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PREPARATION METHODS AND PROPERTIES OF EXTENDED-SOURCE MATERIALS

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Abstract: Extended source materials can spontaneously initiate redox reactions upon contact with oxygen in air, and they possess irreplaceable application value in fields including infrared jamming, special ignition devices and emergency heat sources. This paper introduces the mainstream material systems of extended source materials at home and abroad, systematically compares the process characteristics of different preparation methods, emphatically analyzes the factors affecting the performance of extended source materials, and discusses the application status and development trends of such materials in complex-scenario, civil emergency response and other fields.
Keywords: Extended source materials; Preparation methods; Performance

1 INTRODUCTION

Extended source materials are a class of functional materials that undergo spontaneous redox exothermic reactions merely by contacting oxygen in ambient air without an external ignition source. Their reaction process releases massive heat accompanied by strong infrared radiation. Compared with traditional energetic materials, they feature fast response and high energy density [1]. With the growing demands for complex-scenario applications and civil emergency response, expanded-source materials have become critical components for infrared jamming loads and micro-ignition devices [2-3].

Early research on extended source materials focused on single metallic elements (e.g., nano iron and magnesium), yet such materials suffered drawbacks including easy oxidation, poor storage stability and uncontrollable combustion performance [4]. In recent years, scholars worldwide have developed multi-component systems such as alloy-based, carbon-supported and porous structured materials via composite modification and structural design, which greatly improve the comprehensive performance of materials [5-6]. Based on domestic and international research achievements, this paper systematically reviews material system classification, preparation routes and performance influencing factors, providing references for follow-up research and engineering application of Extended source materials.

2 CLASSIFICATION OF MAIN SYSTEMS OF EXTENDED-SOURCE MATERIALS

Extended source materials are mainly divided into three categories: single metal/alloy systems, metal matrix composite systems and carbon-supported composite systems.

2.1 Single Metal / Alloy Systems

2.1.1 Monometallic systems

Represented by nano iron, magnesium and aluminum, monometallic systems realize room-temperature self-ignition by reducing particle size to nanoscale to raise surface activity. As particle diameter decreases, the ratio of surface atoms to bulk atoms rises sharply. Surface atoms feature lower coordination numbers, leading to distinct thermophysical and electrical properties compared with bulk atoms. When the surface-to-bulk atomic ratio reaches a critical threshold, bulk materials exhibit surface atomic characteristics, prominently embodied by drastically increased specific surface area and enhanced reaction activity [7]. Nano aluminum particles with diameter below 68 nm possess self-ignition performance [8].

2.1.2 Alloy systems

Multi-metal composite alloys are adopted to optimize comprehensive performance, typical examples including iron-aluminum alloy, nickel-aluminum alloy and Al-Si-Mg alloy. After activation with strong alkali, Fe-Al and Ni-Al alloys form porous structures to shorten self-ignition response time; the addition of magnesium in Al-Si-Mg alloy reduces melting point (minimum 564.09 ℃) and elevates combustion rate and energy release efficiency [5].

2.2 Metal Matrix Composite Systems

2.2.1 Metal-oxidizer composite systems

Metallic fuels (Al, Mg, Fe) are composited with oxidizers (PTFE, KP, MoO_3) via mechanical milling for uniform mixing, followed by filtration separation and vacuum drying to obtain composites [9]. Mechanically activated Al-PTFE composites can be ignited at 871 K, with peak combustion temperature ranging from 850 ℃ to 950 ℃ [10].

2.2.2 Metal-ceramic composite systems

Ceramics serve as matrix to disperse self-igniting metal particles, e.g., porous self-igniting iron-ceramic composites. The ceramic matrix provides structural support with iron particles dispersed inside; the material undergoes self-ignition within 2 seconds upon air exposure, with combustion temperature between 600 ℃ and 800 ℃ [11].

2.3 Carbon-Supported Composite Systems

Carbon aerogel and carbon nanotubes (CNT) act as carriers to load metal oxides or carbonitrides, endowing materials with high specific surface area and electrical conductivity. Porous materials based on multi-walled carbon nanotubes (MWNTs) loaded with self-igniting α-iron nanoparticles can adjust self-ignition response speed by modifying carbon carrier structures [12]; TiCN/CNT composite system achieves a specific surface area of 276 m^2/g, and carbon carriers facilitate charge transfer during combustion to strengthen radiation performance [6].

3 DOMESTIC AND OVERSEAS PREPARATION METHODS

3.1 Mechanical Activation Method

Mechanical activation generally prepares composites from metal powders and metal oxides or fluoropolymers via mechanical force. Mechanical activation refines particle size, enlarges interfacial contact area, shortens diffusion distance, promotes uniform dispersion of components and improves reaction activity, with superior effects compared with simple nanoscale physical mixing. Jun Tao et al. adopted a Spex 8000M high-energy ball mill to grind Al-PTFE composites for 1 h, achieving homogeneous particle dispersion, and the self-ignition response speed was tripled relative to simple physical mixing [10]. Reference [9] applied soft-wall milling jars with optimized ball-to-powder ratio and milling media to realize large-scale safe preparation of nano energetic materials, cutting production cost by 70% compared with ultrasonic methods, which offers a feasible route for engineering application of nano energetic materials. This process features simple operation and wide adaptability for multi-component composite fabrication; nevertheless, long-duration milling easily causes particle agglomeration, requiring strict control of milling time and ball-to-powder ratio.

3.2 Vapor / Liquid Phase Deposition Method

Vapor deposition (magnetron sputtering) or liquid coating (tape casting, vacuum impregnation) forms uniform self-igniting coatings on substrate surfaces. Reference [13] adopted vacuum deposition, magnetron sputtering and other vapor deposition processes to deposit combustible layers (preferred magnesium layer thickness: 40–60 μm) on carbon fiber substrates under oxygen-free environments to avoid interfacial oxide film formation. Reference [14] deposited self-igniting materials on metal foil substrates via physical vapor deposition, enabling customized infrared emission signatures for decoys. The resulting thin films are uniform and porous with excellent repeatability. Groven et al. prepared carbon nanotube-based self-igniting materials by pressure filtration of aqueous dispersions containing multi-walled carbon nanotubes (MWNTs) loaded with self-igniting α-iron nanoparticles, followed by hydrogen reduction [12]. Reference [6] fabricated high-specific-surface-area, conductive nano carbon-supported metal oxide composites by vacuum impregnation of metal oxide sols using carbon aerogel (CA) or carbon nanotube/carbon aerogel composite (CA-CNT) carriers. The obtained materials possess ultrahigh specific surface area (maximum 2054 m^2/g), favorable electrical conductivity, strong thermal stability and stable pore structures. This technique produces highly uniform coatings with controllable structures, yet vapor deposition equipment entails high cost, and liquid deposition requires post-treatment including calcination and reduction.

3.3 Coating Activation Method

Coating activation involves coating energetic slurry onto substrates, followed by sintering curing and activation treatment to form self-igniting coatings. In reference [15], iron and aluminum powders were mixed with solvents and binders, dip-coated or spray-coated onto ultra-thin steel foils, rapidly heated to 500 ℃, then further heated to 800–1000 ℃ under mixed hydrogen-argon atmosphere to synthesize iron-aluminum alloys. Finally, hot caustic aqueous solution (10%–20% concentration) leaches aluminum from alloys, leaving porous iron with strong self-ignition performance. Wang Haiqi coated stainless steel foils with suspension composed of TZ powder and binders, followed by activation to fabricate self-igniting materials [16]. This process delivers high activation efficiency and excellent self-ignition performance, yet strong alkali solutions are highly corrosive; activation temperature and duration must be precisely controlled to prevent excessive substrate corrosion.

3.4 Sol-Gel Method

The fundamental principle of sol-gel chemistry lies in hydrolysis and condensation reactions of molecular precursors in solution to generate nano primary particles termed “sol”. Further condensation connects sol particles to form a three-dimensional solid network named “gel”, with solvent liquid retained inside pores. Evaporation of liquid phase yields dense porous solids known as “xerogel”; supercritical extraction removes pore liquid to eliminate surface tension

induced by liquid shrinkage, producing “aerogel”. Sol-gel materials exhibit unique advantages including high specific surface area, high porosity and tiny primary particle size, which enhance reaction activity. Therefore, sol-gel chemical routes are highly attractive for low-temperature synthesis of homogeneous materials with tunable composition, morphology and density [15]. Lawrence Livermore National Laboratory, USA adopted sol-gel hydrogen reduction method: ferric chloride hexahydrate as precursor, propylene oxide as gelling agent, Fe_2O_3 aerogel area source was formed via sol-gel process, then reduced under mixed H_2-Ar atmosphere at 350–700 ℃ to prepare porous self-igniting materials [15]. Wu Xiaoyan et al. synthesized cobalt ferrite via sol-gel route with ferric nitrate and cobalt nitrate as raw materials and citric acid as complexing agent [17]; ammonia water was dropwise added to adjust pH of initial mixed solution. The obtained xerogel exhibits self-ignition characteristics, and pure $CoFe_2O_4$ powder can be acquired after drying self-igniting powder at 600 ℃ for 2 h. The sol-gel method leverages structural regulation advantages to construct high-porosity self-igniting materials, enabling precise control over chemical composition and reaction rate of energetic materials with safe processing conditions.

4 PERFORMANCE INFLUENCING FACTORS

Self-ignition occurs when the heat generation rate from oxidation exceeds heat dissipation rates via conduction, convection and radiation. Combustible substances with larger specific surface area ignite more readily; hence porous combustible materials are easier to ignite compared with dense bulk solids [18]. Nanoscale particles with smaller size possess larger specific surface area and higher reaction activity; porous structures facilitate oxygen diffusion to shorten ignition delay. The ratio between metal fuels and oxidants as well as alloy element content directly determine combustion completeness [10]. Process parameters including milling duration, activation temperature and calcination conditions regulate particle dispersion and surface activity; for instance, two-step milling improves combustion efficiency of B-Ti-W composites [19]. Doping metallic powders such as Ti and B effectively shortens combustion time and elevates combustion temperature [20]. Guo Kai et al. studied energy-release characteristics of expanded-source combustion system under different pressure conditions [21]. When air pressure dropped from 101 kPa to 30 kPa, the ignition time of expanded-source materials doubled, total energy release decreased by 44.78%, and combustion area decreased by 45.95%, while the fluctuation of peak temperature and average temperature was less than 3%.

5 CONCLUSIONS

As functional materials featuring fast response and high energy output, extended-source materials and their preparation/performance optimization technologies have become research hotspots worldwide. This paper systematically summarizes core characteristics of elemental-metal/alloy, metal-matrix composite and carbon-supported composite systems, compares advantages and disadvantages of preparation methods including mechanical activation, vapor-/liquid-phase deposition, coating activation and sol-gel method, and analyzes influence rules of structure, components, process and air pressure on material performance.

Three core challenges require priority exploration in future research:

1. Balance high reaction activity and long-term storage stability via developing long-acting anti-corrosion coatings;
2. Optimize preparation processes to realize low-cost large-scale mass production;
3. Expand multi-band response capability to meet demands of complex countermeasure scenarios.

With the progress of material science and preparation technologies, extended-source materials will show broader application prospects in complex-scenario, civil, energy and other fields.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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