Chapter 7
Ultrasound-Assisted Synthesis of Nanostructured Oxide Materials: Basic Concepts and Applications to Energy

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ABSTRACT

This chapter is focused on the use of high intensity ultrasound for the preparation of nanostructured materials with an emphasis on recent prominent examples of the production of dense or porous metal oxides through sonochemical and ultrasonic spray pyrolysis routes. Sonochemistry enables the synthesis of oxides that are often unachievable by traditional methods or affords known materials with shape, size, and nano/microstructure control under fast reaction conditions. The fundamental principles of acoustic cavitation, as well as the main ultrasonic parameters affecting the cavitation phenomenon, are first summarized. Next, the applications of ultrasound in the synthesis of nanostructured oxide materials following both preparation methods are reviewed. Particular focus is given to the ultrasound-assisted synthesis of metal oxide nanoparticles for energy applications.

DOI: 10.4018/978-1-5225-3903-2.ch007
INTRODUCTION

The advent of nanoscience prompted the search for advanced nanostructured materials for a large variety of applications in catalysis, energy, materials science, and even at the frontier of chemistry and biology. This can be attributed to a wide range of peculiar physical characteristics. Nanometer-sized materials exhibit properties distinct from their bulk counterparts, owing to their controlled size, shape and nanostructure. A large variety of synthesis strategies have been explored for the preparation of nanomaterials, including solid-state reactions, wet chemistry procedures (e.g. impregnation, deposition-precipitation and auto-combustion methods, as well as sol-gel, hydrothermal and solvothermal syntheses), and gas phase techniques (e.g. chemical vapor deposition and laser pyrolysis decomposition of volatile organometallics) (Guo et al., 2015; Zhao et al., 2015; Deshmukh & Niederberger, 2017; Yang et al., 2017). The importance of selecting an appropriate synthesis route in designing nanostructured materials with the aim of controlling the morphology, nanostructure, composition, particle size and surface area is currently a driving force for the development of new synthetic methodologies. Since most of the conventional preparation methods require a lot of chemicals (precursors, solvents and additives), along with multi-step processes to produce catalytic materials, the development of greener, cost-effective and generalized synthetic routes remains a subject of intense research. In this respect, the utilization of high intensity ultrasound (US) offers a straightforward and powerful tool for nanostructured catalysts preparation. Numerous nanosized materials have already been reported through ultrasound-assisted synthesis routes. Many excellent review articles can be found in the literature, offering a comprehensive discussion on the matter (Gedanken, 2004; Bang & Suslick, 2010; Xu et al., 2013; Hinman & Suslick, 2017; Geng et al., 2012; Pollet, 2010; Yu et al., 2016). Colmenares and co-workers (2016) recently comprehensively reviewed the advances made in the sono-synthesis of photoactive materials and their application in photocatalysis and solar cells. Additionally, the most relevant progresses in the coupling of ultrasonic waves and metal-based reagents in target organic synthesis have just been reviewed by Domini et al. (2017).

When high intensity ultrasound is applied to liquids, an acoustic cavitation phenomenon occurs, which affects chemical reactivity. Unique reaction conditions are therefore generated that can be exploited to prepare nanomaterials. Sono-synthesis has been reported to possess numerous advantages over conventional methods. These includes, but are not limited to, (1) low temperature synthesis of nanostructures without any external heating, (2) fast reaction time, (3) high purity phase, (4) more uniform particles size distribution (limited growth of particles), (5) size and shape control, (6) chemical composition control, (7) crystallinity control, (8) improvement of textural properties (i.e. surface area), (9) synthesis of nanostructured materials unavailable by traditional routes, (10) flow and scalable synthesis (case of ultrasonic spray techniques).

In this contribution, prominent examples of nanostructured oxide materials will serve as a perfect demonstration of what can be done through sonochemistry. The coverage focuses essentially on the last decade. The chapter is organized into three main sections with the first one covering the unique features of sonochemistry. More precisely, this section aims at providing a primary understanding of the basic principles of acoustic cavitation and of the main ultrasonic parameters relevant to materials synthesis. Next, the powerful characteristics of ultrasound in nanostructured oxide particles synthesis is demonstrated with emphasis on direct sonochemical reactions (section 2) and ultrasonic spray pyrolysis (section 3). Such ultrasonic spray technique is best used to generate microdroplets reactors for the production of nanostructured materials through nebulization. In recent years, a myriad of nanostructured metal oxides