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Metal-based nanoenergetic materials: Synthesis, properties, and applications

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ABSTRACT

Metal particles are attractive candidate fuels for various propulsion and energy-conversion applications, primarily due to their high energy densities. Micron-sized particles present several drawbacks, such as high ignition temperatures and particle agglomeration, resulting in low energy-release rates. Nanoparticles, on the other hand, are quite attractive due to their unique and favorable properties, which are attributed to their high specific surface area and excess energy of surface atoms. As a result, there is a growing interest in employing metal nanoparticles in propulsion and energy-conversion systems. The present work provides a comprehensive review of the advances made over the past few decades in the areas of synthesis, properties, and applications of metal-based energetic nanomaterials. An overview of existing methods to synthesize nanomaterials is first provided. Novel approaches to passivate metal nanoparticles are also discussed. The physicochemical properties of metal nanoparticles are then examined in detail. Low-temperature oxidation processes, and ignition and combustion of metal nanoparticles are investigated. The burning behaviors of different energetic material formulations with metal nanoparticles such as particle-laden dust clouds, solid propellants, liquid fuels and propellants, thermite materials, and inter-metallic systems are reviewed. Finally, deficiencies and uncertainties in our understanding of the field are identified, and directions for future work are suggested.

Contents

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1. Introduction

Energetic materials release large amounts of chemical energy quickly in the form of heat during combustion. In monomolecular energetic materials, fuel and oxidizer groups are present within a single molecule and the reaction rate is thus controlled by breaking and formation of chemical bonds (chemical kinetics) [1]. The energy densities of monomolecular energetic materials are, however, limited [1]. This can be attributed to chemical stability requirements and limitations on the physical density of materials [2]. Composite energetic materials, on the other hand, are synthesized by physical mixing of fuel and oxidizer particles. Fig. 1 shows a composite energetic nanomaterial consisting of aluminum and molybdenum trioxide (MoO_3) particles [3]. The nano-aluminum particles are spherical in shape and have an average diameter of 80 nm, while the MoO_3 particles are sheet-like particles with a length of 1 μm and thickness of 20 nm. The solid propellant employed in the U.S. Space Shuttle solid rocket boosters is another example of a composite energetic material. It consists of ammonium perchlorate crystals and aluminum particles in a polymer binder [4]. The overall reaction rate of composite energetic materials is typically controlled by mass diffusion, since the fuel and oxidizer particles are separate entities [1]. The resulting rates of energy release are lower than the corresponding values that could be attained in a kinetically-controlled process [1].

The energy density of conventional energetic materials can be substantially increased by the addition of metal particles. Fig. 2 shows enthalpies of combustion of monomolecular energetic materials and metals in pure oxygen under stoichiometric conditions. On a volumetric basis, the enthalpy of combustion of metals is as high as 138 kJ/cm^3, substantially greater than those of monomolecular compounds (~10–30 kJ/cm^3). One of the most energetic, beryllium, is seldom used, due to its extreme toxicity, relative scarcity, and high cost [5]. Among the elements listed here, boron has the highest volumetric energy density of 138 kJ/cm^3. Ignition of boron particles is, however, significantly delayed by the presence of an oxide (B_2O_3) layer [6–8]. The ignition temperatures of boron particles in oxygenated environments vary in the range of 1500–1950 K, regardless of