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ABLATION AND DRIVE OF TYPICAL MULTI-LAYER FLYERS BY HIGH POWER LASER BEAM

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Laser driving technology is an important technology in high energy physics, shock wave physics and explosive initiation application. In this paper, velocities and impact stresses of four types of laser-driven flyers (Al, Al/Al_2O_3/Al, CuO/Al_2O_3/Al, (CuO/Al)/Al_2O_3/Al) prepared via magnetron sputtering were obtained by photonic Doppler velocimetry (PDV) and a self-made polyvinylidene fluoride (PVDF) stress sensor at ns-class pulse width.The results showed that velocities and integrity of flyers were influenced by their diameters. Compared with Al single-layer flyer, other multi-layer flyers with Al_2O_3 insulation layer owned lower velocity but better integrity and initiation properties.CuO/Al as the ablation layer enhanced the velocities and shock initiation properties of multi-layer flyers. Velocity of a flyer improved with the increasing laser energy while shock initiation property did not perform in the same way. These results provide some references for the design of multi-layer flyers applied to laser-driven initiation technology.

I. INTRODUCTION

Laser-driven flyer technology is definedthat using substances with high pressure and temperature produced by laser ablation to drive the flyer to reach high velocity. It is widely used in dynamic high-pressure physics and rapid initiation of high explosives due to its accurate time control, ultra-fast response and strong ability to resist electromagnetic interference [1]. As is shown in Fig. 1, a typical multi-layer flyer driven by pulsed laser is composed of three layers.

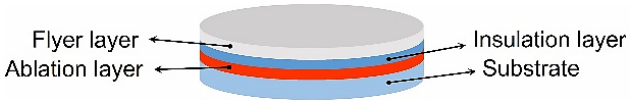


Fig. 1. Structure of the multi-layer flyer.

When a pulsed laser penetrates through the transparent substrate, absorption of laser energy will instantaneously occur inside the ablation layer which will be vaporized to generate plasma to drive the flyer out. The insulation layer can appropriately control the generation of plasma and prevent flyer layer from melting to ensure the integrity of flyer. J.L. Labaste [2] demonstrated performances of flyers were influenced by optical and thermodynamic properties of materials. Greenawa [3] found the addition of Al_2O_3 layer between Al layers increased the flyer velocity by 30%. Stahl [4] proved the C layer between substrate and flyer improved its velocity by absorbing more laser energy. Hatt [5] found Mg as the material of ablation layer enhanced the velocity of flyer by 27% compared with Al.

In general, studies of the regularities for velocity, impact morphology, impact stress and shock initiation properties of mainstream laser-driven flyers have not gone much

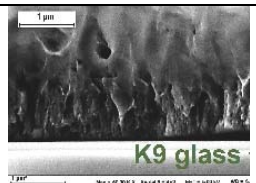
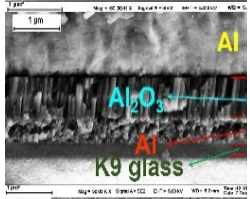
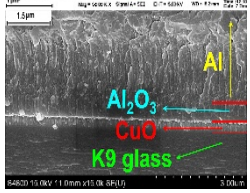
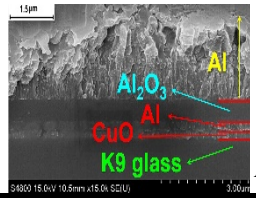
further. This paper mainly aims at velocity and shock initiation properties of six typical multi-layer flyers driven by ns-class pulsed laser.

II. EXPERIMENTAL DETAILS

II.1. Preparation of the multi-layer flyers

Several materials selected were deposited on φ 5mm×2mm thick K9 glass substrate layer by layer to form multi-layer flyers via magnetron sputtering with the power of 240W. The details of different types of flyers prepared are listed in Table 1. Each layer can be distinguished in SEM images of the cross section of flyers. The interfaces between layers were considered as the evidence of their inseparable coalescence.

Table 1. Details of the multi-layer flyers prepared via magnetron sputtering.

Types of flyers	Samples of flyers	SEM images of the cross section of flyers	Structure of the flyer	Materials of the layer	Thickness, μm
Al			Single layer	Al	6.0
$Al/Al_2O_3/Al$			Flyer layer	Al	4.0
			Insulation layer	Al_2O_3	1.0
			Ablation layer	Al	1.0
$CuO/Al_2O_3/Al$			Flyer layer	Al	4.0
			Insulation layer	Al_2O_3	1.0
			Ablation layer	CuO	0.5
$(CuO/Al)/Al_2O_3/Al$			Flyer layer	Al	4.0
			Insulation layer	Al_2O_3	1.0
			Ablation layer	CuO/Al	0.5/0.5

II.2. Experimental setups

Figure 2 shows the schematic view of experimental setup. A Q-switched Nd:YAG (6.5ns, 1064nm, 350mJ) solid pulsed laser was set to carry out experiments. The laser beam is able to form a light spot on the substrate of flyer with the diameter of 0.6mm after adjusted by reflectors and focusing lens.

When the pulsed laser was triggered to beam onto the substrate, some transfer of energy occurred between laser and flyer. In consequence, the flyer was sheared off by the edge of accelerating chamber and accelerated through the chamber to impact on the glass.

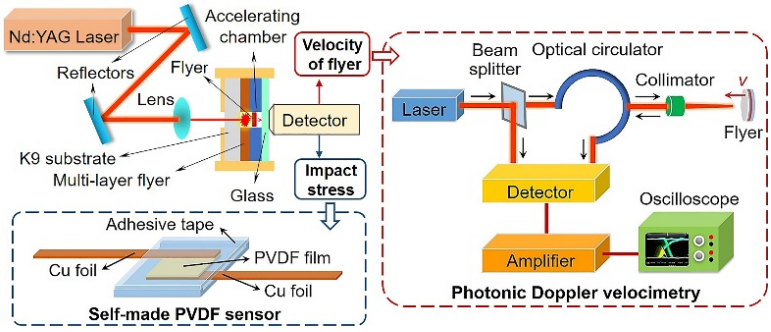


Fig. 2. Schematic view of the experimental setup.

As is illustrated in Fig. 2, the velocities of flyers were obtained by photonic Doppler velocimetry (PDV). And the relative impact stresses of flyers were obtained by a self-made polyvinylidene fluoride (PVDF) sensor, which was prepared as a film with the size of 5mm×5mm×50μm whose dynamic piezoelectric coefficient was calibrated as 21pC·N^{-1}. The PVDF sensor adhered on glass was able to capture the signal when impacted by a flyer [6,7]. Accordingly, the impact stress is able to be calculated by [8].

III. RESULTS AND DISCUSSION

III.1. Velocity regularities of laser-driven flyers

III.1.1. Effect of flyer diameter

In order to figure out the effect of diameter to flyers, three types of accelerating chambers were designed with the diameters of 0.4mm, 0.6mm and 0.8mm, respectively. The velocities of corresponding Al single-layer flyers under different laser energies acquired by PDV tests were shown in Fig. 3. As is shown, flyers with diameters of 0.4mm and 0.6mm owned steadily-increased velocities with the increase of laser energy. However, it was captured that the velocity of 0.8-mm-diameter flyer decreased gradually when the laser energy was greater than 212mJ. On one hand, it can be explained that the flyer was instantaneously cut off because of higher laser energy. As a result, the time of energy deposition on the flyer was less than that of lower energy, which cause the decrease of flyer velocity. On the other hand, higher laser energy produced stronger plasma. Thus, more energy would be wasted on blocking the laser and puncturing the air.

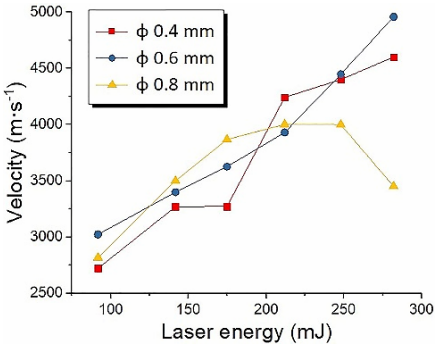


Fig. 3. Velocity variation of the flyers under different laser energies.

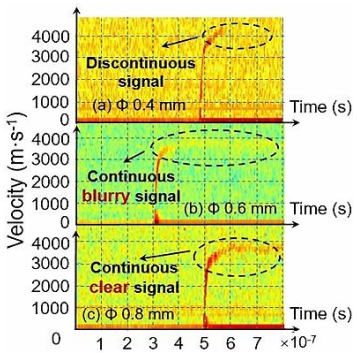


Fig. 4. Velocity history of Al single-layer flyers with different diameters.

Besides, it shows the velocity history of Al single-layer flyers with different diameters in laser energy of 212mJ in Fig. 4. The discontinuous signal in Fig. 4(a) indicated that the flyer has been broken and melted before it reached maximum velocity. Therefore, this illustrated that there exists a range of diameters for flyers to ensure both adequate velocities and their integrity.

III.1.2. Effect of flyer types

Figure 5 shows the velocities of three groups of flyers (Al and $Al/Al_2O_3/Al$, $CuO/Al_2O_3/Al$ and $(CuO/Al)/Al_2O_3/Al$) measured by PDV. Basically, velocities of flyers increased with laser energies.

It is obviously demonstrated that with the addition of Al_2O_3 insulation layer, velocity of $Al/Al_2O_3/Al$ multi-layer flyer decreased by about $400 m \cdot s^{-1}$ compared with Al single-layer flyer. This is because Al_2O_3 layer is heavier than Al layer with the same thickness due to its higher density. More energy consumption thus occurred inside the Al_2O_3 layer and velocity of the flyer was reduced down as a result.

Velocity of $(CuO/Al)/Al_2O_3/Al$ flyer did not exceed that of $CuO/Al_2O_3/Al$ flyer until the laser energy was greater than 282mJ. The thicknesses of both CuO and Al layers are 0.5μm listed in Table 1. Accordingly, it can be inferred that the ablation depth of pulsed laser was less than 0.1μm with laser energy less than 282mJ. When the laser energy exceeded 282mJ, ablation depth of laser exceeded 0.5μm. Then redox reaction occurred partially between CuO and Al layers to release energy. Consequently, $(CuO/Al)/Al_2O_3/Al$ flyer was accelerated to achieve the velocity higher than $CuO/Al_2O_3/Al$ flyer.

Rising edge time is defined as the time during which the velocity of flyer increases from 10% to 90%. Statistical results of rising edge times for flyers under different laser energies were shown in Fig. 6. With the increase of laser energy, it took shorter time for flyers to be accelerated from static state to extreme-velocity state. The rising edge time of laser-driven flyer is mainly between 15ns~35ns, which is less than that of 100-ns-class exploding foil initiator (EFI).

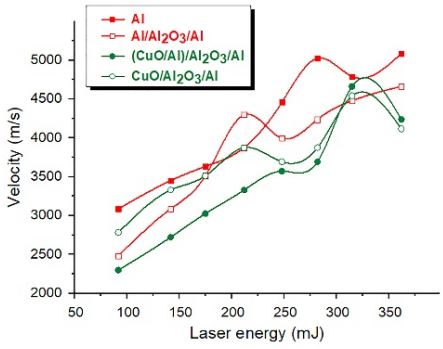


Fig. 5. Velocity of three groups of flyers under different laser energies.

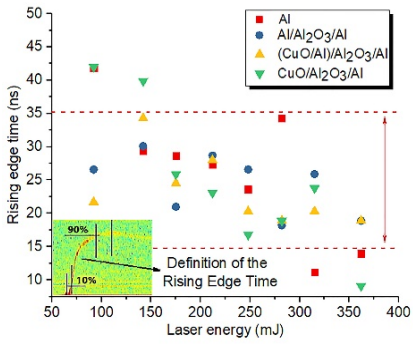


Fig. 6. Rising edge times of six types of flyers under different laser energies

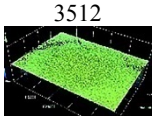
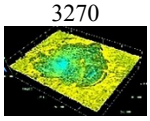
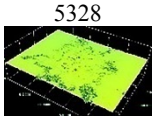
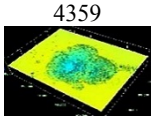
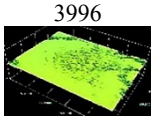
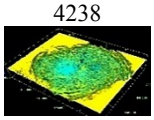
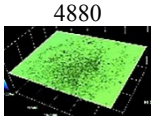
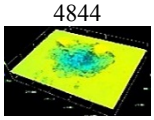
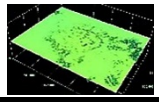
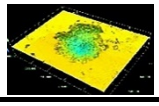
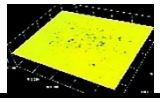
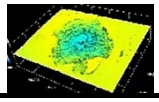
III.2. Shock initiation regularities of laser-driven flyers

III.2.1. Impact craters of flyers

3-D profile of craters on transparent glasses impacted by flyers shown in Table 2 were characterized using laser scanning confocal microscopy (LSCM). In the same laser energy, Al flyer with higher velocity merely formed a few grainy small pits. In

comparison, impact craters formed by $Al/Al_2O_3/Al$ flyer were obvious. This proved that multi-layer flyers behaved better in keeping the integrity of flyers to improve initiation efficiency. Among the flyers tested, $Al/Al_2O_3/Al$ flyer performed better in velocity and impact depth, which is due to the effect of Al_2O_3 insulation layer.

Table 2. 3-D impact craters of transparent glasses impacted by different flyers.

Laser energy, mJ	Al	$Al/Al_2O_3/Al$	Laser energy, mJ	Al	$Al/Al_2O_3/Al$
	Velocity of flyers, $m \cdot s^{-1}$			Velocity of flyers, $m \cdot s^{-1}$	
175	3512	3270	282	5328	4359
					
212	3996	4238	315	4880	4844
					
248	4364	3875	362	5328	4602
					

III.2.2. Shock initiation properties

The criterion for shock initiation of flyers can be expressed by [9]

$$P^2\tau \geq E_c, \tag{1}$$

where P is impact stress, τ is equal to the duration of impact stress approximately, and E_c is defined by explosives to be initiated. The impact stresses of flyers prepared obtained by PVDF sensor and values of calculated value $P^2\tau$ were shown in Fig. 7 and Fig. 8.

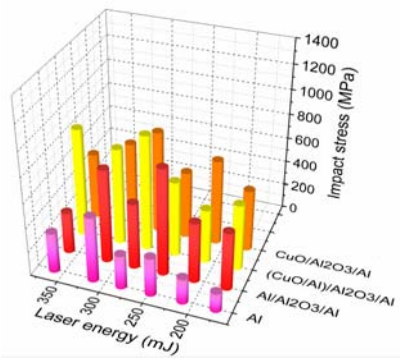


Fig. 7. Impact stress of six types of flyers under different laser energies.

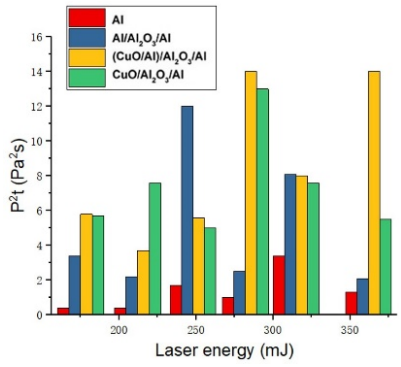


Fig. 8. Initiation property of six types of flyers under different laser energies.

It was observed that both impact stresses and value of $P^2\tau$ of multilayer flyers were distinctly higher than those of Al single-layer flyer due to their integrity of flyers. The additions of Al layer into $CuO/Al_2O_3/Al$ improved the impact stresses similarly to the velocity regularity. Nevertheless, the initiation properties of flyers did not absolutely increase with the increasing laser energy. This is because a certain range of laser energy

is corresponding to a specific flyer to attain maximum initiation property. Moreover, initiation efficiency tended to reduce a result of the consumption of flyer integrity by the out-of-range laser energy.

IV. CONCLUSION

Velocities and impact stress of four types of laser-driven flyers were obtained via PDV system and self-made PVDF sensor. The results showed that velocity and integrity of flyers were influenced by their diameters. Velocities of flyers increased with laser energy. Compared with Al single-layer flyer, multi-layer flyers with Al_2O_3 insulation layer owned lower velocity but better initiation properties due to its protection for integrity of flyers. CuO/Al as the ablation layer behaved well in improving velocity and initiation property of flyers by using the energy released by redox reaction after laser ablation. The factor that determined initiation property was not the laser energy, but the matching of laser energy and specific flyer. These regularities are helpful while designing laser-driven flyers for initiation of explosives.

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