Available online at www.sciencedirect.com

ScienceDirect

Proceedings of the Combustion Institute 36 (2017) 2283–2290

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Tailoring burning rates using reactive wires in composite solid rocket propellants

Sarah Isert [a,*], Colin D. Lane [b], I. Emre Gunduz [a], Steven F. Son [a]

[a] *Maurice J. Zucrow Laboratories, Purdue University, 500 Allison Rd., West Lafayette, IN 47905, USA*
[b] *Department of Engineering Mechanics, United States Air Force Academy, Colorado Springs, CO 80840, USA*

Received 2 December 2015; accepted 22 June 2016
Available online 4 July 2016

Abstract

Tailoring solid propellant burning rates is a perpetual goal of solid propellant designers. Many methods have been used to alter the burning rate including changing the propellant formulation, adding burning rate modifiers, and changing the propellant core shape. Alternatively, metallic fibers such as copper and silver have been added to propellants to increase the burning rate by providing fast heat diffusion paths. However, these metallic wires do not significantly add further to the energetics and have a limited tailoring range. In this paper we describe the effect of embedding mechanically-activated aluminum/polytetrafluoroethylene (Al/PTFE) reactive foils, nickel/aluminum nanofoils and Pyrofuze® self-alloying wire in an AP/HTPB composite propellant. We quantify the resulting burning rate and compare the burning rate to propellants with embedded copper wires. We find that the nickel/aluminum nanofoils and Pyrofuze® wire provide a constant increase in local burning rate regardless of pressure, while the local burning rates of propellants with Al/PTFE foils change as a function of pressure. The Al/PTFE foil is consumed, releasing significant gas, unlike the other materials investigated. The Al/PTFE foil combustion products contribute to the energy and gas production of the propellant, resulting in a propellant efficiency larger than typical wired propellants. While the other materials increase propellant burning rate by causing an increase in surface area and therefore mass burning rate, the aluminum and carbon liberated by the Al/PTFE wire reaction can oxidize with the propellant products and increase the temperature of the combustion gases. Additionally, Al/PTFE or similar reactive wires could result in a decrease in slag production compared to inert and self-alloying wires (i.e., copper, nickel/aluminum nanofoils and Pyrofuze®) and may be better suited to use in propellants due to the high burning rate tailorability and the participation in propellant combustion.

Keywords: Embedded wires; Ammonium perchlorate composite propellant; Enhanced burning rate; Mechanically-activated powder; Self-alloying materials

1. Introduction

Traditional approaches to tailoring propellant burning rates include changing the oxidizer particle size and adding catalysts to the propellant.

---

* Corresponding author.
E-mail addresses: sarah.isert@gmail.com, sisert@purdue.edu (S. Isert).

http://dx.doi.org/10.1016/j.proci.2016.06.141
1540-7489

However, these methods only increase the propellant burning rate up to a certain point and can diminish propellant performance [1,2]. Propellants using novel alternative oxidizers or highly energetic additives could be considered, but may not be suitable due to handling and storage requirements [2,3]. Other approaches are needed to tailor burning rates over a much wider range.

Embedding inert wires into propellants can tailor burning rates, but over a limited range [4–6]. Metal staples cast into propellants provide a low-resistance thermal path for heat flow from the flame into the propellant [1,5,7–11]. Local preheating results in locally faster burning rates and changes the burning surface profile resulting in increased overall mass burning rate. However, inert wires can decrease propellant burning rate and performance [7] and will increase burning rate only if the volume and weight fractions are adequately low [4].

Wired propellants have been used in thousands of fielded sounding rockets and tactical missiles [12]. Embedding wires into a propellant increases burning surface area as the burning surface transforms from nominally flat to cone-shaped [4,10,11,13]. Cones will form if multiple burning rates are present; the fastest burning rate will dominate [14] and the mass burning rate of the propellant is higher than an endburner [13]. Fibers are typically round metallic wires of various diameters, but foils and staples of various thicknesses lengths have also been used [2,6]. They are typically distributed as long strands embedded axially in the propellant or short staples distributed randomly throughout the propellant [1,5], though radial configurations could be considered.

Inert wires considered include copper, silver or silver alloy, steel, tungsten, aluminum, magnesium, low melting point metals plated with high melting point metals, nickel, molybdenum, brass, and platinum [2,3,5,6,9–11,15,16]. Some wires such as aluminum and magnesium can combust with the propellant which is an advantage. Embedded optical fibers have also been used in laser-assisted combustion [17], and Kevlar^{TM} fibers have been observed to act as flame holders [18] and can affect the burning rate. Self-alloying systems such as nickel/aluminum foils [19] or Pyrofuze® (aluminum–palladium core-shell wire) [9] have been proposed for use in propellants, but no results have been presented in the archival literature.

Burning rate enhancement from embedded wires depends on wire thermal diffusivity and melting temperature (both should be high) [1,5,11,16]. For long wires, burning rate increases with increasing wire diameter up to a certain point, after which thermal sink losses become more significant and burning rate decreases [1,4,10,16]. Cross-sectional shape only weakly affects burning rate as long as the length-to-diameter ratio is high [6]. Burning rate increases slightly with staple concentration as the distance between the staples decreases [4,6]. For some propellants the burning rate exponent increased with the addition of the wire [16].

Embedding wires can cause overall performance decrease and lack of burning rate augmentation. Additionally, poor bonding between the fibers and propellant may cause grain cracking [20]. Thermal cycling may cause de-bonding between the grain and fibers [1]. Casting long, straight axial wires can be difficult. Non-uniform wire spacing might provide unintended thrust profiles as the bulk propellants regress [20].

Reactive wires could be fabricated to address some of these drawbacks. Recently, polytetrafluoroethylene (PTFE or Teflon®) particles have been milled into aluminum to form mechanically-activated (MA) composite particles [21]. The milling process produces nanoscale mixing of the components and increased reactivity. The MA powder ignites at lower temperatures than similarly sized neat aluminum particles and burns more completely. Mechanically-activated particle reactivity can be tailored by controlling the inclusion percentage. Though the overall reactivity is altered dramatically, the MA particles remain adequately insensitive to friction, impact, and electrostatic discharge initiation. The powder can be pressed into foils.

The objective of this study is to explore alternatives to inert wires. We examine the burning rates of exothermically alloying nickel/aluminum foils, Pyrofuze® wires, and pressed foils made from MA aluminum/PTFE. The results are compared to propellants with embedded inert copper wires.

2. Methods

2.1. Propellants

Non-aluminized ammonium perchlorate (AP)/hydroxyl-terminated polybutadiene (HTPB) composite propellants with 80 wt% solids loading and a 1:1 bimodal oxidizer size distribution (400 µm coarse AP (Firefox Enterprises) and 20 µm fine AP (ATK)) were used. The binder was R45-M prepolymer (Firefox Enterprises) with Tepanol HX-878 bonding agent (3 M Corporation), icodecyl pelargonate plasticizer (RCS RMC), and Desmodur E744 curative (Bayer Corporation). The propellants were hand-mixed, degassed for 10 min under vacuum, and cast into molds. The burning rate of the baseline propellant was measured to be $2.47 \cdot p^{0.49}$ where p is pressure in MPa.

2.2. Metallic fibers

Four metallic fibers were studied: copper wire, nickel/aluminum foils, Pyrofuze® wire, and aluminum/PTFE foils. The copper wires were 20 gage (0.81 mm diameter). The nickel/aluminum nanofoils (NF80, Indium Corporation) are 80 µm thick and consist of nanoscale alternating layers