Laser-driven flyer plates for shock compression spectroscopy

W L Shaw, A D Curtis, A A Banishev and D D Dlott
School of Chemical Sciences, University of Illinois at Urbana-Champaign, 600 S. Mathews Ave., Urbana, IL 61801

1E-mail: dlott@illinois.edu

Abstract. A laser-driven mini flyer plate system, with 8 GHz photon Doppler velocimeter and high-speed spectroscopic diagnostics, was developed for shock compression spectroscopy. The properties of the flyer plate platform are discussed, and its use in two applications is reported. The two applications were impact initiation of nanotechnology reactive materials and molecular optical emission sensors to monitor mesoscale effects in a shock-compressed polymer.

1. Introduction
Laser-driven flyer plates are a convenient tool for shock compression spectroscopy on a tabletop [1]. Here we describe our laser-driven flyer apparatus with photonic Doppler velocimeter (PDV), and we discuss two applications: impact initiation of nanotechnology reactive materials, and embedded emissive molecular probes to study mesoscale dynamics.

The laser launcher makes it easy to do a lot of shots in a short time. We frequently do 100 shots or more in one afternoon. However there are several well-known issues with laser flyer plates that need to be overcome for precision measurements [2]. When a thin foil is launched by a short-pulse laser with an inhomogeneous beam profile, the state of the flyer and the flyer Hugoniot may be uncertain due to laser heating and reverberating shocks in the flyer. The impact may not be flat and the flyer might not have a single velocity. The shock durations are ns rather than µs, as with guns or explosive charges.

We have studied flyer launch and impact processes, with the goal of creating a shock compression science platform with controlled impact velocities and shock durations. We have simplified the apparatus, to increase usefulness and convenience [1].

2. Flyer plate launcher
The experimental apparatus [1,3-4] is diagrammed in figure 1. The Nd:YAG laser (2.5 J in 10 ns) was a Quanta-Ray Pro 350 from Newport Corp. To improve beam shaping, the laser was constructed with flat cavity mirrors to create a stable oscillator with many cavity modes and poor beam quality ($M^2 = 40$). The poor-quality 12 mm diameter output profile is shown in figure 2. After the laser passed through a Faraday isolator (Electro Optics) and high-power electronic shutter (NM Laser), a telescope expanded the beam to 150 mm. The diffractive beam shaper was provided by Silios. A 150 mm focal length precision bestform lens (Thorlabs) focused the beam to 700 µm in diameter, and at that point the beam had a uniform profile (figure 2). We recently added an all-reflective 2X pulse stretcher based
3. Flyer plate launch and impact dynamics

PDV was used to study flyer launch across a 375 μm gap to impact a glass window, by monitoring the flyer front surface with PDV as in figure 1. Representative data with 100 μm thick Al flyers at 1.5 km s⁻¹ are shown in figure 5. The acoustic round trip time in these flyers was ~32 ns, so with 10 ns and 20 ns pulses this was sufficient to detect flyer speeds. With 10 μm thick flyers the measurements were done with 20 ns pulses, so we used a modified detection scheme with more digitization time. With a 20 GHz digitizer, 20 ns pulses could detect flyer speeds of 0.5 km s⁻¹.

Figure 1. Laser flyer spectroscopy apparatus. Key: PDV = photonic Doppler velocimeter; DBS = dichroic beam splitter, PMT = photomultiplier; MO = microscope objective. Reproduced with permission from reference [1], copyright 2012, AIP.

Figure 2. Launch laser pulse spatial and temporal profiles. Diffractive optics convert the irregular output beam to a tophat.

Figure 3. Velocities of different thickness Al flyer plates as a function of launch laser fluence.

Figure 4. Velocities of 25 μm thick flyers launched from Al foil, and cut out (relief) flyers. Reproduced with permission from reference [1], copyright 2012, AIP.

on reference [5]. Removing or replacing the beamsplitter in the pulse stretcher allowed a quick switch from the stretched 20 ns to the 10 ns pulses (figure 2).

The PDV apparatus [1] was based on a design by Weng [6], with a modified probe. After the 1.55 μm beam exited a single-mode fiber, it was collimated to 800 μm diameter and focused to 70 μm with a 10X microscope objective. The PDV used a 20 GHz detector and an 8 GHz digitizing oscilloscope.

Al flyer plates were launched from 5/8” thick heat-resistant glass substrates (McMaster). Foils (Alufoil) 25-100 μm thick were glued to 2”x2” substrates using low-viscosity epoxy (Eccobond 24, Emerson and Cummings). We could launch 30-40 flyers from each foil/substrate assembly. Figure 3 shows flyer speeds as a function of laser fluence. With 1.9 J pulses at the sample and 700 μm diameter spots, the maximum fluence was 500 J cm⁻². The highest flyer speeds of 4.5 km s⁻¹ were obtained with 25 μm flyers. Usually the laser beam punched out disks from the foil, but at the lowest laser fluences the flyers sometimes did not punch out well. In those cases we used cutout flyers that were mass-produced using electrical discharge machining create 700 μm reliefs by eroding the foil around the disks, as shown in figure 4. With cutouts we could launch at speeds below 0.1 km s⁻¹ [1].
ns pulse durations, the launch was impulsive. Instead of accelerating the flyers gradually, the launch created reverberating shocks within the flyers, producing drumhead motions of the flyer front surface superimposed on the center-of-mass motion (figure 5).

The PDV data in figure 5 show sudden acceleration at \( t = 0 \) with superimposed oscillations. When flyers impacted glass, there was a sudden velocity drop followed by a constant-velocity plateau. This plateau represents the motion of the flyer/target interface at speed \( U_{ip} \), the particle velocity in the target. Subsequently the interface speed drop consisted of two parts, a faster drop of a few ns and a slower drop of 20-30 ns. The plateau duration \( \tau_s \) was 20 ns. A plateau is shown on expanded scale in figure 5b. The 20 ns duration plateau is significant. It proves that flyer/target impact was flat and shocks in the target were steady and fully-sustained for at least 20 ns. Of course the shock continued to propagate at constant speed well past 20 ns, until the rarefaction wave from the back of the flyer reaches the shock front. According to a model devised by us, when the flyer plate impacted the target the plateau duration \( \tau_s \) was the time for the backward-propagating shock in the flyer to reach the flyer/plasma interface.

The magnitude of the sudden velocity drop upon impact can be computed knowing the flyer and target Hugoniot [7]. In many applications such calculations are crucial, when experimenters know the flyer plate speed but not the interface speed \( U_{ip} \), and in such cases lack of knowledge of the flyer Hugoniot would be a serious problem. The shock properties of laser-launched Al foils are not known precisely, but since we measured \( U_{ip} \) directly, we did not need to know the flyer Hugoniot with great accuracy.

It is important to know with certainty that flyer drumhead motions were damped out prior to impact. In figure 5b, for instance, the drumhead velocity on the first reverberation was more than 0.4 km s\(^{-1}\). Figure 5b also shows that these motions have damped out almost entirely prior to impact. In fact the 375 \( \mu \)m gap was selected for this reason. The damping mechanism presumably involved shock energy conversion into heat and into defects in the flyer material. An interesting phenomenon was observed in figure 5a, where the thickest flyer was launched with the shortest pulse. In that case reverberations would be expected to be the worst. After the first maximum there was an unexpectedly efficient damping process, so the ringing damped out even faster than in figure 5b. Thus the damping was associated with the arrival of the reverberating shock at the back surface of the flyer, the flyer/plasma interface. We do not have a complete explanation for the damping but we propose the mechanism depicted in figure 5. The drumhead motion of the rear surface generates a backward-moving shock in the launch plasma, either directly or by spallation of flyer material. The backward shock carries away the drumhead energy.

4. Impact initiation of reactive nanomaterials

Aluminum and Teflon nanocomposites are useful multifunctional reactive materials [8]. Al/Teflon is an extraordinarily energetic material that can release energies in the 15-20 kJ cm\(^{-3}\) range (2-3 times the energy of trinitrotoluene, TNT), while reacting at 3300K [8,9]. In a bit of oversimplification, the chemical reaction can be described as [3,8],

![Figure 5.](image-url)
where Al is the fuel and F the oxidizer. Our studies [3] looked at 12 μm layers of near-stoichiometric mixtures of 50 nm oxide-passivated core-shell Al nanoparticles and 3 μm Teflon powder (DuPont Zonyl MP1200), with a small amount of PMMA binder (PMMA = poly-methyl methacrylate). Control measurements were made on polymer-bonded Teflon particles without Al, solid Teflon foils, and Al without Teflon.

Figure 6 plots the wavelength and time-integrated emission intensities of Al/Teflon after impacts with 50 μm thick Al flyers [3]. The two Teflon only samples emitted weakly. When the flyers were 1 km s\(^{-1}\) and above, the Al/Teflon emission increased explosively.

Two questions about the mechanism: what is the initial chemical step, and how do the Al particles depassivate? When the shock arrived, it initially heated more-compressible Teflon to a greater extent than less-compressible Al. With Teflon impacted above 0.75 km s\(^{-1}\), we observed emission from excited C\(_2\) molecules, proving that Teflon decomposed into carbon and fluorine below the explosion threshold [3]. The inset to figure 6 shows emission and PDV data on Al/Teflon with 1.75 km s\(^{-1}\) impact. During impact, the emission intensities were similar for Teflon alone and Al/Teflon. But just as the flyer velocity dropped to zero, explosive emission appeared from Al/Teflon. This coincidence shows that Al nanoparticles became depassivated and react explosively with the fluorine produced by Teflon decomposition when the shock unloads and the particles come under tension. Apparently tensile forces cracked open the oxide layers [3]. Thus laser flyer plate spectroscopy revealed the fundamental mechanisms of impact initiation of this reactive material.

5. Molecular optical emission sensors to monitor mesoscale effects

In these experiments, we used PDV to detect shocks in a polymer and an embedded emissive molecular sensor to detect local dynamics. The sample was R590 dye in 8 μm thick PMMA, deposited on top of a much thicker impedance-matched substrate. Similar to R640 used in earlier works [4], but with more intense emission, the R590 emission redshift was sensitive to local density. Using the arrangement in figure 1, the dye molecules were excited continuously, and time-dependent emission spectra were monitored with a spectrograph and streak camera. We
determined emission peak redshifts by computing the first moment of each spectrum [1,4].

Figure 7 shows a representative result. A 100 μm thick flyer was launched at 1.1 km s\(^{-1}\) at a thin (8 μm) PMMA/dye layer deposited on top of an impedance-matched substrate. The interface velocity \(U_p = 0.9\) km s\(^{-1}\), which corresponds to 4 GPa. During the steadily-driven part of the shock, the emission redshift increased to a maximum of 32 nm. During the interface velocity decrease, the redshift remained static. After the flyer stopped, the redshift decayed in two parts, with an initial decay constant of ~50 ns plus a long-lived plateau. Clearly the dye response reported processes not seen in PDV. The nature of the slower dye response is related to large-amplitude polymer relaxation mechanisms [10].

**Acknowledgements**

The research described in this study was based on work supported by the US Army Research Office under awards W911NF-10-1-0072 and W911NF-13-1-0217, the US Air Force Office of Scientific Research under award FA9550-09-1-0163, the Defense Threat Reduction Agency under award HDTRA1-12-1-0011, and Office of Naval Research award N00014-12-1-0828. William L. Shaw acknowledges support from the Stewardship Sciences Academic Alliance Program, Carnegie-DOE Alliance Center, under award DE-NA0002006.

**References**

[1] Brown K E, Shaw W L, Zheng X and Dlott D D 2012 *Rev. Sci. Instrum.* **83** 103901
[2] Swift D C, Niemczura J G, Paisley D L, Johnson R P, Luo S-N and Tierney IV T E 2005 *Rev. Sci. Instrum.* **76** 093907
[3] Zheng X, Curtis A D, Shaw W L and Dlott D D 2013 *J. Phys. Chem.* **C** **117** 4866-75
[4] Brown K E, Fu Y, Shaw W L and Dlott D D 2012 *J. Appl. Phys.* **112** 103508
[5] Khare R and Shukla P K 2010 Temporal stretching of laser pulses *Coherence and Ultrashort Pulse Laser Emission*, ed F J Duarte (Rijeka, Croatia: InTech)
[6] Weng J, Wang X X, Ma Y, Tan H, Cai L, Li J and Liu C 2008 *Rev. Sci. Instrum.* **79** 113101
[7] Forbes J W 2012 *Shock Wave Compression of Condensed Matter. A Primer* (New York: Springer)
[8] Koch E-C 2012 *Metal-Fluorocarbon Based Energetic Materials* (Weinheim, Germany: Wiley-VCH)
[9] Densmore J M, Biss M M, Homan B E and McNesby K L 2012 *J. Appl. Phys.* **112** 084911
[10] Kim H, Hambrir S A and Dlott D D 1999 *Phys. Rev. Lett.* **83** 5034-7