Combustion and Flame 161 (2014) 322–331

Contents lists available at ScienceDirect

Combustion and Flame

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

Conversion of aluminum foil to powders that react and burn with water

Ashvin Kumar Narayana Swamy, Evgeny Shafirovich *

Department of Mechanical Engineering, The University of Texas at El Paso, 500 W. University Ave., TX 79968, USA

ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form 21 August 2013
Accepted 21 August 2013
Available online 13 September 2013

Keywords:
Metals combustion
Aluminum
Water
Hydrogen
Ball milling

ABSTRACT

In the US, the total amount of aluminum scrap and waste, including foil, is outpacing efforts to recycle it into conventional aluminum materials. It would be attractive to develop technologies for converting aluminum foil scrap and waste to useful products and energy carriers. The present paper focuses on the feasibility of converting foil to activated Al powders that chemically split water, releasing hydrogen. As a method for this conversion, high-energy ball milling of Al foil with sodium chloride is investigated, with removing NaCl from the obtained powder by dissolution in cold water or methanol. The powders are characterized using BET specific surface area analysis, laser diffraction particle size analysis, scanning electron microscopy, and energy dispersive X-ray spectroscopy. The obtained micron-sized Al powders readily react with warm (35–80 °C) water. Hydrogen evolution is studied using water displacement, while solid byproducts are examined by X-ray diffraction and thermal analysis. The powders are also mixed with gelled water at various mass ratios and combustion of these mixtures is studied in argon environment. With increasing Al concentration, the combustion front velocity increases despite the decrease in the combustion temperature. The burning rate of the stoichiometric mixture of the activated Al powder with water is comparable with the values reported previously for the mixtures based on nanoscale aluminum, while the content of active Al in the obtained micron-sized powder is significantly higher.

© 2013 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

1. Introduction

Currently, significant efforts are made over the world to develop more efficient routes for recovering, reusing or recycling the byproducts and waste streams that are generated during production and use of materials [1–4]. Since aluminum is one of the main metals in a modern technological society, enormous amounts of aluminum scrap and waste are generated by industries and consumers [5–8]. A significant fraction of them is recycled. For example, in 2003, the worldwide production of primary aluminum was 27.4 million tons, while the production of secondary (recycled from scrap) aluminum was approximately 13.1 million tons [6]. In the European Union, due to limited ore mining and energy constraints, the production of secondary aluminum exceeds that of primary aluminum [6]. Although secondary aluminum production from scrap needs much less energy than production of primary aluminum from ore, it still remains an energy and resource extensive method and involves harmful chemicals, so that alternative methods for recycling aluminum are being investigated [4]. On the other hand, in the United States, the total amount of aluminum scrap and waste is outpacing efforts to recycle it into conventional aluminum materials [8]. Thus, it would be attractive to develop technologies that convert Al scrap and waste to other useful products or energy carriers.

A large fraction of Al scrap and waste is foil [6–8]. Aluminum foil is widely used for packaging, household, and engineering applications. Currently, only part of the used foil is recycled into the secondary aluminum. Also, industrial production of Al foil generates significant amounts of foil scrap [9,10]. Thus, enormous amounts of foil scrap and waste are available for the conversion to useful products.

In the present paper, we propose to convert the foil scrap and waste to activated Al powders that chemically split water. This reaction could occur in two modes. One is a low-temperature (less than 100 °C) process, which could be used for on-demand hydrogen generation from water in fuel cell power sources [11] and energy storage systems. The other is combustion of aluminum with water for combined hydrogen and power generation [12–14] as well as for underwater [15,16] and space [17,18] propulsion.

The reaction of aluminum with water has been studied by numerous researchers. This reaction is inhibited by a protective oxide film on the aluminum surface. To overcome the film resistance, various methods such as corrosion of Al in strong alkaline solutions, amalgamation, alloying with dopants (e.g., bismuth and gallium), and the use of very high temperatures have been proposed (see, for example, reviews [11,19,20]). Recently, it has been reported that high-energy ball milling of aluminum powder with

---

* Corresponding author. Fax: +1 915 747 5019.
E-mail address: eshafirovich2@utep.edu (E. Shafirovich).

0010-2180/$ - see front matter © 2013 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.combustflame.2013.08.017

water-soluble inorganic salts such as sodium chloride (NaCl) produces an activated aluminum powder that readily reacts with hot water [21–23]. Sodium chloride can be dissolved in cold water after milling and the remaining Al powder retains a high reactivity [22]. As compared with other methods for Al activation, milling with salt offers a number of advantages such as the low cost of NaCl (which can also be recycled) and the fact that no rare, corrosive, toxic or environmentally harmful compounds are needed.

A major obstacle to industrial production of activated Al powders by ball milling is the relatively high cost of the commercial micron-scale Al powders that are used as a precursor. Recovery of Al from ore or from byproducts of Al reaction with water consumes a lot of energy and hence leads to high costs for the powders. The energy consumed in producing Al powder could be significantly reduced by using recycled aluminum foil where aluminum is contained in a metallic, non-oxidized form. Indeed, compared with the use of primary aluminum, the use of secondary aluminum for the reaction with water promises dramatic gains in energy efficiency and reduced hydrogen costs [24]. Conventional methods for recycling aluminum scrap and fabricating powder, however, involve several processes such as melting and atomization. Aluminum flake powder has also been obtained by ball milling of Al foil with stearic or oleic acid, but, at the used rotation speed of 120 rpm, production of 10-μm particles required many hours of milling [9,10]. Thus, it is attractive to explore the feasibility of direct production of the activated Al powder from aluminum foil scrap and waste through high-energy ball milling with sodium chloride.

The obtained activated Al powder could be used for on-demand hydrogen generation from hot water and as a fuel component in energetic materials. Note that the use of nanoscale Al in propellants has limitations such as a low content of active aluminum and a high cost. The use of activated micron-scale Al powders is now of great interest [25]. Aluminum–water mixtures are a new class of energetic materials that are promising for underwater and space propulsion as well as for hydrogen/power generation. Combustion of these mixtures has been investigated by several research teams [26–39]. It is important to note that these mixtures were combustible only if at least part of the used Al powder was nanoscale. Even a small addition of commercial micron-scale Al powders decreased the burning rate [34,35,37]. The replacement of nanoscale Al powders in energetic materials by activated micron-scale Al powders, obtained from Al foil, would decrease the costs and increase the energy density due to a higher content of metallic Al.

The objectives of this paper are to fabricate activated Al powders from aluminum foils using high-energy ball milling with sodium chloride, characterize the obtained powders, and investigate their reactions with water in both the low-temperature (35–80 °C) and combustion modes.

2. Experimental

2.1. Fabrication of powders from aluminum foil

In most experiments, aluminum foils (ultra-pure, thicknesses 15 μm, 23 μm, and 36 μm, VWR) were used as starting materials. The foils were cut into square (10 mm × 10 mm) pieces, mixed with sodium chloride (>99.0% purity, Sigma–Aldrich) at 1:1 mass ratio, and milled in a planetary ball mill (Fritsch Pulverisette 7 Premium Line), using 80-mL zirconia-coated grinding bowls and zirconia grinding balls, in either air or argon environment.

The milling process involved four cycles and the decrease in the diameter of grinding balls from 10 mm to 5 mm and then to 2 mm (Table 1). The use of larger balls at the beginning allowed faster conversion of the foil to a powder, while the use of smaller balls at the end made this powder finer. The powder-to-balls mass ratio was about 1:11. The rotation speed was the maximum recommended by the manufacturer (Fritsch) for the specific ball size: 850 rpm for 10 mm, 1000 rpm for 5 mm, and 1100 rpm for 2 mm. Each milling step was followed by a cooling pause. The total time of the milling steps was 30 min.

To determine the feasibility of making activated powders from used beverage cans, the top and bottom ends of a Pepsi® can were removed and the rest of the can was cut into four pieces. To remove the paint and protective coating from the cans, the pieces were immersed in concentrated sulfuric acid (ACS grade, 95% w/w, LabChem) for 30 min, then removed and washed under tap water. The obtained foil pieces had a thickness of approximately 100 μm. They were subjected to two different milling procedures, conducted in air. The first procedure was the same as described above (Table 1). In the second procedure, the first two milling steps lasted 15 min each and the number of milling steps at 1100 rpm was increased to six, with the total time of the milling steps being equal to 60 min.

To obtain Al without NaCl, the powders were washed for 2–5 min in cold (<15 °C) deionized water. After passing the solution through a filter paper (about 20 min), the resulting Al powder was left overnight to dry.

To investigate a potential effect of washing in water on the Al surface, the powders obtained by milling were washed in methanol (ACS grade, LabChem), which does not oxidize Al. The washing in methanol was followed by the same filtration and drying procedure as after washing in water.

The Al/NaCl and Al powders were characterized using Brunauer–Emmett–Teller (BET) specific surface area analysis (Microtrac SAA), laser diffraction particle size analysis (Microtrac Bluewave), scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM-EDS, Hitachi S-4800). The particle size analysis was conducted using isopropyl alcohol as a liquid carrier and ultrasonic treatment (40 W, 30 s) for deagglomeration.

2.2. Experimental procedure for kinetic studies of the reactions between the obtained powders and warm water

To study the reaction, 0.7-g samples of the obtained powders were submerged in 750 mL of deionized water heated to 35 °C, 50 °C, 65 °C, or 80 °C using a digital hotplate (Scilogex MS7-H550-Pro). During the process, the temperature of water increased by 2–2.5 °C due to the exothermic reaction of Al with water and returned to the initial value after the completion of the reaction. The amount of released gas was monitored using water displacement in an inverted graduated cylinder. Specifically, the water level in the cylinder was recorded every minute until most hydrogen was released. Based on the measured volume, the number of moles of the released hydrogen was calculated using the ideal gas equation and assuming that the released gas is pure hydrogen and the gas temperature is equal to the water temperature in the inverted cylinder (atmospheric pressure was measured by a digital barometer). The reaction extent was then calculated using the fact that 1 mol of Al theoretically releases 1.5 mol of H_2 from water, independently on whether the reaction produces bayerite:

$$\mathrm{Al} + 3\mathrm{H_2O} \rightarrow \mathrm{Al(OH)_3} + 1.5\mathrm{H_2} \tag{1}$$

or boehmite:

$$\mathrm{Al} + 2\mathrm{H_2O} \rightarrow \mathrm{AlO(OH)} + 1.5\mathrm{H_2} \tag{2}$$

Solid products of the reaction were separated from the solution by filtering and, after drying, examined using X-ray diffraction analysis (Bruker D8 Discover XRD) and thermoanalytical methods (Netzsch TG 209 F1 Iris).

Download English Version:

https://daneshyari.com/en/article/168815

Download Persian Version:

https://daneshyari.com/article/168815

Daneshyari.com