Progress in Materials Science 88 (2017) 1–48

Contents lists available at ScienceDirect

Progress in Materials Science

journal homepage: www.elsevier.com/locate/pmatsci

Recent advances and remaining challenges of nanostructured materials for hydrogen storage applications

Xuebin Yu [a,*], Ziwei Tang [a], Dalin Sun [a], Liuzhang Ouyang [b], Min Zhu [b,*]

[a] Department of Materials Science, Fudan University, Shanghai 200433, China
[b] School of Materials Science and Engineering, South China University of Technology, Guangzhou 510641, China

ARTICLE INFO

Article history:
Received 7 January 2017
Accepted 5 March 2017
Available online 18 March 2017

Keywords:
Hydrogen storage materials
Nanostructures
Carbon
Metal-organic frameworks
Organic polymer networks

ABSTRACT

The rapid and extensive development of advanced nanostructures and nanotechnologies has driven a correspondingly rapid growth of research that presents enormous potential for fulfilling the practical requirements of solid state hydrogen storage applications. This article reviews the most recent progress in the development of nanostructured materials for hydrogen storage technology, demonstrating that nanostructures provide a pronounced benefit to applications involving molecular hydrogen storage, chemical hydrogen storage, and as supports for the nanoconfinement of various hydrides. To further optimize hydrogen storage performance, we emphasize the desirability of exploring and developing nanoporous materials with ultrahigh surface areas and the advantageous incorporation of metals and functionalities, nanostructured hydrides with excellent mechanic stabilities and rigid main construction, and nanostructured supports comprised of lightweight components and enhanced hydride loading capacities. In addition to highlighting the conspicuous advantages of nanostructured materials in the field of hydrogen storage, we also discuss the remaining challenges and the directions of emerging research for these materials.

Contents

* Corresponding authors.
E-mail addresses: yuxuebin@fudan.edu.cn (X. Yu), memzhu@scut.edu.cn (M. Zhu).

http://dx.doi.org/10.1016/j.pmatsci.2017.03.001
0079-6425/

1. Introduction

The last three decades have witnessed dramatic progress in the field of nanoscience and technology, which has had a correspondingly dramatic impact on diverse fields of science, engineering, industry, and commercial sectors [1,2]. Owing to their reduced size, nanoscale materials typically demonstrate unique physical and/or chemical properties distinct from their respective bulk materials, which enables new opportunities for applications in catalysis, electronics, biology, and energy storage [3–7]. In particular, nanomaterials exhibit numerous advantages for energy storage applications. For example, with the decreasing size of a material, the surface-to-volume ratio increases tremendously. Moreover, the atoms on the surface may have some dangling bonds that are extremely active and tend to form bonds with surrounding molecules or particles to reduce the surface energy. These characteristics of specific surface area, surface energy, and surface chemistry play an important part in energy storage applications due to the physical or/and chemical interactions that are involved at the surface or interface [8–18]. These surface effects may have significant influences on the kinetics and thermodynamics of heterogeneous reactions occurring at the interface, and the nucleation and subsequent growth when phase transitions are involved. In addition, nanomaterials with smaller dimensions may afford more favorable heat, mass, and charge transfer, as well as facilitate dimensional changes with regard to certain chemical reactions and phase transitions [19–23].

On the other hand, the continued increase in greenhouse gas emissions coupled with the rapid depletion of fossil fuel reserves require the development of clean, renewable energy sources to meet the burgeoning demands of the world's population. Hydrogen is a predominant candidate as a future energy carrier for sustainable development. For the wide application of hydrogen-powered fuel cell vehicles, it is of considerable importance to develop a feasible on-board hydrogen storage system [24–29]. Nevertheless, safe and compact storage of hydrogen in a solid medium is the most demanding and challenging requirement for realizing a hydrogen economy as far as mobile and stationary applications are concerned. Generally, hydrogen can be stored in the form of high-pressure gas, cryogenic liquid, or chemically or physically bonded to a suitable solid-state material. Among these approaches, solid-state storage can potentially provide the highest hydrogen density, and may yield the highest utility towards the practical implementation of hydrogen storage [30–38]. However, no material has yet been found that meets the following criteria simultaneously: a comparatively high hydrogen density of 2.5 $kW\,h\,kg^{-1}$ (7.5 wt.% for net useful energy per maximum system mass) or 2.3 $kW\,h\,L^{-1}$, moderate thermolysis temperatures of 333–358 K, good reversibility, and fast hydrogen adsorption and desorption kinetics [39].

The utilization of nanotechnology appears to be an efficient strategy to address the challenges mentioned above. Nanostructured materials can facilitate molecular hydrogen (H_2) storage by providing a high surface area or by incorporating or trapping hydrogen in nanoporous media. The increased surface area and porosity of nanostructures afford additional binding sites on the surface and in the pores that can improve the storage mainly through physical adsorption [40–42]. For chemical adsorption, nanomaterials can increase the kinetics of hydrogen uptake and release from hydrides, and their storage properties can be tailored by tuning the particle sizes. For example, with a metal hydride in which the hydrogen is stored in the interspace or held by chemical bonds, the kinetics of both adsorption and desorption processes can be enhanced simply by reducing the particle size of the metal. In general, the reduction in the particle size of hydrides into the nanoscale may exhibit the following influences: shortening of the ion diffusion path along the lattice of the solid phase; inducing the exposure of reactive planes, edges, and corners; creating defects within the lattice of the nanoparticle; and facilitating mass transport and intermolecular reaction [43–45]. These characteristics permit a faster rate of hydrogen release and uptake from nanostructured materials than that from their corresponding bulk counterparts.

Several excellent review articles have been published regarding the physical hydrogen storage properties of specific nanomaterials [46–56], the effects of special nanomaterials on the hydrogen storage performances of hydrides [57–60], and the hydrogen storage performances of nanoconfined [45,61–65] or nanostructured [66–71] hydrides. Most of these reviews have highlighted and demonstrated the abovementioned aspects of nanomaterials in hydrogen storage applications.