Preheating Technique to Enhance the Laser Ablation Impulse from Polymer Materials

Koichi Mori and Akihiro Sasoh
Department of Aerospace Engineering, Nagoya University, Nagoya, Japan

Abstract
A novel preheating technique to enhance laser-ablative impulse is investigated. In this technique, target material is first heated to an appropriate temperature by irradiating with a continuous laser. Impulse is generated by irradiating an intense laser pulse on the preheated material. In the experiment, polymer materials are preheated simply using an electric heater to investigate the effect of the material temperature on the laser ablative impulse. A pulsed TEA CO_2 pulse laser is used to generate impulse. The results demonstrate that the present technique is useful for Poly-vinyl Chloride (PVC), Acrylic resin (PMMA), and Carbon Fiber Reinforced Plastic (CFRP). The momentum coupling coefficient of PMMA has a peak at the temperature close to the glass transition temperature.

1. INTRODUCTION

Space-debris de-orbiting will be realized by irradiating a laser beam remotely from the ground or from a satellite on orbit as illustrated in Fig. 1. Laser ablative impulse generation will be applied also to a micro-thruster for orbit transfer of a micro-satellite, and to the launch from the ground [1]. In order to realize these applications, it is necessary to understand the physics of laser ablation processes. A number of studies have been conducted to understand the physical processes of the laser-ablative impulse generation [2–6]. Phipps et al [6] measured the laser-ablative impulse of metals and polymers, and proposed a scaling law among the laser intensity, wavelength, and pulse-width. From their results, the impulse-to-energy ratio, the so-called momentum-coupling coefficient, C_m increases with decreasing laser intensity independent of the detailed material characteristics, and it is the order of 10 μNs/J. For laser intensity less than 10^7 W/cm^2, C_m is dependent on the material properties. This low intensity regime is what the present study aims to clarify. Watanabe et al. investigated the impulse for plastic materials with CO_2 laser pulse at 10^6–10^7 W/cm^2. Among plastic materials, Polyacetal (POM) generates C_m higher than 200 μNs/J, and its characteristics are investigated in detail in [7, 8].

It is essential to develop new techniques to enhance C_m. For example, the laser de-orbiting of space-debris by laser will become realistic if we attain high thrust at low-power density of the laser beam. Double-pulse techniques have been demonstrated. Maher and Hall [9] irradiated the double CO_2 laser pulses on an aluminum surface. For the period separation between two pulses around 10 ms, the impulse by the double pulse irradiation was three-times as high as by a single pulse irradiation. In SDIO laser propulsion project, the effects of the double CO_2 laser pulse onto plastic materials on the impulse performance are investigated [10]. Uchida et al. used a Ti-sapphire laser with pulse width at 20 ps and pulse separation at 11 ns. Bursting irradiation of the pico-pulses onto an aluminum surface attained C_m more than ten-times as high as irradiation of a single nanosecond pulse [11].

In the present paper, another novel double beam technique is challenged to enhance the laser-ablative impulse at moderate laser power density. The target is preheated by continuous beam, and pulse laser is irradiated to generate an impulsive thrust as illustrated in Fig. 2. Preheating may change the optical and mechanical properties of the target material surface. The absorption efficiency of polymer at high temperature condition is not understood well. Absorption coefficient may be increased with temperature. For the mechanical properties, thermoplastic polymers easily get soft or liquefied. If the surface of target is liquefied by preheating, impulse enhancement due to liquid-layer-confinement should be promising [12]. In the present experiment, the effect of the preheating is investigated. The target materials are heated on a flat-plate-heater statically, and then a laser pulse is irradiated.

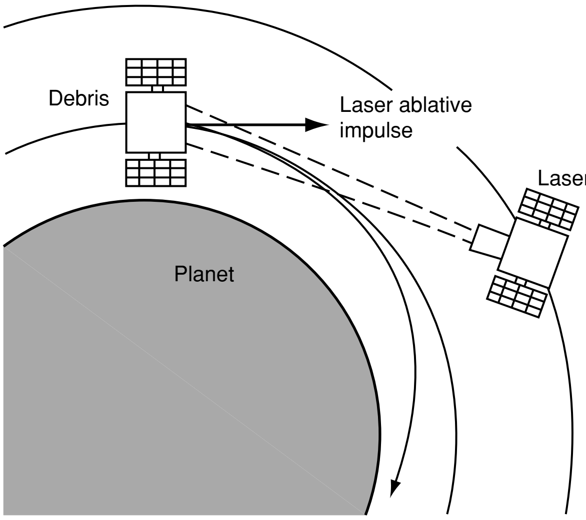

Figure 1. Space debris de-orbiting.

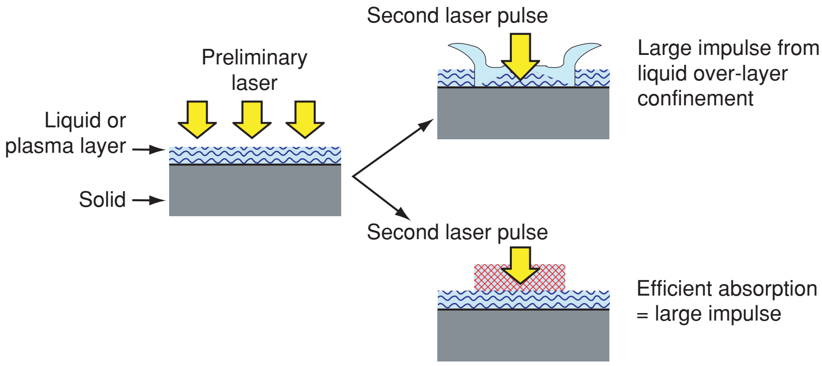

Figure 2. Schematic of double laser ablation.

2. EXPERIMENTAL SETUP

Figure 3 shows the schematic of the experimental setup. A TEA CO_2 pulse laser is used. The laser beam is focused on polymer materials using a Zn-Se lens whose focal length is 200 mm. The spot diameter and the laser pulse energy are kept at 5.0 mm and 3.2 J, respectively. Shot-to-shot scattering of the laser energy is around 5%. Because TEA CO_2 pulsed laser is used for the experiments, the laser energy density is mostly uniform over the spot. The laser fluence is kept at 17.0 J/cm^2. Target material is mounted on an electric heater, and its surface temperature is maintained at a constant value from the

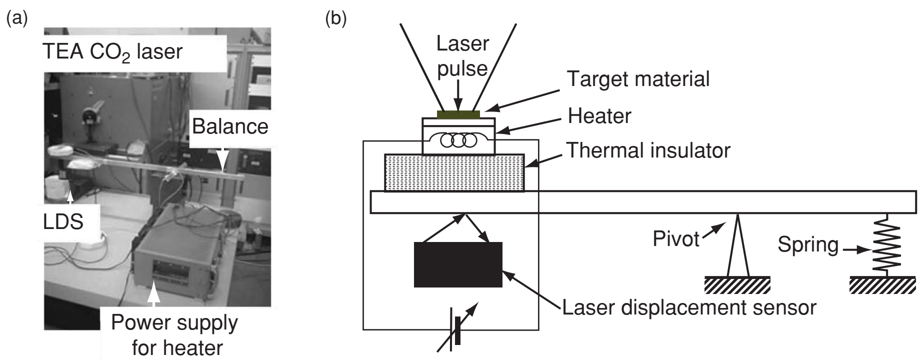

Figure 3. Schematic of experiment: single pulse irradiation on a preheated target materials.

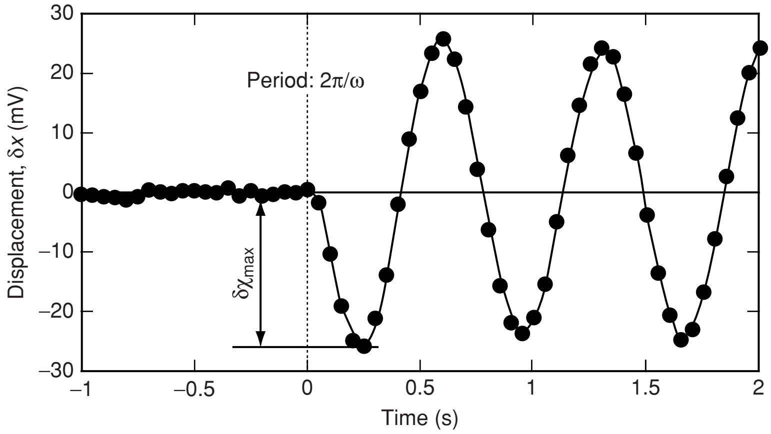

Figure 4. Oscillation of pendulum.

Table 1. Properties of polymer materials at room temperature.

Material	Glass-transition temperature [°C]	Density [g/cm^3]	Specific heat [J/Kg K]
PVC	82	1.16~1.35	1260~2090
PMMA	129	1.17~1.20	1460
EP	–	1.9	1100

room temperature to 300°C by adjusting the electrical power fed to the heater. The temperature of the target surface is monitored using a radiation thermometer. The heater is mounted on the tip of a balance to measure the impulse generated by the laser pulse irradiation. The other tip of the balance is supported by a spring. The heater and the balance are thermally insulated. The arm and the springs are never affected by the thermal load from the heater. The arm of the balance is made of the aluminum U-shaped beam whose length is 1 m. The oscillation of the pendulum is measured using a laser displacement sensor (LDS).

When an impulse is exerted to the target surface, sinusoidal oscillation of the balance is excited. Typical pendulum oscillation is plotted in Fig. 4. The relation between the impulse, I and maximum displacement of the oscillation, δx_{max} is formulated simply as $I = \omega(\delta f/\delta x)\delta x_{max}$ where ω is max angular frequency of the oscillation, and $\delta f/\delta x$ is the ratio of the static force exerted on the tip of the balance, δf to the corresponding displacement of the tip, δx. $\delta f/\delta x$ is constant measured from the static calibration of the pendulum. The friction at the pivot and the structural dissipation of spring is negligible for the present pendulum.

In order to assure the thermal equilibrium of the target material, the laser beam is irradiated at more than five minutes after the target is mounted on the heater. All the experiments are performed in the air atmosphere. Shot-to-shot scattering in the impulse data is around 15%.

Three different polymer materials, Polyvinyl Chloride (PVC), Acrylic resin (PMMA), and Carbon Fiber Reinforced Plastic (CFRP), are used in the experiment. Epoxy (EP) resin is used for the CFRP test panel. These materials are chosen because they are used broadly in aerospace applications. Both PVC and PMMA are thermoplastic resins that get soft when heated to the glass transition temperature. On the other hand, epoxy resin is thermosetting resin. Moreover, the carbon inside CFRP is well known to absorb infrared radiation efficiently. Properties of target materials are summarized in Table.1.

3. RESULTS

Figure 5 shows the relation between C_m and the temperature for PVC. The temperature is changed from 20°C to 220°C. The laser fluence, F, is kept at 17 J/cm^2. Two different targets both made from PVC are used: a simple tissue of 0.2 mm thick and a tissue of 0.5-mm thick with its back surface coated by evaporated aluminum. In spite of the difference in the thickness and the backside surface, C_m data of two cases agree with each other. C_m increases proportionally with the temperature. The glass transition

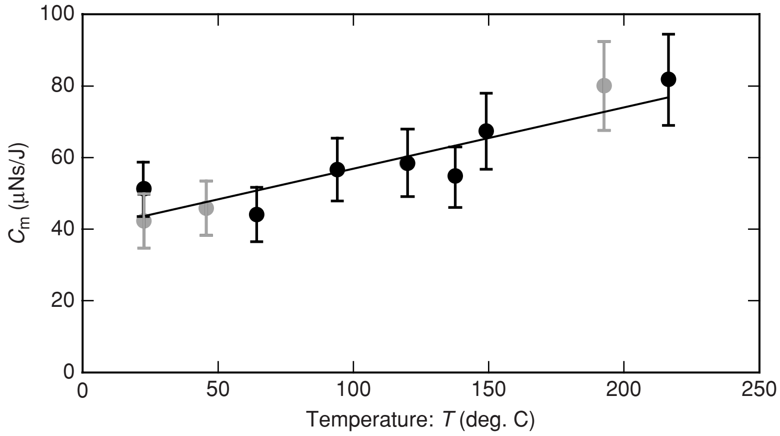

Figure 5. Momentum coupling coefficient of PVC. (●) 0.2-mm thick sheet, (●) 0.5-mm thick sheet with aluminum-coated backside. $F = 17$ J/cm^2.

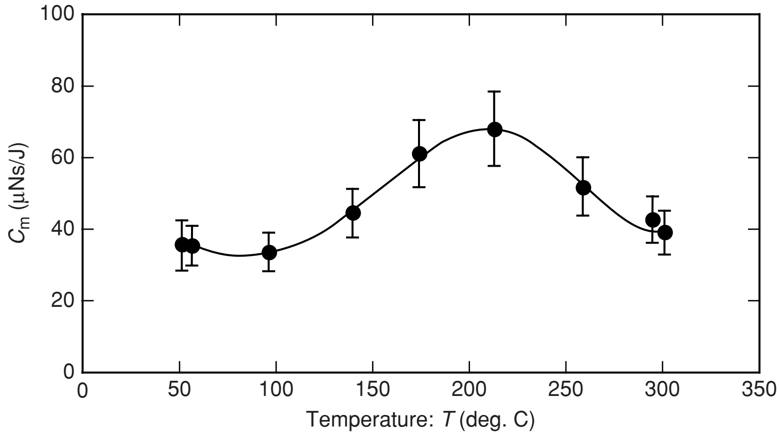

Figure 6. Momentum coupling coefficient of a CFRP panel. $F = 17$ J/cm^2.

temperature of PVC is 82°C and the melting temperature is 180°C. The present results show no symptoms at these characteristic temperatures. Experiments cannot be continued at temperature higher than 220°C because the PVC sheet is melted and smoke is generated.

Figure 6 shows the results for a CFRP. Temperature is changed from 50°C to 300°C. C_m is almost constant from 50°C to 100°C. At temperature higher than 100°C, C_m increases with the temperature, and then has a peak around at 220°C where the increments of C_m become 50%. Although the detailed composition of the epoxy resin is not identified in the present target material, the present result is useful because it suggest that the pre-heating method is promising to generate high impulse on CFRP panels.

Figure 7 shows the relation between C_m and the temperature for PMMA. The laser fluence is kept at 17 J/cm^2. The surface temperature is normalized by the glass transition temperature, T_g in Kelvin. T_g of the planar PMMA is 129°C. At 19°C ($T/T_g = 0.15$), C_m is around 20 µNs/J. C_m increases with increasing T. At 200°C ($T/T_g = 1.6$), the C_m reached its maximum at 42 µNs/J. At higher temperature, C_m decreases gradually with T. The increase in C_m at T/T_g 1.6 may be originted from the change in the optical and mechanical properties of the material surface with the temperature. Especially above T_g, the target material becomes similar to liquid changing the mechanical properties. Moreover, from the observation of the target PMMA material, air bubbles are generated inside the PMMA at $T = 280$°C. This may change the absorption properties and the dynamical characteristics.

The present result may motivate the double-beam technique. Moreover, the present experiment demonstrates that the impulse characteristics of high-temperature materials are different from the one at normal-temperature. Several concepts of laser launch vehicle utilize such plastic ablators as POM (Polyacetal) on board [1, 7, 8]. The repetitive laser pulse irradiation at high-repetition rate onto the

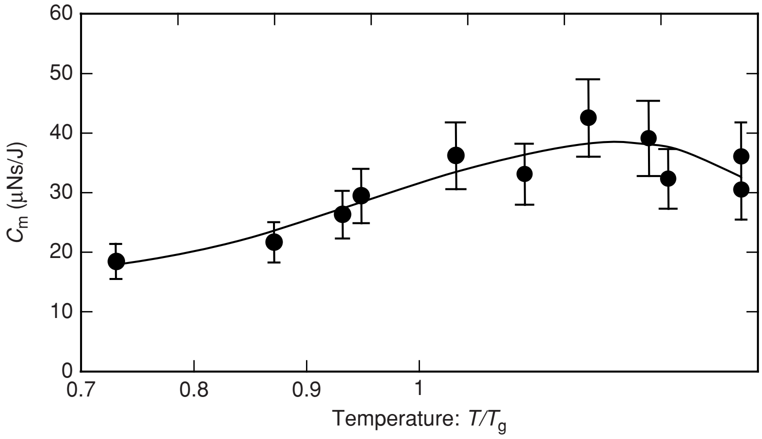

Figure 7. Momentum coupling coefficient of PMMA. $F = 17$ J/cm^2.

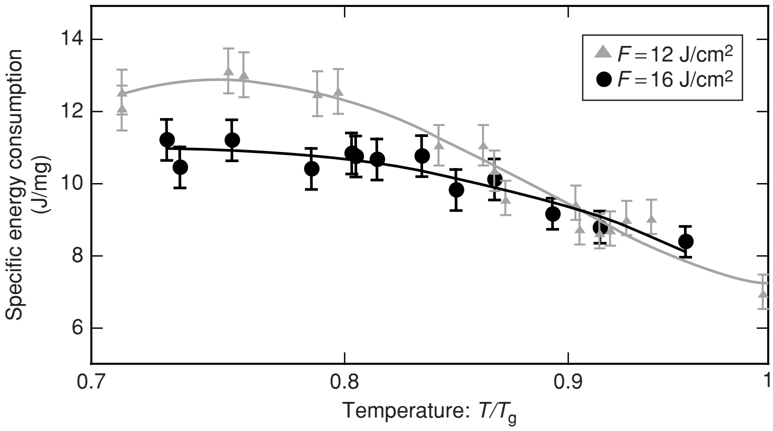

Figure 8. Specific energy consumption of PMMA. (▲) $F = 12$ J/cm^2, (●) $F = 16$ J/cm^2.

ablator should increase its surface-temperature. In the tested case, C_m increased with T, while the ablated amount of mass may be increased with T. This must be considered to calculate the amount of mass on board required for a single flight of the laser launcher.

At room temperature, C_m is around 40 μNs/J both for PVC and CFRP, and it is around 20 μNs/J for PMMA. These values are much lower than C_m measured for Polyacetal (POM) in the previous study. [7, 8] Apart from the difference in material properties, it should be because the experiments are conducted in the air atmosphere using a relatively small laser. In the previous study [8], a large laser facility was used and the laser energy was around 100 J / pulse. On the other hand, in the present study, it is 3 J /pulse. C_m in the air atmosphere is affected by the laser pulse energy because of the confinement effect. When the laser pulse energy is large, pressure on the target surface is kept high for a long time. The specific energy consumption shown below is close to those obtained in the experiments for POM.

Figure 8 shows the relation between the specific energy consumption and the temperature for PMMA. The laser pulse is irradiated 20 times on a PMMA target in one trial keeping the temperature of the target constant. The specific energy consumption is defined as the ratio of the cumulative laser energy irradiated on the target to the ejected amount of mass. The ejected amount of mass is estimated from the mass of a tissue measured before and after a trial using a digital weight scale. The numbers of irradiation are determined by tradeoff between the precision of the weight scale and the available weight of tissue, and the error in the weight measurement is around 0.2 mg. Typical weight change of a target in one trial is 20 mg. The error in the weight measurement in the data is around 1%. Overall error in the estimated value of specific energy consumption is 5%. It mainly originates from the scattering in the laser pulse energy. In a part of preliminary tests, the effect of the numbers of irradiation on the mass yield is investigated. The number of irradiation is changed from 10 times to 40 times, and the ejected amount of mass is measured. The scattering of specific mass consumption in these tests is within the measurement errors. As is clear in Fig. 8, the specific mass consumption is sensitive both to the laser fluence and the temperature. The temperature is varied from 13°C up to T_g = 129°C. In all the tested cases, ejection of white smoke from the target surface into the air is seen after each laser pulse irradiation. The ejected mass is almost constant at low temperature up to $T/T_g \sim 0.8$ whereas it is sensitive to the laser fluence. In this range of the laser fluence, specific energy consumption is saved by increasing the laser fluence. At higher temperature, the energy consumption decreases with temperature. It is interesting that two curves coalesce to each other in spite of the difference in F.

The specific energy consumption is 11 J/mg for F = 16 J/cm^2 at room temperature (13°C). It decreases around by 40% at the glass transition temperature. C_m is 20 μNs/J at room temperature. See Fig. 7. It increases by 50% to 30 μNs/J at the glass transition temperature. The change in the mass and the change in the momentum are closely related and similar to each other. Note that the amount of energy attained by preheating is negligible. When a 10 J pulse of laser beam is irradiated onto the PMMA target, the mass of around 1 mg is ejected. Because the specific energy of PMMA is 1460 J/Kg K, the energy cost to increase the temperature of a 1-mg-PMMA tissue by 100 K is 0.146 J that is around 1% of the laser pulse energy. Hence, the increase in the impulse performance should originate from the influence of the temperature on the optical and mechanical characteristics of polymer.

4. SUMMARY

The present study investigated the feasibility of a double-beam technique to enhance the laser ablative impulse. In preheating experiments, the impulse generated by the TEA CO_2 laser pulse irradiation increases with increasing temperature of the ablator surface. The momentum-coupling coefficient C_m for PMMA increases from 20 μNs/J at a room temperature to 40 μNs/J at 200°C. In the present study, experiments are conducted in the air atmosphere. For the laser launchers using polymer ablators, the performance in continuous operations will be affected by the temperature effects found in the present study. For the mechanisms of the temperature effect, systematic experiments as well as the numerical simulation is indispensable. In order to investigate the applicability of the present preheating technique to the space debris de-orbiting, experiments in vacuum are necessary.

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REFERENCES

[1] L. N. Myrabo: "World record flights of beamed-riding rocket lightcraft", AIAA 2001–3798 (2001).

[2] D.W. Gregg and S.J. Thomas, "Momentum Transfer Produced by Focused Laser Giant Pulses," Journal of Applied Physics, Vol. 37, pp. 2787–2789 (1966).

[3] Pirri, A. N. and Weiss, R. F., "Laser Propulsion," AIAA Paper No. 72-719, AIAA 5th Fluid Dynamics Conference, Boston, MA, 26–28 June 1972.

[4] Pirri, A.N., Monsler, M.J., and Nebolsine, P.E., "Propulsion by Absorption of Laser Radiation," AIAA Journal, Vol. 12, No. 9, Sept. 1974, pp. 1254–1261.

[5] Ready, J. F., "Impulse produced by the interaction of CO_2 TEA laser pulses," Applied Physics Letters, Vol. 25, No. 10, 1974, pp. 558–560.

[6] C. R. Phipps, Jr., T.P. Turner, R.F. Harrison, G.W. York, W.Z. Osborne, G.K. Anderson, X.F. Colris, L.C. Haynes, H.S. Steele, K.C. Spicochi, and T. R. King, "Impulse coupling to targets in vacuum by KrF, HF, and CO_2 single-pulse lasers," Journal of Applied Physics, Vol. 64, 1988, pp. 1083–1096.

[7] Watanabe, K., and Sasoh, A., "Impulse generation Using 300-J Class Laser with Confinement Geometrie s in Air," Transaction of the Japan Society for Aeronautical and Space Sciences, Vol. 48, No. 159, 2005, pp. 49–52.

[8] Watanabe, K., Mori, K., and Sasoh, A., "Ambient Pressure Dependence of Laser-Induced Impulse onto Polyacetal," Journal of Propulsion and Power, Vol. 22, No. 5, 2006, pp. 1150–1153.

[9] W.E. Maher and R. B. Hall, "Experimental study of effects from two laser pulses," Journal of Applied Physics, Vol. 47, pp. 2486–2493 (1976).

[10] J.T. Kare, "Laser Launch—The Second Wave," AIP conference proceedings, Vol. 664, pp. 22–33 (2002).

[11] Uchida, S., et al., "Enhancement of momentum coupling efficiency using ultra short laser pulse," High-Power Laser Ablation, Santa Fe, SPIE, 2000.

[12] Yabe, T., et al., "Microairplane propelled by laser driven exotic target," Appl. Phys. Lett. Vol. 80, No. 4 318.