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A simplified model for ballistic initiation of thin energetic targets by micro-flier impact

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ABSTRACT

Novel techniques involving high-speed impact (~500–1500 m/s) of laser generated micro-fliers with thin metallic targets having a layer of reactive solid deposited on their back side (~10–100 μm) are being developed to interrogate its shock-induced chemistry. Because mass spectrometry is performed in vacuo on the reactive side of the target to identify the chemical species produced, it is important to initiate chemistry without perforation of the target plate by the flier. An analytically tractable model is formulated in this paper to guide experimental development by predicting the ballistic response of large numbers of micro-flier–target configurations in a computationally inexpensive manner. The model is posed in terms of multi-component conservation principles and interaction terms that account for important features of both the early-time wave mechanics and the longer-time target deformation mechanics including flier–target adhesion. The model, validated using published data for larger scale inert flier–target configurations, is used to predict the response of micro-scale configurations consisting of aluminum fliers and steel targets. Scanning Electron Microscopy (SEM) of post-impact, inert flier–target micro-scale configurations is used to both highlight target deformation and damage and to motivate modeling simplifications. To illustrate the model, configurations that result in initiation (detonation) of the high-explosive PETN ($C_5H_8N_4O_{12}$) without perforation of the steel substrate are parametrically characterized in the form of ballistic initiation maps based on its empirical critical shock energy.

1. Introduction

Small-scale (benchtop), high-speed micro-flier experiments are being developed to experimentally interrogate the shock-induced detonation chemistry of small amounts of reactive energetic solids. As illustrated in Fig. 1, researchers at the Air Force Research Laboratory are using a 20 mW fiber-coupled 532 nm YAG laser to propel aluminum fliers ablated from a thin sheet of foil at speeds of 500–5000 m/s into a stationary metallic target plate that has a thin layer of reactive material deposited on its back side. The axi-symmetric configuration consists of a layer of 2024-T4 aluminum foil that is plated onto a glass substrate, a stainless steel mask that separates the flier (formed from the aluminum foil) from a 304 stainless steel target foil plate, a second stainless steel mask that clamps the target plate in place, and an energetic sample. The target plate is clamped at an approximate diameter of 3 mm about the centerline to minimize its effect on the early time impact response. Other representative dimensions are given in the figure.

In the experiment, the laser pulse is fired through the glass substrate which heats, ablates, and propels the roughly circular flier from the plated aluminum foil through the free space of the mask; flier thicknesses are typically 10–50 μm. The flier subsequently impacts the stainless steel target plate, and an impact shock is transmitted to the energetic sample which is situated in a vacuum chamber so that Time of Flight Mass Spectrometry (TOF-MS) can be used to interrogate its shock-induced chemistry. Fig. 2 gives an image of a post-impact target foil and aluminum plated-glass substrate, and an assembled target “coupon.” Each hole-dimple pair seen in the coupon is the result of a single experiment. A target coupon is large enough to allow multiple experiments to be quickly performed in succession, and the impact sites are adequately spaced to minimize interactions between experiments.

To guide development of experiments and assessment of data, it is necessary to characterize both the mechanics of flier–target impact and the energy transmitted to the reactive solid; if sufficient, this energy can initiate detonation of the solid. It is also desirable that the flier not perforate the target plate to prevent contamination of the vacuum chamber used with TOF-MS. The impact response is complex, and is influenced by the initial flier velocity, the flier–target geometry and material properties, and the flier–target impact angle. Mathematical modeling can be used to

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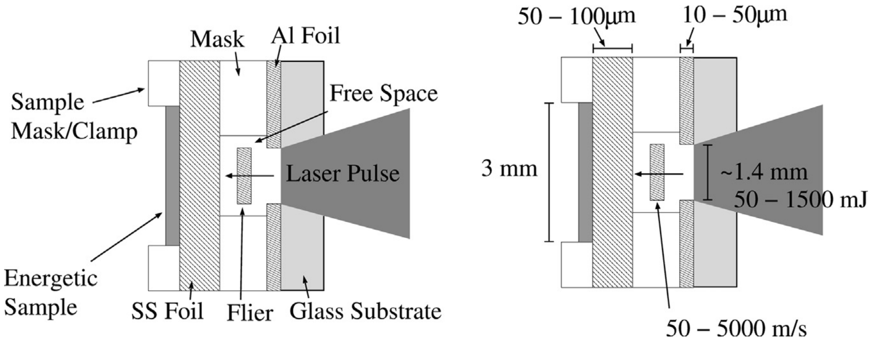

Fig. 1. Schematic of a laser-driven micro-flier and target configuration (not drawn to scale).

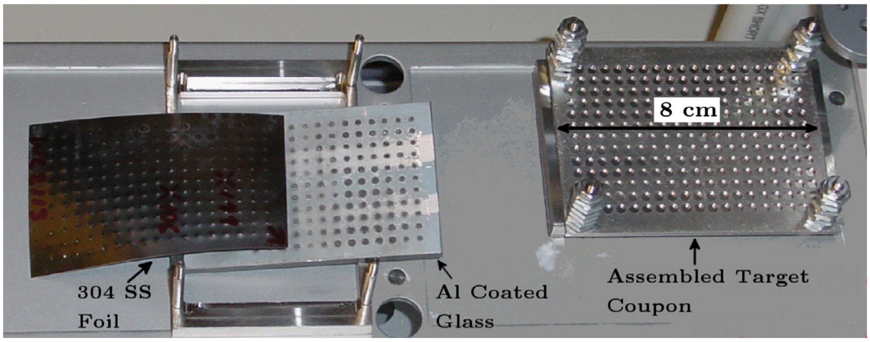

Fig. 2. Pictures of micro-flier and target coupons: (left) post-impact aluminum coated glass substrate and stainless steel foil, and (right) pre-impact assembled flier–target coupon.

describe this response, though choosing an appropriate level of physical and computational complexity depends on the information sought. The goal of this study is to formulate an analytically tractable model that can provide accurate and computationally inexpensive predictions to parametrically characterize micro-flier–target configurations that result in initiation without perforation of the target by the flier. The model should minimally account for the early-time wave mechanics important for flier deceleration and initiation, and the longer-time target plate deformation mechanics important for penetration and perforation. Predictions expressed in the form of *ballistic initiation maps* can enable researchers to characterize key system parameters and to quickly identify candidate configurations over a large parameter space for preliminary design and assessment. These maps can be expressed in terms of controllable parameters such as flier and target thickness, and initial flier velocity (based on laser energy). Though rigorous multi-dimensional and multi-material models could be posed and computationally solved, they would restrict the analysis to narrow regions of parameter space because of computational overhead and would be an unnecessary overkill for preliminary design and assessment. Simplified models can be used to identify candidate configurations over a large design space for more refined analysis in the future. These models can also be used to efficiently characterize the effects of stochastic variations in input parameters on ballistic initiation [1].

Literature addressing the penetration, perforation, and failure of impacting bodies is voluminous (see Refs. [2–6] and the references cited therein); for brevity, only literature that is most relevant to this study is reviewed here. Modeling studies vary in complexity and consist of both analytical and computational approaches. Analytical expressions have been formulated for projectile impact on flat plates to estimate quantities such as penetration depth, ballistic limit, and residual velocity. Some expressions are based on simple descriptions of impact phenomena including the bending and shear plugging of target plates [7–11], while others are based on quasi-static approximations for punch loaded plates [12,13]. Though these expressions often give reasonable estimates, they are typically restricted to low impact speeds and do not account for early-time wave mechanics. Noteworthy is the model formulated by Heyda et al. [14], that accounts for early-time wave mechanics but uses a particularly simple description of target strength that limits its applicability. More recent studies, such as that of Borvik [15], have implemented rigorous constitutive theories into multi-material finite-element codes which require extensive material testing to properly establish values for material and process-dependent parameters. Experimental studies have also been performed to analyze the impact response of large flier–target configurations [15–18] (i.e., flier and target thicknesses of $\sim$10–100 mm). These studies provide data on the time response, ballistic limit, and residual velocity associated with blunt projectile impact on clamped plates. Correlations between quasi-static punch experiments and ballistic behavior have also been experimentally studied by Gama et al. [19]. These studies, which will be discussed later, provide data to validate our model.

Most published studies on laser driven fliers have either addressed novel applications or have used various experimental techniques to characterize ablative formation of micro-fliers from foils [20–26]. Emphasis is often placed on examining the thickness, planarity, and integrity of fliers during flight prior to impact. Of particular relevance to this study is the work of de Rességuier et al. [27] (discussed later), which characterized the dynamic response of small laser-driven fliers during impact on planar targets using a Velocity Interferometer for Any Reflector (VISAR) technique. Laser driven fliers have also been used to simulate hypervelocity impact of space debris on polymer and glass targets, and to qualitatively characterize the damage produced [28,29]. Though these studies may collectively provide insight into the formation and impact of laser-driven fliers, modeling their penetration and perforation of targets has received little attention to date.

The model formulated in this study accounts for both the early-time impact shock physics and the quasi-static strength of clamped plates. Initiation of the energetic solid is based on its empirical critical shock energy threshold. It is important to note that establishing such