Study on the Technology of Laser-Driven Flyer Hypervelocity Launch

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Abstract. The outer surfaces functional materials of spacecraft are exposed to hypervelocity impacting of micro meteoroids and orbital debris in space. The laser-driven flyer (LDF) system can launch a speed of 3~10km/s, a thickness of about 5um aluminum flyer under the experimental conditions. It can well simulate the effects of micrometer space debris impact on the outer surfaces functional materials of spacecraft. In this paper, the laser-driven flyer technique and flyer velocity measurement technique are introduced. The quantitative relationships between the flyer velocity and the laser energy, laser pulse width, and the flyer thickness were analyzed. The damage morphology and performance degradation of outer surfaces functional materials (such as K9 glass and OSR) of spacecraft were experimentally studied under the hypervelocity aluminium flyer impacting.

1. Introduction

In space around the earth, there are a lot of small-sized bodies, such as space debris and space dusts. Space debris is artificially originated fragments upon rockets launch, etc. Space dusts are naturally originated material from comets, asteroid belt between Mars and Jupiter, etc. Their velocities are around 10km/s, threatening to spacecrafts such as space shuttles and artificial satellites. Micro-particles, diameter ranges in the order of micrometer, are very abundant and it is difficult to predict and avoid the collisions between them and spacecrafts. Consequently, they collide with artificial satellites at a rate higher than 1000 particles/m² per year [1]. Therefore, in space development, it is of interest to protect the surface of the spacecrafts towards the collisions.

Among the organic materials, polyimide, heat and radiation resistant polymer material, is widely used as thermal control film. Among inorganic materials, quartz and boron silicate glasses are used for solar panel, and alumina (aluminum oxide) and zirconium (zirconium oxide) are used in optics and silicon is used as semiconductors in sensors. From this viewpoint, we carry out impact of accelerated micro-particles onto these materials, and evaluation of damage at the surface.

Two-stage light gas guns and rail guns have been used for experiments of hypervelocity collision. Recently, however, as a new method of micro-particles acceleration and new application of accelerators, a laser-driven flyer (LDF) method was used to simulate an impact from space micro-debris and dust [2, 3, 4]. LDF technique used in this experiment has several advantages over conventional methods of producing hypervelocity particles. Very little chemical contamination was produced by accelerating a micro-flyer compared to that generated by electric guns or explosives. Aiming was accurate and the micro-flyer could be directed from outside of vacuum chamber used to simulate space. For the simulation of spacecrafts hypervelocity debris with dimensions ranging in the order of micrometer and impact velocities of up to a few km/s, LDF is attractive as an acceleration
technique for debris simulation due to its relative simplicity, low cost, ease of incorporation into a vacuum facility, and high shot rate capability.

**Figure 1.** Laser-induced plasma is produced at the interface with the metal film and the substrate to launch a flyer of the unablated metal.

LDF can be produced by the irradiation of a metal film with a high energy laser pulse, at the interface with the substrate on which the film is deposited. The substrate should be transparent at the laser wavelength and the laser radiation is absorbed in the metal film which ablated and generates plasma at the interface. The plasma expands and the unvaporized layer of film is driven off as a flyer plate. Figure 1 illustrates the technique used to produce the flyer plates. The laser is usually focused onto the film to the required spot size and the flyers, having thicknesses of a few μm, typically achieve velocities of a few km/s. Explosive initiation has been the prime motivation for research into laser-driven flyers [5]. There is also interest in using the high-pressure shocks generated by laser-driven flyers for high strain rate materials testing [6], and here, in micrometeorite and space debris simulations for research into spacecraft materials [3,7].

2. Laser-driven system

2.1 Laser resource

The laser used is an Nd: glass laser operating at the fundamental wavelength of 1.064 μm. It has an oscillator-amplifier configuration and provides a plane polarized TEM00 output. Figure 2 show the spatial distribution of laser beam. The beam diameter is 30 mm and Q switching produced 15ns full width at half maximum (FWHM) pulses with energy up to 20J. The laser beam was focused onto the target with a spot size of 1 mm diameter, using a 200 mm focal length lens.

**Figure 2.** Spatial distribution of laser beam
2.2. Flyer target

A flyer target consisted of an aluminum film deposited on a circular, K9 glass substrate, which was 30 mm in diameter and 5 mm thick. A number of flyers could be launched from a single target by accurately positioning it in the beam path with a translation stage and irradiating sites of unablated film. The aluminum films were deposited onto the substrates by magnetron sputtering. Film thickness was controllable to an accuracy of 10 nm using a quartz crystal monitor and controller.

Recent research has focused on using an additional ablation layer, between the substrate and what forms the flyer in an attempt to improve the energy coupling aspect of the process. The chosen material is more suitable for forming plasma. With a carefully selected and constructed ablation layer, this technique was found to increase the kinetic energy of the flyer by a factor of nearly three. Figure 3 shows the flyer target structures of mono-layer and multi-layer, here the function of Al$_2$O$_3$ layer is the protection of temperature.

![Flyer target structures of mono-layer and multi-layer](image)

Figure 3. Flyer target structures of mono-layer and multi-layer

2.3. Apparatus system

Figure 4 shows a schematic diagram of the laser-driven flyers system. The laser used is a high-power Nd: glass laser with pulse lengths of 15ns and wavelength of 1064nm. The pulse energies available are range from 300mJ to 20J. The laser beam is guided through a set of mirrors into a vacuum chamber operating at a pressure of 0.1Pa. The function of He-Ne laser is collimation on the light path. The laser power meter is used to measure the energy of each laser beam. Before entering the chamber, the laser beam passes through a focusing lens and the diameter of facula is about 1mm. Inside the chamber, the laser beam irradiates an aluminum film with thickness of a few micrometers through a K9 glass substrate. The laser beam passes through the K9 glass and hits the aluminum/glass interface. At the interface, a high-temperature and high-pressure plasma is formed, which then expands perpendicularly to the aluminum film. A pressure gradient between the plasma pressure on one side and the vacuum zero pressure on the other side causes unvaporized layer of film acceleration, which results in an aluminum layer to fly away at hypervelocity of a few km/s. The size of aluminum flyer is related to the size of irradiated laser spot. By changing the distance between the focusing lens and the target, the size of the spot can be controlled, so that the velocity of the flyer can be controlled.
3. Flyer velocities measurement

For the velocity measurement of flyer, several methods are introduced, include: piezoelectric sensor, laser scattering, laser shutoff and velocity interferometer [8, 9]. The method of piezoelectric sensors utilizes sufficiently large, high bandwidth piezo sensors mounted on the back of the specimen to record time of arrival, laser signal as the original signal, flight spacing known, allowing the velocity calculation. Figure 5 shows the typical signal of piezoelectric sensors and laser signal. Apparently, sensitivity of this technique is very limited. The other technique detects scattered laser from flyer passing through a section of the drift tube containing a multiple diagnostic ports. One set of the ports is used to provide three “optical curtain” produced by high intensity laser. The “other set of ports” are fitted with sensitive photomultiplier tubes to look for scattered laser from the passing flyer. Spacing between the optical curtain known, the velocity of flyer can be calculated.

Another very simple velocity measurements setup in situ utilizing optical curtain is using the method of laser shutoff, shown schematically in Figure 6. The direction of He-Ne laser beam is
orthogonal to the trajectory of the flyer, and by using a prism the beam crosses the flyer path twice. The distance between the two parallel beams is about a few millimeters. A photodiode attached to the oscilloscope receives the continuous laser signals. When flyer interrupting laser signal for two times, two peaks will be detected by the oscilloscope, allowing the velocity calculation.

Velocity measurements of the flyer can also use a velocity interferometer system for any reflector (VISAR). This technique uses an interferometer to measure a small Doppler shift in light frequency given to a beam of a “green light” from a diode laser as it is reflected from the moving flyer surface. The Doppler shift produces a number of light fringes in the interferometer proportional to the flyer velocity. Counting the number of recorded light fringes produced in a given time and multiplying by a velocity-per-fringe constant of the interferometer, a velocity can be obtained.

![Image of flyer velocity measurement setup with laser shutoff]

**Figure 6.** Schematic description of the flyer velocity measurement setup with laser shutoff

4. Materials and characterization analysis techniques

The morphology of craters and fractures resulting from the debris impacts is studied using laser microscope, scanning electron microscope (SEM) and atomic force microscope (AFM), etc. Impact effects on the internal three-dimensional microstructure are studied by means of confocal laser scanning microscope (LEXT OLS3000, Olympus Corporation). Olympus has developed LEXT — a new confocal laser scanning microscope for ultra-precise measurement and observation with the highest levels of reliability. No vacuum pump down or sample preparation are required, and sample can be placed directly on the microscope stage as they are. Both 3D observation and high-precision 3D measurement are possible in real time. With much higher resolution than conventional optical devices but just as many different observation methods, the result is world-leading plane resolution which clearly resolves 0.12μm line and space patterns of 0.01μm height. Every user can make quicker, more accurate specimen analyses all based on a strict traceability system. In addition, measurement involves no contact with the specimen, so there is no danger of damaging it.
5. Some research development and discussions

5.1 Target-making methods
Several kinds of target-making methods have been studied on in the past experiments, including thermal diffusion method, magnetron sputtering method and gluing method. The results indicate that an integral flyer is obtained by thermal diffusion method. The flyer produced by magnetron sputtering method is so brittle that it is fully broken up not to get the integral flyer. Although gluing method may produce the flyer, the aluminum film is torn in the middle of laser. Figure 7 (a) ~ (d) shows the experiment result of several kinds of methods separately.

![Figure 7](image)

Figure 7. Results of several kinds of target-making methods. (a) Flyer target prepared by gluing. (b) Flyer target prepared by thermal diffusion. (c) Flyer target prepared by magnetron sputtering. (d) Thermal diffusion flyer target after multiple launching.

| laser energy(J) | spot size (mm) | flyer thickness (μm) | flight distance (mm) | velocity (km/s) |
|-----------------|----------------|---------------------|---------------------|----------------|
| 0.36            | 1              | 7                   | 3                   | 5.5            |
| 0.6             | 1              | 7                   | 3                   | 6.4            |
| 1.15            | 1              | 7                   | 3                   | 8.3            |

5.2 Calibrating of the relationship between flyer velocity and laser energy
As described in Section 3, the flyer velocity is a function of the laser beam spot size and pulse energy. Table 1 shows the measured flyer velocities as a function of the laser’s pulse energy. It is noted that at the pulse energy attainable (1.15J), a flyer velocity of 8.3km/s is measured. The aluminum flyer film is used in space debris impact because aluminum has a density close to average reported density of debris in low earth orbit (LEO). The method of velocity measurement is using PVDF piezoelectric sensor, described in Section 3.
5.3 Impacting effects of K9 glass

Figure 8 shows the typical features of impact damage in K9 glass by the flyers with 1mm diameter and 7 um thickness, and the damage morphology measured by confocal laser scanning microscope. The hypervelocity flyer only damage the surface of the glass, no cracks was detected in the target. This indicated that not only the velocity but also the impact momentum is the strong factor influence on the impact characteristic. The transmittance of the glass before and after 4 times impact at 8.3 km/s were measured and compared in Figure 9. It shows that the transmittance decrease from 0.87 to 0.78, the transmittance decreases about 10%.

**Figure 8.** The Typical features of impact damage in k9 glass by flyer plates with 1mm diameter and 7 um thickness launched by a laser-driven flyer facility. (a) The picture of the damage. (b) The confocal laser scanning image of the damage. (c) The confocal laser scanning 3 dimension image of the damage.

**Figure 9.** Comparison of the transmittance before and after impact by small flyer
5.4 Impacting effects of OSR thermal control material

The experiments have been also gone on OSR thermal control material. Flyer, of 1mm in diameter and 5μm in thickness, the impact velocity is 4.7km/s. The typical impact image is shown in Figure 10, in this figure, the cracks produced by flyer impact are distinctness. The solar absorptance of OSR thermal control material before and after flyer impact is shown in Figure 11. The solar absorptance of OSR thermal control material increase distinctness after flyer impact. The capability of OSR thermal control material drop sharply.

![Figure 10. The impact image of OSR thermal control material](image1.png)

![Figure 11. The solar absorptance of OSR thermal control material before and after flyer impact](image2.png)

6. Conclusions

A laser-driven flyer ground simulation system has been developed for the launch of flyer with 1mm in diameter and a few μm in thickness to simulate space debris hypervelocity impact, achieving velocities up to 8.3km/s. Although the experimental results are semi-quantitative and primary, our focus is on demonstrating the suitability of laser-driven flyer technique for space debris hypervelocity impact damage, rather than drawing specific scientific conclusions from the data.

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8. References

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