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RESEARCH ARTICLE

Plasma characteristics of energetic liquid polymer ablated by nanosecond laser pulses

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Abstract The plasma characteristics of carbon-doped glycidyl azide polymer (GAP) are investigated ablation by nanosecond laser pulses. For the GAP energetic liquid, a specific impulse of 840 s and an ablation efficiency up to 98% are obtained, which can be attributed to the low mass loss owing to the carbon doping. A comparison between the chemical energies shows that the carbon-doped GAP provides better propulsion than pure GAP. This indicates that even for an energetic liquid, an efficient approach to enhance the thrust performance is to reduce the splashing. High ablation thrust could be achieved at a low laser fluence and high carbon content.

Keywords laser plasma, energetic liquid, carbon content

1 Introduction

The laser plasma thruster, a new micro-propulsion technology device, can be employed for space, sea, and various other applications [1–4]. In laser plasma propulsion, the interaction process is related with the propellant states and properties. Therefore, ablation propellants have to be extensively analyzed. The coupling coefficient depends on the state of the propellant; it is only tens of dyne/W for solid propellants [5]. Liquid propellants can provide a high coupling coefficient; however, it will be accompanied with a low specific impulse [6]. In order to simultaneously obtain a high coupling coefficient and high specific impulse, liquid propellants can be doped with solid absorbers. After the doping, the liquid is similar to a jelly and exhibits both liquid and solid properties [7,8]. In addition, by investigating the properties of propellants, energetic liquids have been recently proposed [9,10]. For example, glycidyl azide polymer (GAP) has been attracting a significant attention owing to its high viscosity and stored chemical energy, which can be released during the laser ablation process and can significantly improve the ablation efficiency [9]. Furthermore, based on the chemically stored energy and laser energy, a hybrid thruster system can be developed. Shadowgraph images of liquid carbon-doped GAP have revealed that the splashing behavior was almost avoided and that the specific impulse was improved to hundreds of seconds [8,11]. However, the dependence of the thrust as a function of the laser fluence and carbon content has not been yet extensively studied.

In this study, a liquid GAP doped with carbon black is ablated by nanosecond laser pulses. Based on the target momentum and mass loss as well as ablation pressure, the plasma thrust characteristics are analyzed for different laser fluences and carbon contents. In particular, the coupling coefficient, specific impulse, and ablation efficiency are measured. The origin of the high specific impulse and ablation efficiency is discussed. The energetic liquid polymer is promising for laser plasma propulsion applications.

2 Experimental methods

The container employed in the experiment is an aluminum cuboid with dimensions of 4 mm × 5 mm × 8 mm. A cavity with a depth of 1.5 mm and a diameter of 1.5 mm in the cuboid is used to hold the liquid GAP. A beam splitter is used prior to the irradiation of the GAP by the laser pulse. One part of the energy is incident on the energy meter (for monitoring purposes), while the other part is focused by a lens ($f = 200$ mm, $\Phi = 50$ mm) into the bottom of the cavity. The employed laser pulse has a wavelength of 1064 nm. The laser pulse duration is 10 ns, and the maximum laser pulse energy is ~ 500 mJ at a wavelength of 1064 nm. The target velocity is measured by a photo-

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electric device [12,13]. As shown in Fig. 1, a He-Ne laser beam is used as the probe beam, which is reflected by two mirrors and provides two probe beams. After the laser ablation, two signals are recorded by an oscilloscope. The target velocity is calculated as the ratio between the distance between the two beams (Δl) and time delay (Δt) between the two signals. In addition, the transient pressure during the laser ablation is monitored using a commercial force sensor with a precision of ~ 0.05 N. The force sensor is mounted behind the target. The pressure force signal is recorded by the oscilloscope; the value of the pressure can be calculated using the signal amplitude.

3 Results and discussion

Carbon black (with particle diameter in the range of 100–130 nm) is added to the liquid GAP to produce the liquid propellant. Before ablation, the composite liquid is dispersed by a magnetic stirrer for 10 min to prevent agglomeration. The value of the mass loss, caused by one laser pulse ablation, is directly measured by a balance with a precision of 0.01 mg. The carbon contents are 0, 5, 10, 15, 20, 25, and 31 wt%; 31 wt% is the highest realized content of carbon at the employed experimental conditions.

Owing to its exothermic decomposition, GAP has a high ablation efficiency and requires a low incident laser intensity to induce the plasma formation [9]. The dependences of the coupling coefficient, specific impulse, target momentum, and mass loss as a function of the laser fluence are shown in Fig. 2. It shows that the laser fluence has a significant effect on the thrust performance. With the increase of the laser fluence from 3 to 15 J/cm^2, the coupling coefficient decreases from 323 to 189 dyne/W, while the specific impulse increases from 2.5 to 9.6 s. These values of the coupling coefficient and specific impulse are very close to those that correspond to non-energetic liquids such as water and glycerol [7]. The coupling coefficient is defined as the ratio between the target momentum and incident laser energy, while the specific impulse is the ratio between the target momentum and mass loss. An inversely proportional relationship between the coupling coefficient and specific impulse is observed, which agrees with the theoretical prediction [14].

On the other hand, with the increase of the laser fluence, the target momentum increases from 9.7 to 28 g·cm/s. The mass loss caused by one laser pulse is several milligrams. Owing to the plasma shielding effect, even for high fluences, larger than 8 J/cm^2, the mass loss is almost unchanged. The residual volume in the container shows that the GAP is almost consumed during the process. Instead of being ionized into plasma, most of the GAP is not ionized and it is splashed into droplets during the plasma expansion. According to the definition of the specific impulse as the ratio between the target momentum and mass loss, a high mass loss implies a low specific impulse. Furthermore, this indicates that the splashing is the dominant contribution to the thrust, compared with the chemical energy released from the decomposition.

In order to evaluate the effect of the carbon black on the ablation, experiments were performed at different carbon contents, at a fluence of 15 J/cm^2 as shown in Fig. 3. It shows that the coupling coefficient and specific impulse are sensitive to the carbon content. The coupling

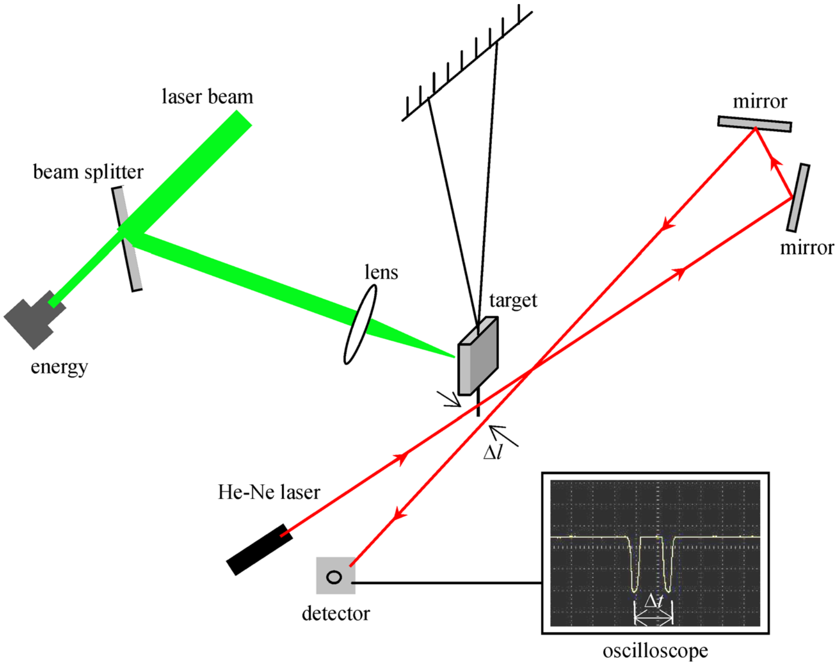

Fig. 1 Schematic of the experimental setup with two crossing beams for the measurement of the target velocity

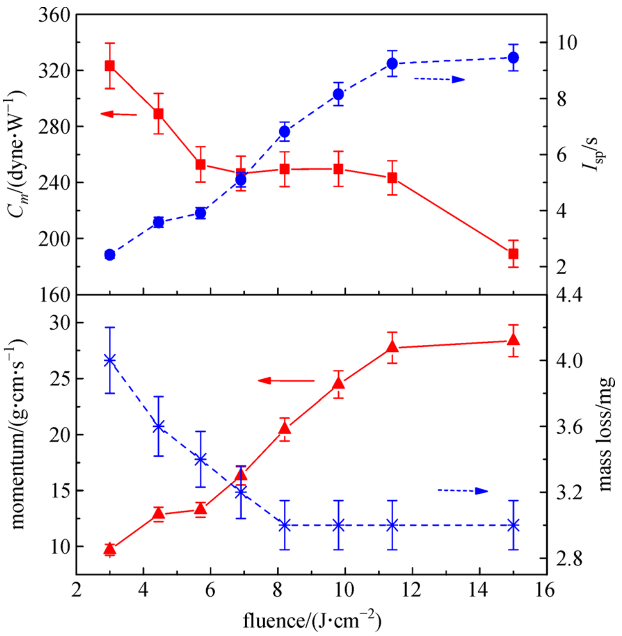

Fig. 2 C_m (coupling coefficient), I_{sp} (specific impulse), target momentum, and mass loss as a function of the laser fluence for ablation of pure GAP

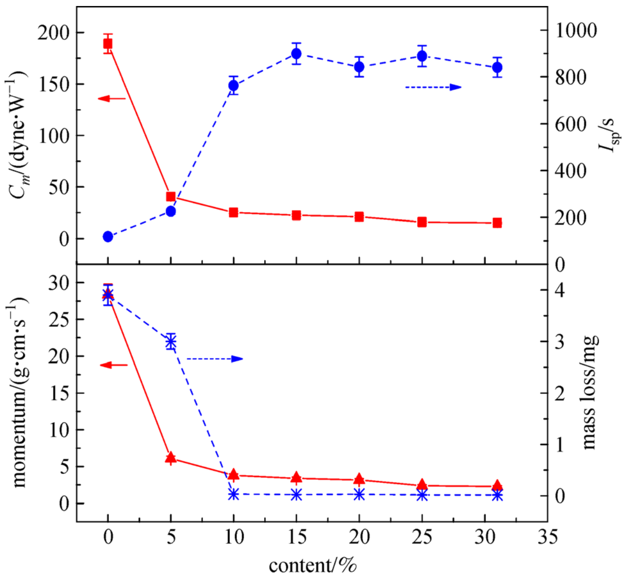

Fig. 3 Dependences of the C_m (coupling coefficient), I_{sp} (specific impulse), momentum, and mass loss as a function of the carbon content for a laser fluence of 15 J/cm^2

coefficient decreases from 189 to 15 dyne/W, with the increase of the carbon content from 0% to 31%. However, the specific impulse exhibits an increasing tendency; it begins to rapidly increase to a value of 800 s for contents larger than 5%. The highest value of ~ 840 s is obtained for a carbon content of 15%. Compared with the pure GAP (Fig. 2), which provides a mass loss of several milligrams, for the carbon-doped GAP, the mass loss is decreased to ~ 0.02 mg (Fig. 3). The mass loss is almost inversely proportional with the specific impulse. As the specific impulse is determined by the target momentum and mass loss, a more rapid decrease of the mass loss, compared with that of the target momentum, yields a high specific impulse.

It is known that the penetration depth is strongly dependent of the carbon content. If the carbon content is larger than 31%, the laser pulse cannot penetrate the GAP; it only reaches the GAP surface. The plasma will be induced on the surface. In this case, the laser intensity is lower than that at the focal point. The intensity, in turn, influences the ablation thrust. In order to confirm this statement, we performed an experiment to reveal the dependence of the ablation pressure as a function of the focal position, as shown in Fig. 4. Different focal positions are obtained by changing the position of the focal lens; the zero position corresponds to the focal point at the cavity bottom and the position of 1.5 mm corresponds to the case where the laser pulse is focused on the target surface. It can be noticed that the ablation pressure has its maximum value of ~ 1800 mN at the position of 0.5 mm. The position values indicate that an efficient ablation will occur when the plasma is induced within the liquid, which is referred to as a confinement ablation. The GAP volume is important for the confinement ablation. Owing to the confinement type of ablation, a high ablation pressure and high coupling coefficient can be obtained. If the focal position is further away from the surface (e.g., at 2.0 mm), the laser pulse starts to defocus and a low ablation pressure is provided. In addition to the carbon content, the maximum pressure is also related with the laser energy, lens's focal length, and incident laser wavelength.

Using the target momentum $m\Delta v$, the coupling coefficient C_m can be expressed as [15,16]

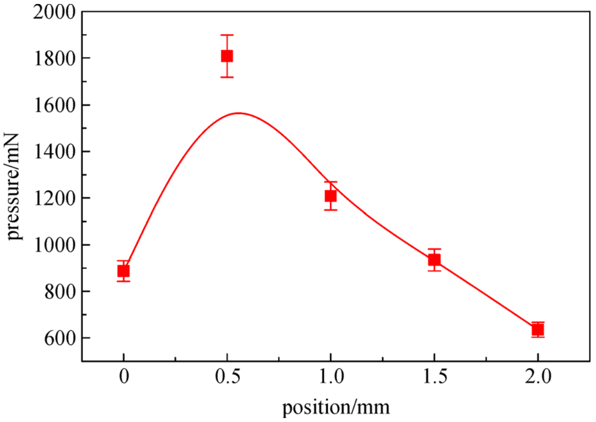

Fig. 4 Dependence of the ablation pressure as a function of the focus positions for carbon-doped (5%) GAP. The position of zero corresponds to the cavity bottom, while the position of 1.5 mm corresponds to the target surface

$$C_m = \frac{m\Delta v}{E} = \frac{F}{P}\,[\text{dyne/W}], \tag{1}$$

where E is the incident laser energy, F is the thrust, and P is the incident laser power. Then, the specific impulse $I_{\rm sp}$ can be expressed as

$$I_{\rm sp}g_0 = v_{\rm E} = C_m Q^* \ [\text{cm/s}], \tag{2}$$

where $v_{\rm E}$ is the exhaust velocity, and Q^* is the specific ablation energy. Using Eq (1) and (2), the ablation efficiency η, defined as the efficiency of conversion of the laser energy into exhaust kinetic energy, can be written as

$$\eta = \frac{1}{2}C_m v_{\rm E} = \frac{1}{2}g_0 C_m I_{\rm sp}. \tag{3}$$

It is obtained that the ablation efficiency is determined by the coupling coefficient and specific impulse.

The dependence of the ablation efficiency as a function of the laser fluence and carbon content is shown in Fig. 5. It can be noticed that the efficiency is sensitive to both carbon content and laser fluence. With the increase of the laser fluence, the efficiency increases and then it reaches the maximum value of ~ 11% at 11.4 J/cm^2. For fluences higher than 15 J/cm^2, the efficiency decreases. It is believed that the plasma shielding effect reduces the ablation efficiency. For the GAP energetic propellant, the energy provided by decomposition has no evident effect on the thrust performance; the obtained thrust effect is similar to that of a non-energetic propellant. This indicates that the performance is mainly determined by the physical properties such as flowability and viscosity; the energy supplied by decomposition has a minor contribution.

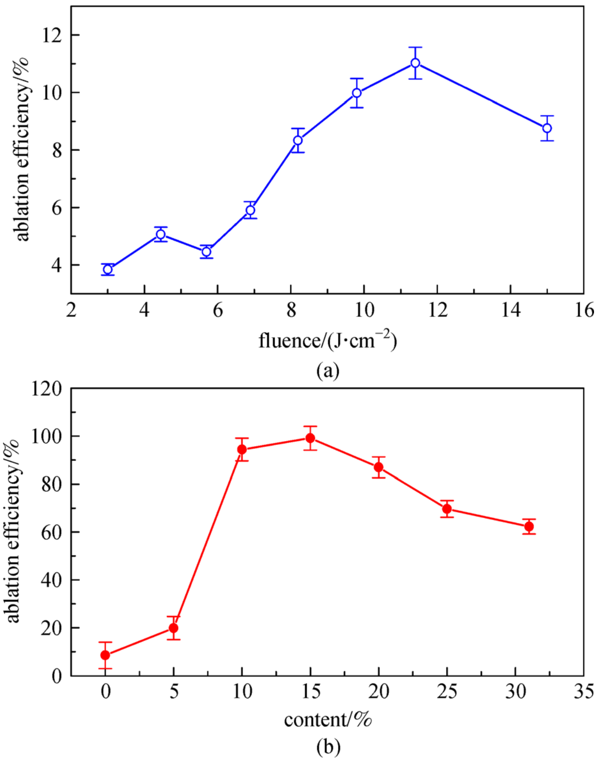

Fig. 5 Dependence of the ablation efficiency as a function of the (a) laser fluence for pure GAP and (b) carbon content for a laser fluence of 15 J/cm^2

A comparison of the effects of laser fluence and carbon content on the ablation efficiency shows that the carbon content can provide significantly larger ablation efficiency than that provided by the laser fluence; an efficiency of ~ 98% is obtained at a carbon content of 15%. This means that the carbon doping is an efficient method to improve the ablation efficiency. With the increase of the carbon content, the laser focal position and laser intensity vary. When the plasma is induced on the GAP surface, the mass loss has its minimum value, while the specific impulse and ablation efficiency have the highest values.

4 Conclusions

The energetic GAP liquid was ablated and characterized during the nanosecond laser pulses ablation. It was shown that the carbon doping is more efficient than the laser fluence for the improvement of the thrust performance. A specific impulse of up to ~ 840 s was achieved, owing to the low mass loss for a high carbon content. However, the chemical energy which is released from GAP has no evident effect on the performance, and it has even a similar value to those of non-energetic liquids. For all liquid propellants, splashing always accompanies the ablation process. This indicates that the thrust performance can be improved by reducing the splashing volume, by doping with absorbers, or by increasing the viscosity. For the doping with carbon black, the agglomeration of carbon nanoparticles will affect the thrust, hence it should be prevented in future studies.

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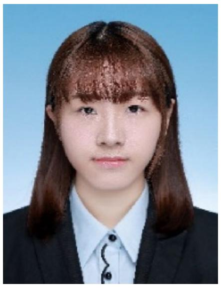

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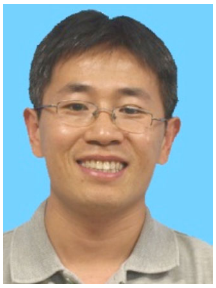

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