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Combustion synthesis of zero-, one-, two- and three-dimensional nanostructures: Current trends and future perspectives

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ABSTRACT

The combustion phenomenon is characterized by rapid self-sustaining reactions, which can occur in the solid, liquid, or gas phase. Specific types of these reactions are used to produce valuable materials by different combustion synthesis (CS) routes. In this article, all three CS approaches, i.e. solid-phase, solution, and gas-phase flame, are reviewed to demonstrate their attractiveness for fabrication of zero-, one-, two-, and three-dimensional nanostructures of a large variety of inorganic compounds. The review involves five sections. First, a brief classification of combustion synthesis methods is given along with the scope of the article. Second, the state of art in the field of solid-phase combustion synthesis is described. Special attention is paid to the relationships between combustion parameters and structure/properties of the produced nanomaterials. The third and fourth sections describe details for controlling material structures through solution combustion synthesis and gas-phase flame synthesis, respectively. A variety of properties (e.g., thermal, electronic, electrochemical, and catalytic) associated with different types of CS nanoscale materials are discussed. The conclusion focuses on the most promising directions for future research in the field of advanced nanomaterial combustion synthesis.

Contents

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1. Introduction

Combustion is a complex phenomenon involving self-sustaining chemical reactions accompanied by rapid heat release that typically occurs in the form of a high temperature reaction front. Heat, light, and work (engines) are the primary areas for application of combustion processes. However, in some cases, the main purpose for these reactions is the formation of condensed combustion products, i.e. the synthesized materials. This synthesis method may be considered as one of the most economical routes for preparation of advanced materials, including zero-, one-, two-, and three- dimensional nanostructures. Compared to other high-temperature techniques for fabrication of nanostructures, such as arc discharge [1], pulsed laser synthesis [2], microwave heating [3], and chemical or physical vapor deposition methods (CVD and PVP) [4,5], combustion does not require any external heating sources, since the process uses heat produced by exothermic reactions. Moreover, the short reaction duration and rapid product cooling can result in the formation of non-equilibrium products with unique electrochemical, physical, biological, and mechanical properties [6].

Depending on the physical state of the reactive media, three types of combustion processes for the synthesis of nanostructured materials can be distinguished: solid-phase combustion synthesis (SP-CS), solution combustion synthesis (SCS), and gas-phase flame synthesis (FS).

In SP-CS processes, a self-sustaining combustion wave propagates in a solid mixture due to the heat released in the chemical reaction. Solid-phase combustion was discovered by Prof. Merzhanov in 1967 and is also known as self-propagating high-temperature synthesis (SHS) [7,8]. SP-CS has become a very popular approach for preparation of various types of inorganic compounds, such as metals, alloys, oxides, metal carbides, borides, silicides, *etc*. In principle, this approach works for any solid-state exothermic mixture that is capable of maintaining a self-sustaining reaction and leads to the formation of valuable condensed products. Usually a short heat pulse is locally applied to the surface of the solid reactants, which initiates the combustion process. A thermal wave forms after ignition and propagates through the bulk sample, converting the precursor powder mixture into the desired products.

In SCS, the initial reactive media is an aqueous solution of fuel and oxidizer [9]. SCS involves many different physical, chemical, and mechanical steps. However, all of these approaches include one common step: initially solid precursors, i.e. fuel (e.g. glycine, urea, citric acid) and oxidizer (e.g. metal nitrites) are dissolved in a liquid solvent (e.g. water), making a reactive solution with reagents mixed on the molecular level. Depending on the type of precursors, as well as on the conditions used for the process organization, SCS may occur either by volume or layer-by-layer propagating combustion modes. Among the numerous papers published in recent years in the SCS field, the synthesis of oxides dominate. Recently, pure metals and alloys, along with metal sulfides and carbides, have also been produced by this method.

In FS processes, the chemical reaction occurs between gaseous components [10,11]. FS involves combustion of gaseous fuel such as hydrocarbons and hydrogen in oxygen. In another procedure, the precursor, which is gas or liquid droplets, is injected into the burner and condensed particulates are formed. FS is routinely employed for large-scale manufacturing of carbon black and different oxides such as fumed silica, pigmentary titania, zinc oxide, and alumina nanopowders. Currently, FS has also been successfully utilized to produce 1D functional nanostructured materials grown directly on substrates.

This review article consists of five main sections: (1) Introduction, (2) Solid-phase combustion synthesis, (3) Solution combustion synthesis, (4) Gas-phase flame synthesis, and (5) Conclusions and perspectives.

Section 2 describes the synthesis of various nanostructured materials by the SP-CS approach. Many aspects of the SP-CS process are discussed, including thermodynamics, high-temperature-chemistry, and reaction mechanisms. In addition, relationships between combustion parameters and the structural characteristics of as-prepared nanomaterials are outlined. The SP-CS method highlights 0D, 1D, 2D, and 3D advanced inorganic compounds such as, transition metals (Ti, Zr, W, Mo, Ta, and Nb), non-metals (B, Si, and C), metal