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Experimental and numerical modelling of the ignition of solid propellant

R. Charlery [a,c,*], M. Renouf [b], A. Saulot [a], N. Daly [c], Y. Berthier [a]

[a] LaMCoS, University of Lyon, CNRS, INSA Lyon, F-69621 Villeurbanne, France
[b] LMGC, University of Montpellier 2, CNRS, F-34096 Montpellier, France
[c] HERAKLES—SAFRAN Group, 91710 Vert-le-Petit, France

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ABSTRACT

Mixing processes of solid propellants can result in friction. Solid propellant ignitions can be observed under safety tests. Analysing a solid propellant elementary friction test from a mechanical, thermal, and physiochemical point of view, it appears that specific friction conditions allow the emergence of component flows in the solid propellant volume, readying the self-ignition. Numerical simulations of the solid propellant elementary friction test involve discrete elements to model these dynamic behaviours of the components within the contact.

Indeed, comparisons between experiments and simulations are performed on mechanical parameters and on the evolution of the solid propellant components within the contact. Such comparisons exhibit qualitative and quantitative results by validating local parameters (adhesion), which make understand the solid propellant ignition scenario.

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1. Introduction

Solid propellants are very sensitive compounds that explode because of different types of external stresses, such as contact pressure, temperature, shock or shearing [1]. They are used in different applications such as military devices (ammunitions and missiles), space launchers (Ariane 5 boosters and pyrotechnic devices), and automotive safety (inflator for airbag systems) [1].

Various studies have investigated the explosion of energetic materials for its applications. When rubbed against a rotating disk, local heating phenomena, called hot spots, can be observed within the energetic material [2]. These hot spots are mainly due to contacts between solid components contained in the solid propellant [3–5]. These solid components improve the shearing sensitivity of the energetic material when their melting point is higher than the ignition temperature of the energetic material [6]. This is even truer if the stress applied to the energetic material is more intense. To date, laboratory evidence showed that the ignition of an energetic material hardly occurs when it is rubbed between metallic bodies [5]. However, in the reality of industry, some ignition incidents occur when solid propellants are sheared between metallic bodies [7]. Indeed, during the manufacturing process of solid propellants in Twin Screw Extruders (TSEs), the working parts are made of metal: screws are made of a copper–aluminium alloy and barrel elements are made of nitrided steel. TSEs are new continuous mixing devices used to manufacture new energetic solid propellant formulations [8,9].

Thus, with industrial safety concerns, going against laboratory evidence, the issue is to understand how a solid propellant ignites when sheared between two first bodies, whether metallic or not.

To make a step forward in this understanding, a combined experimental/numerical approach has been developed. From an experimental point of view, a pin-on-plate tribometer, called TriboME, has therefore been used to reproduce some of the conditions that favour the ignition of a solid propellant under friction conditions. With this type of device, the solid propellant ignition can be recorded simultaneously in infrared and visible domains and the associated contact forces can also be determined using a bi-axial sensor. Then a numerical approach based on Discrete Element Method (DEM) is used in view to offer or not the confirmation of the solid propellant rheology and to identify the role of local parameters such as cohesion forces and local friction factors between solid components of the solid propellant.

After a description of the TriboME device, the measured friction factor and associated videos of the solid propellant shearing test, the influence of system parameters on the solid propellant ignition is interpreted. Due to these system parameters and after-test

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[*] Corresponding author at: LaMCoS, University of Lyon, CNRS, INSA Lyon, F-69621 Villeurbanne, France. Tel.: +33 4 72 43 72 45; fax: +33 4 78 89 09 80.
E-mail address: rudy.charlery@insa-lyon.fr (R. Charlery).

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observations obtained from this experimental approach, the numerical simulation of this friction test takes place. Results are analysed and compared to experimental ones.

2. Material and methods

2.1. TriboME setup

Coming from the normalised security test Julius Peters [10], the TriboME device is an instrumented pin-on-plate tribometer, Fig. 1, designed to ignite a solid propellant by friction of the pin on the plate.

Because of the transparency properties of the sapphire in visible and infrared domains, the pin is made of sapphire to enable the friction track observation during the friction test. The plate is made of the same different metallic materials as those of screws and barrel elements, contents in the Twin-Screw Mixer device (TSM): nitrided steel and copper–aluminium alloy, in order to be closer to the contact conditions encountered in the TSM.

In the philosophy of the tribological triplet [14] and considering the contact between the pin, the solid propellant and the plate, the sapphire pin and the metallic plate are called *first bodies*. The solid propellant, laid on the plate, is called the *third body*.

A normal force, F_Z, is applied through the pin to the solid propellant with a referenced weight fixed to a lever arm. A force sensor is added under the plate in order to record the normal and tangential forces (F_Z, F_Y) undergone by the solid propellant, as the mobile first body is the plate.

As the aim of the setup is to track solid propellant ignitions (sparkle, explosion or smell and smoke), a test will be called positive if one of these phenomena is recorded, using two high speed-recording cameras simultaneously record infrared and visible videos of the friction test.

Owing to the TriboME device, both tangential and normal forces (F_Y, F_Z) are then measurable during a solid propellant friction test. The referenced weight ($w=10.012$ kg), fixed on the sixth notch of the lever arm (Fig. 1), applies a vertical load F_Z (353 N), characterised by a primary frequency f_z equals to 15 Hz. To highlight the ignition characteristics of the solid propellant in infrared and visible domains (explosion and temperature), suitable cameras are used: the VisionResearch high speed recording camera Phantom V710 (with a frequency of acquisition of 10,000 Hz, a resolution of 240 × 200 pixel and an exposure time of 50×10^{-9} s) and the FLIR infrared camera Jade III MWIR (with a frequency of acquisition of 177 Hz, a resolution of 340 × 260 pixel and an integration time of 20×10^{-6} s).

Due to the addition of this equipment (sensors and cameras) within the TriboME device, it is thus possible to study the preferential mechanical and thermal conditions for a solid propellant ignition.

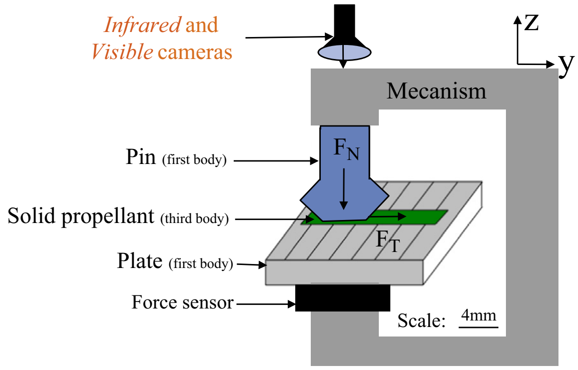

Fig. 1. TriboME device.

2.1.1. Test objectives

After preliminary tests that aimed to define the influencing conditions that favour the ignition of a solid propellant when introduced between two friction first bodies, the following tests are set to highlight these conditions. These depend on:

- The mechanism (the TriboME device): friction acceleration, friction factor, etc…
- The first bodies (pins and plates): the nature of the material.
- The third body (the solid propellant): motions of the solid propellant components.

2.1.2. Test conditions

One cycle test is a one-way sliding motion of 10 mm, applied by the plate (an acceleration–deceleration motion, Fig. 3) and separated into five phases.

2.2. Specimens: First and third bodies

2.2.1. Pin and plate: First bodies

First of all, some solid propellant ignitions are observed in twin-screw extruders [7] that use metallic working parts:

- Barrel elements are made of nitrided steel.
- Screws are made of a copper–aluminium alloy.

In order to study the influence of the mechanism of the TriboME device at its boundary limits on the solid propellant tribological response ($V_{\text{plate max}}=66$ mm s^{-1} and $F_{Z\ \max}=353$ N), metallic first bodies are also used in this study (Fig. 2a–d).

Next, the standard NF T 503 70 fixes the geometries and the dimensions of the porcelain first bodies [10], Fig. 2e and f. These first bodies are the reference ones because all the energetic materials are tested with these ones in the literature [1,10]:

- striated porcelain plate: 25 mm long, 25 mm width and 5 mm thick
- striated porcelain pin: radius of $R_y=5$ mm and a radius of curvature of $R_z=10$ mm

Metallic specimens are machined from the same materials as the working parts of the twin-screw extruder. Both dimensions and geometries are the same as those made of porcelain, except for the plate width:

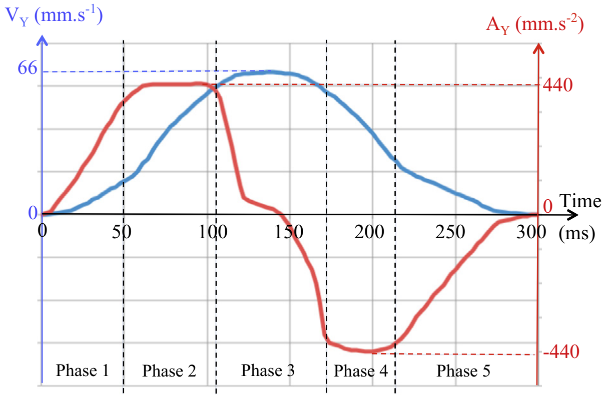

Fig. 2. Plate speed (*VY*) and plate acceleration (*AY*) variations on the TriboME device.

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