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Review

Metal hydrides in engineering systems, processes, and devices: A review of non-storage applications

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ABSTRACT

Metal hydrides have garnered much interest in scientific and engineering communities since their discovery in 1866 because of the wide range of applications they offer (Bowman et al. and Mueller et al.). A comprehensive review of selected applications involving metal hydrides in engineering systems, processes and devices has been presented in this paper. The applications of metal hydrides can be broadly classified into seven distinct categories, which are: 1) *thermal systems*, 2) *energy systems*, 3) *actuation and sensing*, 4) *processing*, 5) *semiconductors*, 6) *biomimetic and biomedical systems, and 7) nuclear applications* in addition to hydrogen storage. There have been several brilliant reviews published on hydrogen storage in metal hydrides. The focus of this review is on non-storage metal hydride applications. The fundamentals and working principles of engineering systems, processes, and devices based on metal hydrides have been concisely provided. Besides hydrogen storage, metal hydrides have been proposed and demonstrated for applications in hydrogen compressors, refrigerators, and actuators. Optical and electrical properties of hydrides can be exploited in the design of sensors and energy efficient windows. The hydriding and dehydriding processes are effective in preparing implants for osseointegration in addition to being economic. Certain hydride materials are more effective neutron moderators compared to the conventional ones in nuclear power plants. All such applications involving metal hydrides are revised and briefly discussed along with their working principles in this article.

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Introduction

Metal hydrides were first discovered in 1866 by Thomas Graham [1]. The first metal hydride discovered was palladium hydride (PdH_x) [1,2]. Numerous other metal hydrides have been discovered after palladium hydride. They have been established as excellent media for on-board or stationary hydrogen storage. The sole reason behind the superiority of metal hydrides as storage media over competing/existing technology is their ability to store large amounts of hydrogen at densities greater than cryogenically stored liquid hydrogen. Moreover, the discharge pressure can be close to atmospheric pressure at moderate temperatures for some hydrides, which

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makes them more suitable for portable systems. Besides, the properties of hydrides such as storage capacity, operating pressure and temperature can be altered by alloying as well as other mechanical means. Thus, metal hydrides are vigorously researched for on board vehicular hydrogen storage systems that are capable of storing enough hydrogen to cover approximately 300 miles of conventional driving range with a single refill.

Apart from hydrogen storage, metal hydrides had been integrated in various engineering applications. These systems take advantage of high storage capacity of metal hydrides and temperature/pressure swing dependent sorption method. The concept of temperature swing causing a low pressure absorption and high pressure desorption is utilized in designing thermally driven hydrogen compressors. Based on the fact that absorption and desorption processes are exothermic and endothermic, respectively, metal hydride storage systems can be engineered to supply heated or cooled air for application in air conditioning, refrigeration, and heat pumps. Those properties can also be exploited in designing thermochemical heat storage system. Apart from thermal systems, metal hydrides are also well known for their application in energy systems such as metal hydride batteries and fuel cells. AB_5 type metal hydrides are used in the production of more than a billion batteries every year. Proton exchange membrane (PEM) fuel cells have the potential to replace the internal combustion engine in future. The chemical energy of hydrogen stored in metal hydrides is converted to DC power in these cells, which can be used to drive the DC motor of the vehicle. The ultra-high storage capability of a metal hydride can be translated to high force to weight ratio from the desorbed hydrogen, which makes it a suitable candidate for actuation of robotic arms and biomimetic muscles.

There are some metallic hydrides, which exhibit optical and electrical property change on top lattice expansion while they undergo hydrogen absorption. Changes in such properties make them potential candidates for designing gas sensors capable of integrating micro systems. The change in optical properties in the presence of hydrogen enables application of metal hydrides in smart windows. Certain metallic coatings have been found to switch from transparent to opaque in the presence and absence of hydrogen, respectively. Hydrogen purification and isotope separation processes have also been demonstrated using metal hydride as a storage material. From a mix of gases, only hydrogen gets absorbed in the storage material and the remaining gases can be purged by previously purified hydrogen gas. Certain metals like palladium show affinity towards different isotopes of hydrogen in different temperature ranges. Such properties are taken advantage of, in the design of isotope separation processes for industrial applications.

Finally, comparatively newer field of applications have been proposed and demonstrated by integrating hydrides materials in semiconductor electronics, osseointegration, and fast nuclear reactors. Certain hydrides show *p*-type and *n*-type conductivity as revealed from the analysis of their band structure. Such hydrides open up the potential of a new era of ‘hydride electronics’. Some biocompatible metals such as titanium are used in living systems for implantation. Very often the material needs to be transformed into powder before it is compressed into desired shape. This process is expensive and can be replaced with an economic hydrogenation/dehydrogenation process, which eventually breaks up crude particles or agglomerates into finer powder after repeated cycles of sorption. The ability of hydrogen atoms in a hydride to moderate fast neutrons in nuclear reactors encouraged researchers to use hafnium hydrides as neutron moderators. Also, certain actinide hydride fuels have been suggested as transmutation targets of long lived nuclear wastes.

Metal hydride has been an interesting topic among scientists and engineers with ongoing research emphasis. As time progresses and hydrogen evolves as a future fuel to suffice the world's energy needs, new generation of metallic alloys could be developed to minimize the shortcomings of the contemporaries. Along the way, hydrides have found interesting engineering applications besides hydrogen storage. Many more applications of hydride may be underway as new characteristics of such materials are discovered. This article summarizes the fundamentals behind the applications of metal hydrides in thermal, energy, actuator and sensors, industrial, biomedical, and nuclear systems as proposed and demonstrated in research and publications.

Metal hydride basics

Although, there are at least fifty metallic elements in the periodic table that can store hydrogen, only a handful of them are suitable for storing it at moderate temperatures and pressures. The process is nearly reversible and can be expressed by the following equation.

$$M + \frac{x}{2}H_2 \leftrightarrow MH_x \pm \Delta H \quad (1)$$

where M and H represent metal and hydrogen atoms, respectively. Note that x is the non-stoichiometric coefficient and ΔH is the reaction enthalpy. The sorption process is exothermic when hydrogen is absorbed in and endothermic when hydrogen is desorbed from the alloy.

Hydrogen is stored in the interstitial sites of metals with densities greater than liquid hydrogen as shown in Fig. 1. Even though mass percentage seems to be very low, for portable applications such as vehicular hydrogen storage, hydrides are very attractive alternatives because of ultra-high density. The limiting condition for applicability of metal hydrides is generally related to the applicable temperature and pressure. AB_5 type hydrides such $LaNi_5$, however, show reversible sorption at desirable ranges of operating temperature and pressures. It is the extremely high density with moderate operating conditions that makes metal hydride a suitable candidate for portable hydrogen storage applications.

The most important feature of a metal hydride storage system is its plateau pressure, illustrated in Fig. 2(a). This is the pressure at which metal hydrides reversibly absorb/desorb large quantities of hydrogen. For applications such as batteries, this plateau pressure is desired to be close to the ambient pressure, which allows designing the container with light weight material. There is a difference between equivalent pressures for absorption and desorption in the pressure-composition isotherms. This hysteresis can be reduced by

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