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Grit-mediated frictional ignition of a polymer-bonded explosive during oblique impacts: Probability calculations for safety engineering

Eric Heatwole*, Gary Parker, Matt Holmes, Peter Dickson

Los Alamos National Laboratory, WX-6, Los Alamos, NM 87545, USA

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ABSTRACT

Frictional heating of high-melting-point grit particles during oblique impacts of consolidated explosives is considered to be the major source of ignition in accidents involving dropped explosives. It has been shown in other work that the lower temperature melting point of two frictionally interacting surfaces will cap the maximum temperature reached, which provides a simple way to mitigate the danger in facilities by implementing surfaces with melting points below the ignition temperature of the explosive. However, a recent series of skid testing experiments has shown that ignition can occur on low-melting-point surfaces with a high concentration of grit particles, most likely due to a grit–grit collision mechanism. For risk-based safety engineering purposes, the authors present a method to estimate the probability of grit contact and/or grit–grit collision during an oblique impact. These expressions are applied to potentially high-consequence oblique impact scenarios in order to give the probability of striking one or more grit particles (for high-melting-point surfaces), or the probability of one or more grit–grit collisions occurring (for low-melting-point surfaces). The probability is dependent on a variety of factors, many of which can be controlled for mitigation to achieve acceptable risk levels for safe explosives handling operations.

1. Introduction

Polymer-bonded explosives (PBXs) are composite materials consisting of an energetic crystalline solid mixed with a polymeric binder. PBXs are typically pressed at high pressures to form consolidated, high-density billets with properties amenable to precision machining. The use of compliant polymeric binders also frequently improves safety by reducing ignition sensitivity to impact stimuli. The resulting PBX parts are often integrated as energetic components in weapons, or for other applications where tight dimensional tolerance and geometric complexity are required.

During operations at facilities where PBX charges are handled, there exists the potential for high-consequence accidents. Of particular concern are oblique impacts where a PBX part is dropped onto a surface at an off-normal incident angle resulting in frictional heating from the bulk translational motion of the explosive against the impact surface. On its own, simple friction of the PBX against a clean surface does not produce sufficiently high temperatures on a relevant timescale to cause ignition [9]. The risk for frictional interactions causing ignition is drastically enhanced, however, by surface contamination with high-melting point grit particles. If the grit becomes embedded in the explosive upon contact, it will translate across the impact surface, and the interaction of these two high-melting point materials can cause rapid localized heating. Recently, much effort has gone into (1) understanding the physics of hot spot formation and ignition during these types of accidents; (2) probabilistic risk assessment; and (3) developing appropriate mitigation strategies for these risks. These are the motivations for the work presented in this article.

2. Background

Research by Bowden and Ridler [3] conclusively showed that, during frictional interactions, surface heating is limited to the lower melting point temperature of the two interacting materials. Following the onset of melt, a thin fluid layer forms and lubricates the interface causing frictional force and work to decrease. For most secondary explosives the melting point of the explosive is typically too low to cause ignition on the timescale of a glancing impact event before bouncing occurs and contact ceases (typically 1–1.5 ms). Above a minimum ignition temperature, the time to ignition, t, for HMX-based explosives is directly related to temperature by

* Corresponding author.
E-mail addresses: heatwole@lanl.gov (E. Heatwole), gparker@lanl.gov (G. Parker), mholmes@lanl.gov (M. Holmes), dickson@lanl.gov (P. Dickson).

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$\log(t) \propto 1/T$ [9]. In order for ignition to occur on the timescale of an impact event (~1.5 ms), temperatures in excess of around 600 °C are required; this is significantly higher than the melting temperature of PBX 9501. The lower temperature hot spots will cool and quench when the surfaces lose contact on bounce.

However, ignition has been observed when low-melting point PBX charges experience oblique impacts on high-melting point surfaces [1]. An explanation for how kinetic energy is converted to high-temperature hot spots can be had from early research done by Taylor and Weale [11] who observed explosive sensitization when grit was present, though they attributed the effect to a tribochemical mechanism. Later work by Bowden and Gurton [2] clarified the mechanism by linking ignition to grit-heating. These researchers showed that frictional heating of explosives on clean, high-melting point surfaces did not cause ignition, but with the introduction of loose, hard, high-melting point grit particles ignition was frequently observed. The mechanism for heating and ignition was determined to be the frictional interaction of the high-melting point grit contaminate against the high-melting point surface; the grit became sufficiently hot, rapidly enough to form a critical hot spot [8] in the surrounding explosive and ignition ensued. Building upon these conclusions, Dyer and Taylor [7] demonstrated, once again, that grit–substrate friction was an important mechanism for ignition in pressed and cast explosives. They also proposed grit–grit interactions as another plausible source of frictional heating in their experiments. So long as there was a possibility for any two high melting point materials to rub against each other in the presence of an explosive the conditions for ignition could be met. Recent work investigating oblique impacts with a polymer-bonded explosive designated as "PBX 9501" (95% wt. HMX, 5% wt. plasticized Estane™) has provided evidence that the grit–substrate mechanism dominates on high-melting point, grit contaminated surfaces, such as sanded glass [10,5,4].

With this knowledge some seemingly obvious protective measures could be taken to reduce the probability of grit-mediated ignition while handling explosives over high-melting point surfaces (e.g., concrete floors). These might include use of low-melting point surface coverings (e.g., floor mats and plastic coatings) and housekeeping practices to maintain surface cleanliness. Following this reasoning, it was deemed valuable to test the efficacy of a low-melting point surface covering, as well as gather data to help define cleanliness standards for operational surfaces in terms of areal grit-coverage density (i.e., particles per unit area).

This paper presents a subset of recent experimental results obtained from an oblique impact testing program where PBX 9501 was impacted into grit contaminated high- and low-melting point substrates and where ignition was observed [10]. The primary focus of this paper is to describe a method for probabilistic risk assessment that can be used to justify a mitigation strategy (based on the areal grit coverage density) for frictional ignition mechanisms involving grit heating.

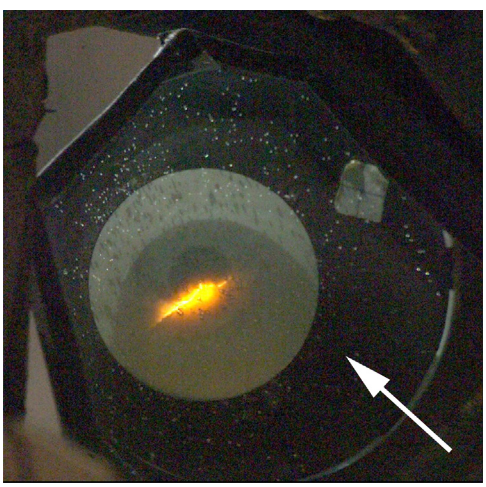

Fig. 1. Still frame from high-speed video showing the polycarbonate–PBX interface during an oblique impact into a stationary heavily sanded polycarbonate target. Ignition, with flame spread into a crack, is seen. The arrow indicates the direction of travel for the PBX.

3. Experimental setup

The oblique impact experiment, frequently referred to as a "skid test", uses a rigid-arm pendulum (Fig. 4) to deliver explosive

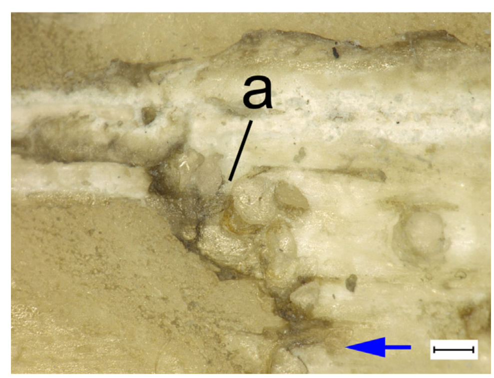

Fig. 3. Higher magnification micrograph of the PBX 9501 surface shown in Fig. 2. A grit–grit collision site (a) is evident. The arrow indicates the direction of travel for the PBX. The scale bar has a length of 250 μm.

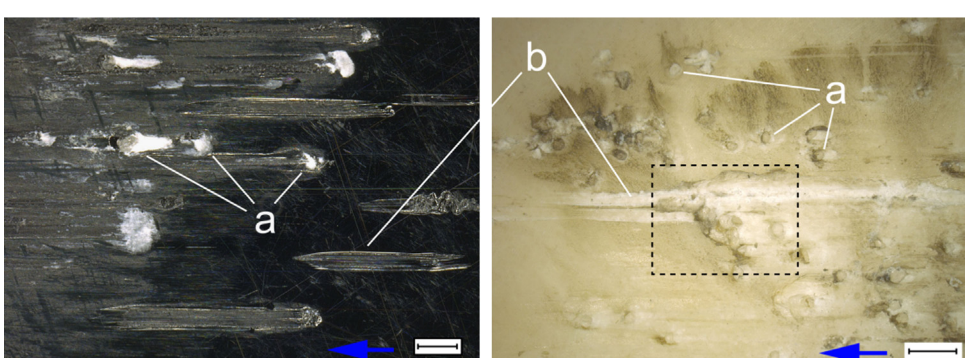

Fig. 2. Micrographs of the surfaces of polycarbonate (left) and PBX 9501 (right) after impact. The polycarbonate was heavily sanded (particle size range of 150–250 μm). Embedded grit particles (a), as well as gouged tracks (b), are evident in both materials. The dashed box surrounds a grit–grit collision site and is shown with higher magnification in Fig. 3. The arrows indicate the direction of travel for the PBX. The scale bars have lengths of 500 μm (left) and 1000 μm (right).