Underwater Microwave Ignition of Hydrophobic Thermite Powder Enabled by Magnetic Encapsulation

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Highly energetic thermite compounds have potential applications in combustion synthesis of various materials and processes, but they are hard to ignite by conventional means. A new technique for ignition of pure thermite powder in air atmosphere, using localized microwaves, was demonstrated recently. This exothermic zero-oxygen-balanced reaction may occur underwater, but due to the hydrophobic properties of the particles the powder tends to agglomerate in the liquid-air surface when contacting with water. Here we present a utilization of the magnetic features of the thermite powder in order to facilitate the penetration of pure thermite into water without a physical contact. The required magnetic field structure is studied, and its implementation in practice is presented. Thermite ignition underwater is demonstrated by localized microwave heating of the thermite batch. The reaction is confirmed by ex-situ XPS analysis. Potential applications of this combustion technique underwater, e.g. for detonation, wet welding, thermal drilling, and material processing, are discussed.

Keywords: Thermite, Localized microwave heating, underwater ignition, combustion.

INTRODUCTION

Self-propagated thermite reactions between metal-oxide and metals typically burn at high flame temperatures, and require high ignition temperature as well. This highly exothermic reaction has inherent zero-oxygen balance and it burns slowly by diffusion mechanism. Therefore, thermite can react in oxygen free environment such as vacuum or underwater, but the powder needs to be packed properly in the challenging environment. The localized microwave heating (LMH) [1, 2] enables to heat objects rapidly by a localized thermal-runaway process [3]. Recently we found that pure thermite powders can be ignited effectively by LMH, in a rapid, stable, and low-cost operation [4, 5]. Thermite reaction as a self-propagated, high-temperature synthesis (SHS) process is utilized for combustion synthesis (CS) applications. The hard materials fabricated are characterized by superior micro-structural and mechanical properties, obtained in low cost, energy saving, and rapid processes [6]. The Microwave energy applied for CS improves the product due to the volumetric heating evolved [7].

Micron sized hydrophobic particles tend to agglomerate in contact with water due to the inter-particle capillary forces. The *liquid marble* is a general term for the structure created by the hydrophobic powder interaction with liquid droplet, in which the particles stick to the liquid-air interface. Magnetic fields are used to manipulate liquid marbles with magnetic powders [8]. Water-in-air powder system can turn into air-in-water foam by changing the air-water ratio [9].

Ignition of hydrophobic thermite powder in oxygen-free environment, such as underwater, is performed today by solidification and coating techniques [10, 11]. Underwater ignition of pure aluminum powder was demonstrated by intense DC current pulse (>100 kA) [12]. Combustion of highly energetic thermite compounds underwater may open new possibilities of material processing. Sintering by combustion synthesis of the thermite powder underwater may involve different features of the constructed material. Specifically, iron oxides (existed on Mars for instance) with aluminum are used by SHS to produce ceramic compounds under vacuum conditions [13]. Underwater propulsion by the thermite reaction can be achieved by gas generation from carbon or boron nanoparticles to produce B_2O_3, CO, CO_2 as in [14]. Underwater detonation, in particular nano-thermite, is likely to be the next generation of explosive materials for military applications [15]. Wet welding in which the water is in contact with the welding zone can be done directly on the requested metal substrate.

MATERIALS AND METHODS

In this paper we present underwater ignition of thermite powder by microwaves, enabled by a static non-homogeneous magnetic-field capsulation, as shown in Fig. 1. The Fe_3O_4-Al thermite system is highly hydrophobic powder with ferrimagnetic features due to the magnetite. Thus, the powder tends to stick to the liquid-air surface to minimize the surface tension free energy (which is stronger than gravity). By adding an underwater static magnetic field in parallel to gravity, the thermite powder is agglomerated into a "bubble" shape by the capillary force and sinks towards the underwater magnetic pole. The radiated microwave signal is absorbed by the thermite in an LMH process which initiates ignition and further self-sustain combustion.

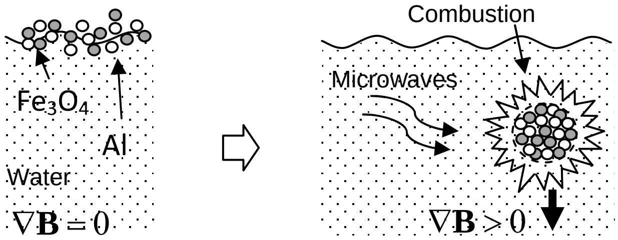

Figure 1. A conceptual illustration of the underwater encapsulation of hydrophobic thermite mixture by magnetic field enabling its LMH ignition.

A large bubble in water has a Bond number $\mathrm{Bo} = L^2/l^2 > 1$, where $L \sim 1$ cm is its typical diameter and $l_c = 2.7$ mm is the water capillary length ($l_c = \sqrt{\gamma/\rho_w g}$ where $\gamma = 72\cdot10^{-3}$ N/m , $\rho_w = 1$ g/cm^3 and $g = 9.8$ m/s^2). Neglecting the surface tension effect, the dominant buoyancy force and the opposing magnetic force induced by an external magnetic field are given by $F_B = (\rho_w V - M)g$ and $F_M = \mu\cdot\nabla\mathbf{B}$, respectively, where V is the bubble volume, M is the mass of the thermite occupied within the bubble, **B** is the magnetic field vector, $\mu = \sigma_m M/S$ is the magnetite's magnetic moment, $S = 1.3$ is the thermite to magnetite stoichiometric mass ratio, and $\sigma_m = 0.1$ Am^2/g is the magnetite's magnetic moment [15]. The minimal magnetic field gradient required to maintain the bubble in equilibrium $F_M = F_B$, is

$$\nabla\mathbf{B} = (f - S)\,g/\sigma_m\,, \tag{1}$$

where the weight ratio between the repelled water and the magnetite is denoted by $f = VS\rho_w/M$, and $\rho_m = 5.26\ g/cm^3$ is the magnetite density.

The experimental setup as presented in Fig. 2 includes a microwave cavity fed by a 2.45 GHz, 0.8 kW magnetron via an impedance analyzer (Homer, S-Team Ltd.) which is used for both to measure and tune the load. The thermite powder is composed of magnetite (Iron Black 318) and aluminum powder (Aluminum-400) with ~45 um and ~37 um particle sizes, respectively. The thermite batch is poured into a cylindrical glass container filled with tap water, with a static magnet bar placed underneath it. The latter induces a magnetic field of $\mathbf{B}=174e^{-0.35x}$ Gauss along the distance x (cm) from its pole, oriented in parallel to the gravity force. The magnetic field intensity is measured by a Hall-probe gaussmeter MG-5DP (Walker scientific). An optical spectrometer (Avantes, Avaspec-3648) in the 200-1000 nm wavelength range (with 0.3 nm spectral resolution) is used to capture the light emitted from the underwater combustion. The measured intensity is calibrated by an AvaLight Deuterium-Halogen light source (DH-BAL-CAL UV/VIS). A high speed camera (SV-643C) with 200 frames per second is used to monitor the process. The combustion products are tested by X-ray photoelectron spectroscopy (XPS) in 2.5×10^{-10} Torr base pressure using an Al K_α monochromated source (1486.6 eV) with sputtering rate capabilities of ~31.5 Å/min by 4 kV Ar^+ Ion Gun.

RESULTS AND DISCUSSION

In this experiment, thermite batches in the range of 0.2-2.0 g are ignited in a 10 mm$^\varnothing$ glass test-tube filled with water, where a static permanent magnet placed underneath it encapsulate the batch and enables its ignition. The initial thermite bubble is formed by applying the maximal magnetic field, and is decomposed by reducing it. The water level variation is used to measure the bubble volume *V*, according to Archimedes' principle. The minimal magnetic field gradient required to hold the bubble is presented in Fig. 3a with respect to the repelled water to magnetite weight ratio *f*.

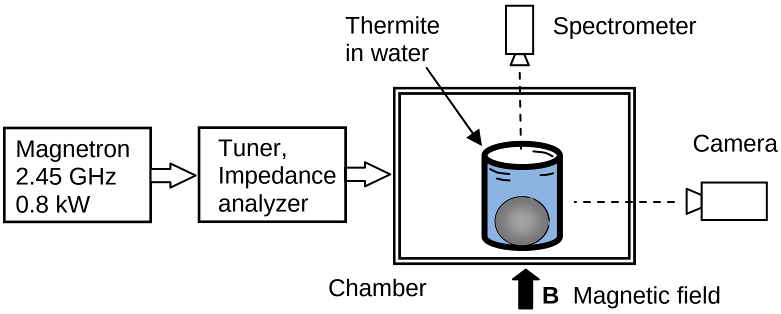

Figure 2. A schematic of the experimental setup utilized to study underwater thermite ignition.

The absorbed microwave energy during the initial heating is presented in Fig. 3b. The ignition occurs at 8.6 s after the microwave signal started (~5 s after the final impedance matching step). The underwater 0.5 g thermite bubble is ignited successively as shown in the inset. The images are captured within ~100 ms time period after the ignition. The initial hotspot ignites the thermite batch and erupts as a mushroom-like flame within the water.

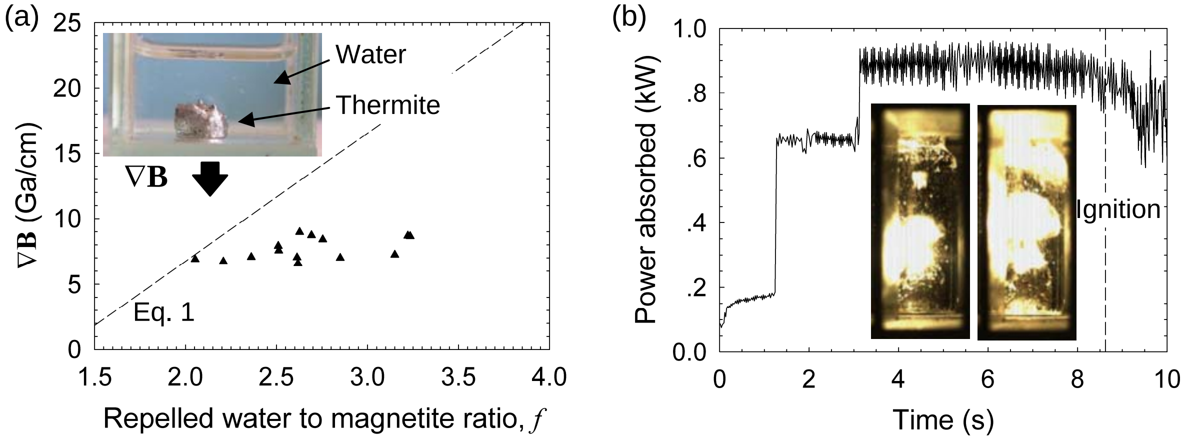

Figure 3. (a) Measurements of the magnetic-field gradient required to encapsulate underwater thermite bubble (as shown in the inset) compared to Eq. 1. (b) The microwave power absorbed and the consequent ignition.

The optical spectrum of the thermite combustion through the water reveals continuum radiation with no atomic lines of iron (as observed at the in air thermite combustion [4]) due to water absorbance. Using Plank's law, the continuum radiation observed fits to a blackbody temperature at ~2100 K. The temperature detected is the lowest in-water flame temperature, due to water cooling. The thermite combustion ejects miniature bubbles towards the glass walls.

The combustion product is a hollow sphere as shown in Fig. 4a. Its surface sphere color reveals the iron-alumina ceramic generated with some small rusty spots. An XPS is taken at this bright surface after removing 0.1 μm thickness by sputtering (30 min), as presented in Fig. 4b. Iron, aluminum and oxygen peaks are observed in the spectral image. The high resolution analysis (0.05 eV/step) reveals the chemical bonding of the materials, indicating that part of the iron is pure and most of the aluminum is oxidized to alumina, as evident by the peak divergence.

Thermite bubble can sustain while the water is frozen into ice, hence alleviating the need for the magnetic-field encapsulation. Frozen ice cubes with thermite bubbles inside are studied as well in this experimental setup. The microwave energy penetrates the ice and heats the thermite up to ignition.

The heat energy from the thermite combustion is transferred entirely to the surrounding environment. For instance, a 1-g batch of thermite provides a *E*=3.67 kJ energy, which can heat up 20 cm^3 water by 43 K. Additive material such as carbon or boron can enhance the gas production, e.g. for propulsion purposes.

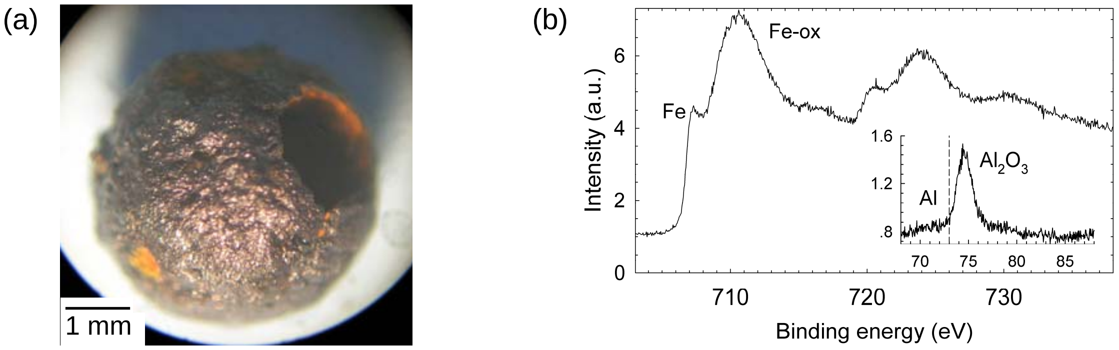

Figure 4. (a) The combustion product generated underwater and (b) its exterior surface XPS analysis.

CONCLUSIONS

Highly hydrophobic pure thermite powder can be encapsulated underwater using magnetic field for the sake of ignition by LMH. The magnetic field shall induce a force larger than the bubble buoyancy and yet weak enough to maintain the ferromagnetic magnetite capillary with the paramagnetic aluminum powder. Once the bubble is formed, it can be maneuvered in the water by varying the magnetic field. The ignition demonstrated here is induced remotely, with no physical contact with the microwave igniter. The latter can be implemented for instance by an open-end coaxial applicator, such as the portable microwave drill [4]. These findings can be used for a variety of applications, such as underwater construction works (e.g. welding, drilling), propulsion, detonation, and CS production of hard materials in oxygen-free environments, such as in space [13], also in a stepwise manner [16].

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