanotechnology can provide a feasible path for the performance breakthrough of radiation protection materials from the microstructure level. Through technical means such as nano-component compounding, nano-structure construction and interface modification, the radiation protection, mechanical and thermal stability of materials can be cooperatively optimized, which further meets the high-end application requirements of protection materials in nuclear energy, medical care, aerospace and other fields. At present, in the actual research and development of nano radiation protection materials, there are still practical problems such as uneven dispersion of fillers in large-scale production, high economic cost of high-end nano raw materials and long-term service performance to be verified in extreme environments. In the future, it is necessary to carry out more in-depth research and exploration around engineering and adaptability. On the one hand, it is necessary to further optimize the preparation process, improve the controllability of large-scale production costs, and promote the effective transformation of laboratory results into industrial-grade products; On the other hand, it is necessary to combine relevant application scenarios to carry out multi-functional integrated optimization design, and further endow materials with additional functions such as radiation sensing, self-repair and antibacterial. With the continuous reform and innovation of nano-preparation technology and structural control means, it can promote the high-quality development of nano-radiation protection materials with light weight, high efficiency and multi-function, provide more reliable technical support for the safety protection of high-radiation scenes, and help the green and high-end innovative development of related industries.

Disclosure statement

The authors declare no conflict of interest.

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