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FLYER VELOCITY CHARACTERISTICS OF THE LASER-DRIVEN MINIFLYER SYSTEM

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Abstract. The laser-driven MiniFlyer system is used to launch a small, thin flyer plate for impact on a target. Consequently, it is an indirect drive technique that de-couples the shock from the laser beam profile. The flyer velocity can be controlled by adjustment of the laser energy. The upper limits on the flyer velocity involve the ability of the substrate window to transmit the laser light without absorbing, reflecting, etc.; i.e., a maximum amount of laser energy is directly converted into kinetic energy of the flyer plate. We have investigated the use of sapphire, quartz, and BK-7 glass as substrate windows. In the past, a particular type of sapphire has been used for nearly all MiniFlyer experiments. Results of this study in terms of the performance of these window materials, based on flyer velocity are discussed.

INTRODUCTION

Pulsed lasers have been used extensively to generate short duration shock waves, including investigations of spall[1,2], detonation of explosives[3], high pressure generation[4], and thin film/coating bond strength measurements[5]. Laser generated shock techniques offer several advantages, including low cost, high shot throughput, and simplified experimental apparatuses. However, these are countered by the requirement for thin samples, complicated laser generated plasma physics and heightened resolution requirements for experimental diagnostics.

In this work a laser is used to launch a 0.05 mm by 3.0 mm diameter copper flyer plate to terminal velocities up to 0.65 km/s. Flyer plates are attached to substrate windows with several microns of adsorbed material sandwiched between for absorption, buffering, and insulation. Unlike direct laser-generated shock techniques laser-launched plates detach plate launch from plate impact. Therefore, the shock generated in the target is de-coupled from laser deposition and buffered from discontinuities in the laser beam profile.

The MiniFlyer has been used to determine spall strengths of target materials and generate Hugoniot data when coupled with velocity interferometry[6,7]. Our goal is to improve conversion of the laser energy into kinetic energy of the flyer plates (achieve higher flyer plate velocities), maintain flat flyer plates (for one-dimensional impact) and understand any change of state of the flyer plate prior to impact. We report the laser energy/flyer velocity relationship as a function of substrate material (launching window material). We also include effects which the various window materials have on flyer plate acceleration and ring

EXPERIMENT

Flyer plates are launched with a single shot Nd:Glass laser that produces a pulse of ~ 20 ns (FWHM) duration and 1.054 micrometer wavelength. A maximum of 5 joules was used for all shots reported here. (At higher energies the laser's Q-switch leaked creating a >0.1 ms long pulse prior to the Q-switched pulse, which yielded lower flyer velocities and unpredictable results.) The launch laser beam is directed through a lens and diffractive optical element (Mems Optical Inc., Huntsville AL) and finally onto the rear of the substrate window.

Digital images of the beam at the position of incidence on the substrate were collected and analyzed.(Beamcode, Coherent Laser Inc.) Two cross-sectional views of the beam profile are shown in figure 1. Just over 80 % of the energy is inside a 3 mm diameter.

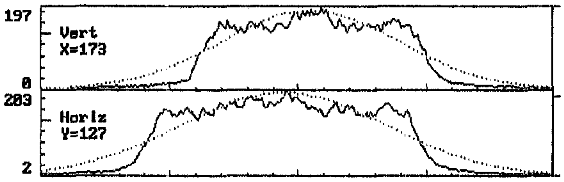

FIGURE 1. Vertical and horizontal cross-sections through the laser beam at the position of incidence on the substrate window. Analysis of the profile indicates approximately 80% of the beam is within a 3 mm diameter.

Four different windows were used in this study: 1) sapphire (Saphikon Inc. NH USA, part # 15959), 2) fused silica, (Heraeus Amersil, part # 27385), 3) High grade BK-7, (Rocky Mountain Instrument Products, CO USA part # WI1901K), and 4) Low grade BK-7, (Esco Products, NJ USA part # P907063). The windows were coated with the following sequential layers: 5,000 Å of carbon, 5,000 Å of aluminum oxide, and finally with either 5,000 Å or 50,000 Å of aluminum. Copper flyers were purchased in 0.05 mm sheets from Goodfellow (OFHC @ 99.95+%) and cut into 3 mm diameter rounds. The flyers were then glued to the substrate windows with the deposited material sandwiched between.

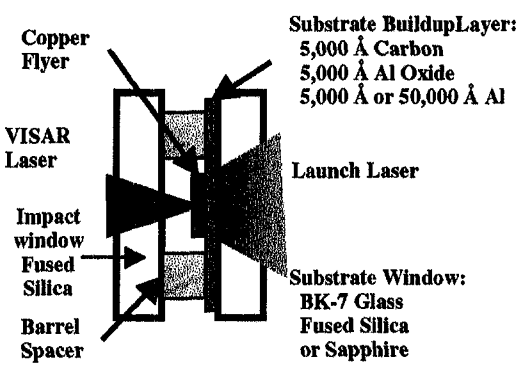

FIGURE 2. Un-scaled schematic of the substrate/flyer assembly prior to firing

The flight path was controlled by placing a spacer (0.125 mm) between the substrate window and the impact window (figure 2) yielding a total flight path of 0.075 mm. All shots were fired in air.

Two Velocity interferometers (VISAR), Valyn International (model VLNV-04), were used to record the velocity profiles. A Coherent Verdi laser was used as the VISAR source and was focused to a spot size of approximately 0.1 mm with 0.1 to 0.2 W of incident energy.

RESULTS AND DISCUSSION

A typical measurement of the flyer velocity versus time is shown in figure 3a. (The result from only one of the two VISARs is shown, since the result determined with the other VISAR agrees with this plot to within 3%.) In this case the window material is high grade BK-7 and the aluminum coating is 5000 Å thick. It is seen that the flyer undergoes a rapid initial acceleration, followed by a slower acceleration until impact occurs. The flyer velocity will eventually reach a limit, if it does not impact a target first. There is a small amplitude oscillation on the measured velocity, due to a shock wave propagating in the flyer. To determine the approximate impact velocity of the flyer and the properties of the oscillation, this oscillation must be separated from the data. To accomplish this, the data is fit to a double-exponential curve. The value of the fit at the time of impact is taken as the flyer impact velocity. The difference between the actual data and the fit is then calculated (figure 3b) to obtain two pieces of information: the period and the magnitude of the oscillation. The period of oscillation is found to be the same as the round trip time for a sound wave in a 50 micrometer thick copper plate. The amplitude of oscillation for this shot is found to be about ± 7.4 m/s at the time of impact. This amplitude determines the minimum uncertainty in the velocity at impact.

Figure 4 shows the velocity versus time curves for four different window materials: quartz, sapphire, and low and high grade BK-7. The laser pulse energy is approximately the same for each shot. It is obvious that the initial flyer acceleration is reasonably independent of the window material; the velocity curves begin in almost identical manners. The flyer from the sapphire window does achieve a slightly higher velocity at first, but its velocity levels out earlier and so this flyer achieves a slightly lower impact velocity. Overall, the accelerations and impact velocities are too similar to suggest any significant differences due to window material.

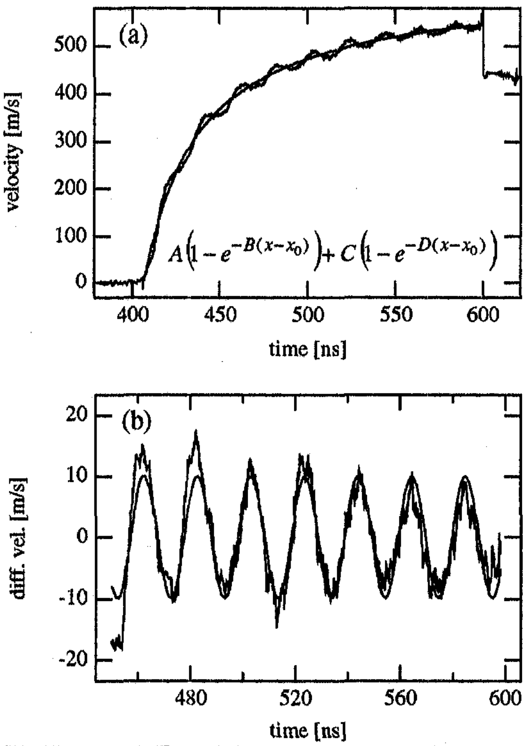

FIGURE 3: a.) Typical flyer velocity versus time profile with double-exponential fit. b.) Difference between velocity data and double-exponential fit, showing oscillation period and amplitude.

However, the amplitude of the oscillations on the velocities appears to be dependent on the window material to a small degree. The amplitude of the oscillations is largest for the sapphire window. This is due to the higher shock impedance of sapphire. The amplitudes of oscillation for the other window materials are lower by approximately 30%. When considering the data for all of the high energy shots (5 Joules, ~650 m/s) we find the same qualitative results. Sapphire has the largest average oscillation amplitude at 10.8 ± 1.6 m/s, while low grade and high grade BK-7 and quartz have slightly lower average amplitudes at 8.8 ± 2.5 m/s, 8.7 ± 1.6 m/s, and 8.0 ± 2.6 m/s, respectively. Thus there is a difference in flyer behavior for the different window materials. However, the difference is sufficiently small to be of no concern in choosing a window material.

The primary goal of our experiments is to determine the effect of window material and substrate thickness on the velocity of the flyer. Figure 5 shows the flyer impact velocity (determined from the double-exponential fits) versus laser pulse energy for

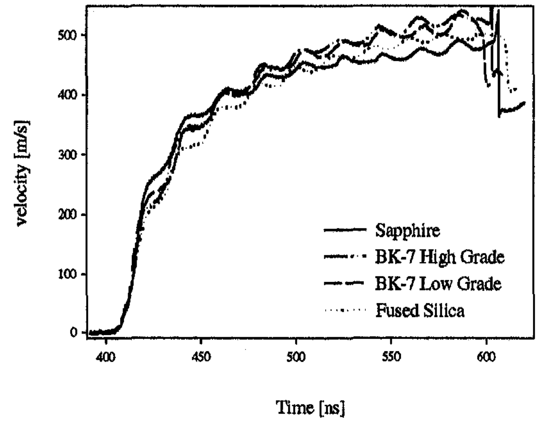

FIGURE 4 Velocity profiles are shown for each substrate windodw material at a laser energy of 3.3 Joules.

all of the window materials and thicknesses of the aluminum substrate. It is obvious that the points cluster together, with only a ten to twenty percent variation in velocities at a given laser pulse energy. The BK-7 windows tend to yield slightly higher velocities than do the quartz and sapphire windows, but this advantage is small. In addition, there is no definite advantage to using either thick (50000 Å) or thin (5000 Å) aluminum coatings. In some shots the thick aluminum yields a higher velocity, in other shots the thin aluminum does. These results are surprising, and may change at higher laser energies.

The highest flyer velocities achieved in our experiments range from 590 to 680 m/s using laser pulse energies near 5 Joules. The trend of the data suggests that even higher velocities should be achievable with higher laser energies. We are currently in the process of improving our laser system to reach 10 Joules and hope in the future to achieve up to 20 Joules to search for a limit to the flyer velocities.

The velocity data fit well to a curve of the form $V = V_0 + A\sqrt{E}$. This is the expected form, since the kinetic energy of the flyer is proportional to the square of the velocity. The V=0 intercept of the fit occurs at approximately 0.1 Joule, so we predict that the flyers can be launched at very low laser energies.

Based on this fit, the efficiency in converting laser energy into flyer energy may be estimated. The mass of the flyer is approximately 3.15 milligrams. The energy of the laser pulse is adjusted to reflect several losses. Only 80% of the pulse energy lies within the 3 mm diameter of the flyer. Also, reflections of around 4% of the energy occur at two surfaces on the window between the diffractive optical element and the flyer window and another 4% reflection occurs at the back surface of the flyer window. Using these adjustments the conversion efficiency is approximately 19%.

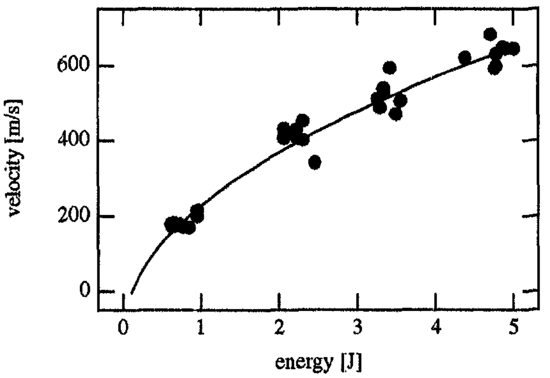

FIGURE 5.: Impact velocity versus laser pulse energy for all of the window materials and both substrate thicknesses.

CONCLUSIONS

From this data we conclude that, for the laser energies used thus far, the window material and the aluminum coating thickness are not critical parameters in determining the flyer velocity, which is similar to the conclusions of Sheffield et. al.[3]. Minor differences are apparent: BK-7 windows produce slightly higher flyer velocities (with high grade BK-7 better than low grade BK-7), while quartz windows produce slightly lower magnitude oscillations in flyer velocity. However, these differences are too small to be of serious consideration in choosing our window and substrate materials. This is very advantageous, since it permits us to choose the most cost effective window material and to specify the manufacturing constraints with broad tolerances, thus reducing cost.

In the future we will continue to increase our laser pulse energies to achieve higher velocities and to search for any limitations. One possible concern is that, at higher energies, absorption by the window could have an effect. However, for BK-7 the internal transmittance of a 1mm thick sample at a wavelength of 1.054 μm is 99.985% [8]. Hence, a 20 Joule laser pulse would only deposit 3.0 milliJoules in the window, which should not damage the window and therefore should have negligible effect. Based on these observations, we are optimistic that we can achieve significantly higher flyer velocities (in the 1.0 to 1.5 km/s range for a 0.05mm OFHC flyer) with this method.

ACKNOWLEDGMENTS

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