Experimental Investigation of Laser Propulsion for Polyoxymethylene Propellants Seeded with Metallic Particles

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ABSTRACT
In order to combine the high momentum coupling coefficient (C_m) of polymeric propellant and the high specific impulse (I_{sp}) of metallic propellant, the propulsion performance of polyoxymethylene (POM) seeded with metallic particles has been studied experimentally with CO_2 lasers in this paper. The results show that seeding metallic particles can improve the laser propulsion performance of POM under certain conditions. The C_m and I_{sp} of POM seeded with Al particles is almost the same as pure POM at lower power density ($<1.7\times10^6$ W/cm^2). At higher power density ($>1.7\times10^6$ W/cm^2), C_m of POM seeded with Al particles decreases significantly while I_{sp} increases significantly. Laser parameters that affect the laser propulsion performance of propellants are very important factors. Comparing the experiments in this paper with Schall, et al. experiments, we can see that seeding metallic particles can improve the laser propulsion performance of POM only with the use of a shorter pulse width of laser. The use of the sharp pulse is more conducive to improve the propulsion performance of POM seeded with metallic particles.

NOMENCLATURE

C_m	Momentum coupling coefficient
I_{sp}	Specific impulse
η	Ablation efficiency
P	Impulse
W	Energy
m	Mass
V_E	Speed
g	Acceleration of gravity
S	Ablated area
τ	Total pulse length

1. INTRODUCTION
Currently, the majority of the propellants used in ablation laser propulsion are a variety of metals and polymers, and a lot of research in this area has been done [1-8]. Metallic propellants have high specific impulses, but the momentum coupling coefficient is generally low. Polyoxymethylene (POM), as one of the polymeric propellants, has attracted more attention due to its high momentum coupling coefficient and clean ablation products. The disadvantage for polymeric propellants is that the ablation mass per laser pulse is large, so the specific impulse is generally low.

In order to combine the higher momentum coupling coefficient of polymeric propellants with the higher specific impulse of metals, metal particles are seeded into the polymeric propellants with the expectation of obtaining higher performance. Schall, et al. [4] reported an experimental investigation of POM propellant seeded with aluminum particles, but found that both the momentum coupling coefficient and the specific impulse were reduced. Cheng, et al. [6] from the University of Science and Technology of China used a propellant of polyvinylchloride (PVC) seeded with iron particles and their results showed that the specific impulse had been significantly enhanced, while the momentum coupling coefficient was slightly reduced. In order to further investigate the effect of adding metal particles on propulsion performance, the propulsion performance of POM seeded with micron-size aluminum particles was studied experimentally with CO_2 lasers in this paper.

2. DESIGN AND PREPARATION OF POM PROPELLANT SEEDED WITH METALLIC PARTICLES

The I_{sp} of PVC propellant seeded with iron particles is about 7 times that of pure PVC propellant [6]. Heat can be released during the process of laser ablation of Al in the air condition. Therefore, we designed three kinds of propellants: pure POM, POM seeded with Fe particles and POM seeded with Al particles. POM is produced by DuPont Company, and the particle diameter of metallic particles produced by China Pharmaceutical Group is about 30~100μm. Mixing POM with metallic particles evenly, the mixture is pressed into sheets in the 190°C environment. Then the targets are cut from the sheets. The target composition is listed in table 1.

Table 1. Target composition

target	mass fraction
POM	100%POM
POM+Fe	80%POM+20%Fe
POM+Al	80%POM+20%Al

3. EXPERIMENTAL INVESTIGATION OF LASER PROPULSION FOR POM PROPELLANTS SEEDED WITH METALLIC PARTICLES

3.1 Experimental Principles and Setup

The experimental system consists of a laser device, a laser energy meter, an electronic analytical balance, an impulse pendulum [8] and a video camera. The laser device(laser1), made by HuaZhong University of Science and Technology, is a pulsed TEA30 CO_2 laser, its wavelength and single pulse energy are 10.6 μm and 20 J, respectively. Laser2(used in the confirmatory experiments), made by HuaZhong University of Science and Technology, is a pulsed TEA300 CO_2 laser, its wavelength and single pulse energy are 10.6 μm and 250 J, respectively. The laser pulse waveform is measured by B749 Germanium Photon drag detector (made by Hamamatsu Photonics K.K.) and Tektronix TDS7154B oscilloscope. The entire pulse width of laser1 is about 5 μs with a narrow peak at the front, and the full-width-of-half-max of the narrow peak is about 67 ns. The model of the laser energy meter, made by Beijing Institute of OPTO-Electronic Technology, is M2000-B. The model of the electronic analytical balance, made by Ohaus Instruments Co., Ltd., is CAV114C, and the readability is 0.0001g.

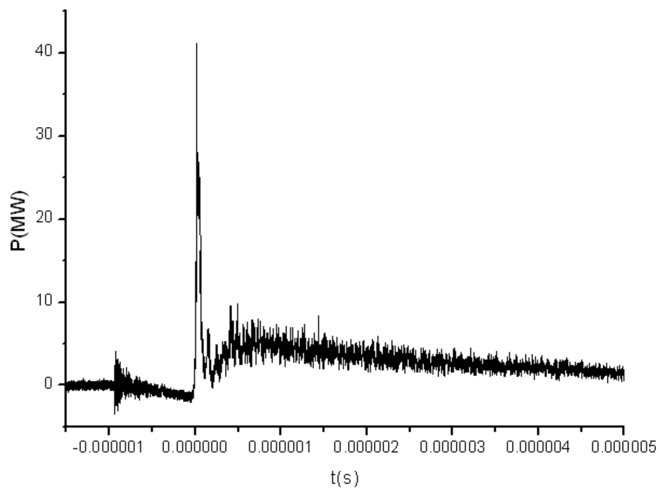

Figure 1. The laser1 pulse waveform

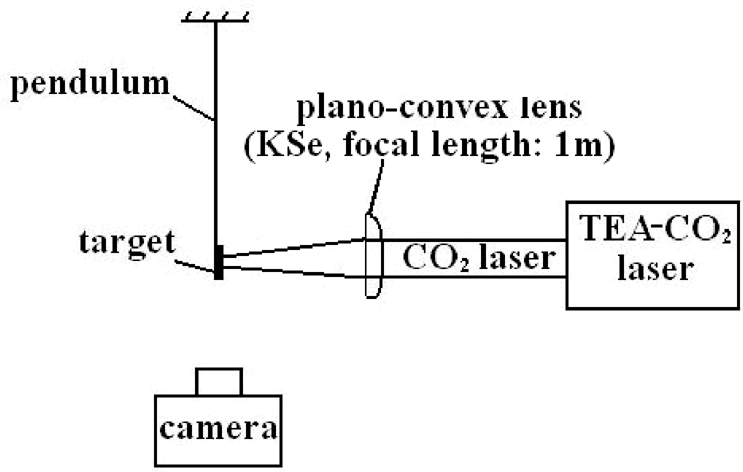

Figure 2. Schematic for the propulsion performance experiment

The experimental setup for the propulsion performance measurement of the propellant is shown in Fig. 2. The target pendulum swings when the CO_2 laser focused through the convex lens ablates the propellant target. The impulse P generated by laser ablation can be obtained from the maximum swing angle recorded by the video camera. The laser energy meter and electronic analytical balance can give the laser pulse energy W and the mass loss Δm per pulse of the target, respectively. Then the momentum coupling coefficient C_m, specific impulse I_{sp} and the ablation efficiency η can be calculated by the equations (1)~(3):

$$C_m = P / W = \Delta m \cdot v_E / W \tag{1}$$

$$I_{sp} = P / (\Delta m g) = v_E / g \tag{2}$$

$$\eta = \frac{1}{2}\Delta m v_E^2 / W = \frac{1}{2} g C_m I_{sp} \tag{3}$$

$$I = W / (\tau S) \tag{4}$$

where v_E is the jet speed of ablation product and g is the acceleration of gravity. Adjusting the laser pulse energy or the distance from the target to the lens can change the laser power density I(calculated by eq.(4), where τ is the total pulse length and S is the ablated area) on the target. Then the relationship between the propulsion parameters of propellants and the power density can be obtained experimentally. Because the mass loss per pulse is small, in order to improve the test accuracy, we weighed the cumulative mass loss of the target after 10 repeated shots, hence each datum on the experimental curves represented the average result of 10 repeated experiments.

3.2 Experimental Results

The experimental C_m versus I curves of three propellants are shown in Fig. 3. It can be seen that with the increase of the laser power density I, the C_m always increases at first and then decreases for all three propellants. The C_m of POM+Al is almost the same as that of pure POM at lower power density ($<1.7\times10^6$ W/cm^2). The C_m of POM+Al decreases observably at higher power density ($>1.7\times10^6$ W/cm^2). At 6.0×10^6 W/cm^2, the C_m of these two propellants have the maximum difference: the C_m of POM+Al is only 10.1 dyne/W, reduced by 36.5%, while the C_m of pure POM is 15.9 dyne/W. The C_m-I curve of POM+Fe is almost parallel to the curve of POM+Al for the most part, but is underneath.

Fig. 4 shows the mass loss per pulse of the propellants at various power densities. The mass loss per pulse Δm of POM+Fe is obviously lower than that of pure POM, which hints the increase of I_{sp} for POM+Fe samples. The Δm of POM+Al is very close to that of pure POM when the power density is low ($<1.7\times10^6$ W/cm^2), however, with the further increase of laser power density, its Δm deceases dramatically and is even lower than the POM+Fe, which directly causes the increase of I_{sp} for POM+Al samples as shown in Fig. 5.

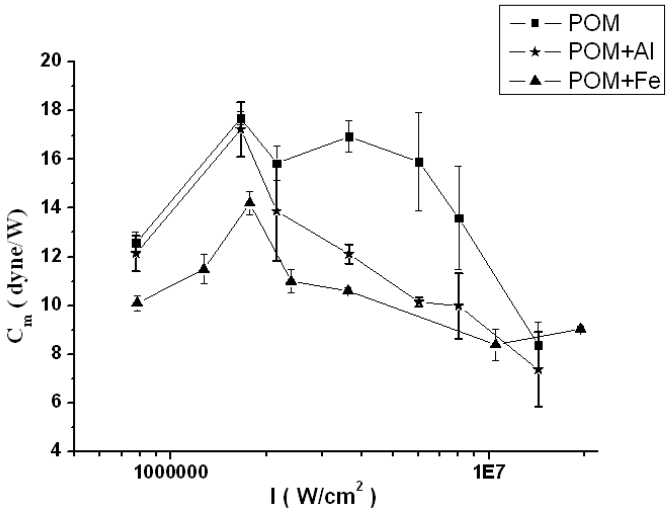

Figure 3. Experimental C_m versus laser power density curves for three kinds of propellants

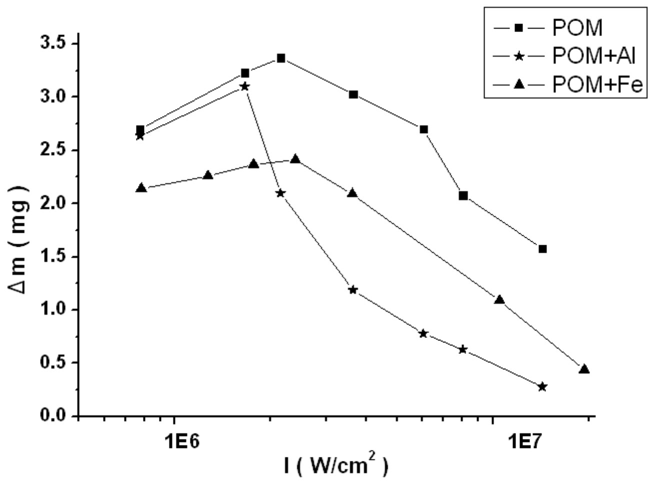

Figure 4. Mass loss per pulse versus laser power density for three kinds of propellants

Fig. 5 shows that the I_{sp} of POM propellants seeded with metallic particles are almost the same as that of pure POM at lower power density ($<1.7\times10^6$ W/cm^2), but when the power density is larger than 1.7×10^6 W/cm^2, the I_{sp} of POM+Al increases dramatically. At the maximum power density (1.4×10^7 W/cm^2) of the present experiment, the I_{sp} of POM+Al increases from 122.2 s to 606.7 s, which is about 5 times that of pure POM samples. The I_{sp} of POM+Fe is almost same as that of pure POM for I $<1.1\times10^7$ W/cm^2. Once the power density is larger than 1.1×10^7 W/cm^2, its I_{sp} also increases quickly, but is still less than that of POM+Al.

Fig. 6 indicates ablation efficiency η at the different power densities. With increase of the power density, the η value of pure POM increases at first and then decreases. The maximum η of pure POM observed in the experiments is about 9% at 8.0×10^6 W/cm^2. It is quite different for POM propellants seeded with metallic particles. As the power density increases, the η values of POM+Al and POM+Fe grow continuously to the maximum values of 21.9% and 15%, respectively, at the maximum power density observed in the experiment.

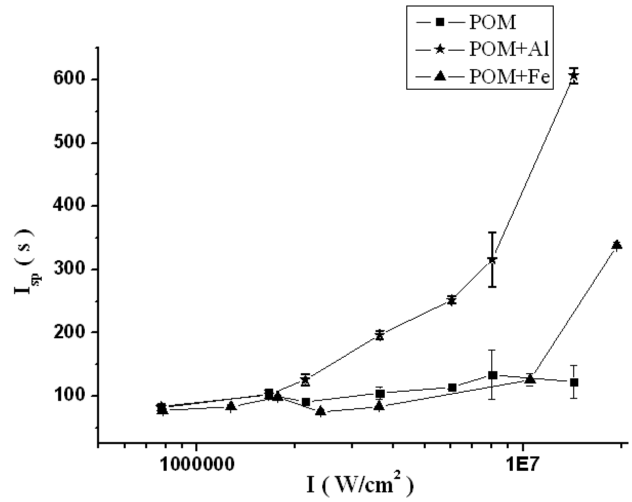

Figure 5. Experimental I_{sp} versus laser power density curves for three kinds of propellants

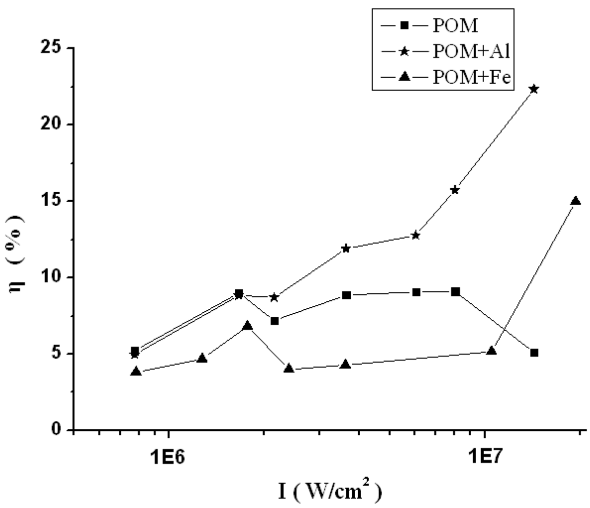

Figure 6. Curves of η versus laser power density

3.3 Comparison with the Experimental Results of Schall, et al.

By seeding POM with Al particles, it will enhance the shielding effect of the laser ablation products since aluminum particles can reduce laser absorption depth, so that we can get a higher I_{sp} value. Schall, et al. did a similar experiment with POM+20% Al particles [4], but their results showed all of the C_m, I_{sp} and η for POM propellant reduced by seeding it with Al particles. Why were their results different from the results shown in this paper? Laser parameters such as pulse width, power density and so on may affect propulsion performance greatly [7]. We think that the different laser pulse widths used in the experiments may be the main reason for this. The pulse width of the laser used by Schall, et al. was about 13 μs [4], and ours is about 5 μs. The laser waveform in Fig. 1 shows that although the pulse width of the laser lasts for about 5 μs, a peak separated from the main pulse profile appears in the first 200 ns, after that the strength of wave is less than 1/5 of the peak. In Schall, et al. experiments, the pulse width they used was wide [4], and no peak separated from the main pulse profile appeared. In fact, the process of laser ablation is that the electrons near the surface between target and air, transfer heat into the target after it absorbs energy, then the heated media expands rapidly to form vapor [9]. The vapor layer near the surface of the target is higher in temperature and free-electron density, and it can absorb laser energy strongly to produce ionization rapidly and completely, forming a high-temperature and high-pressure plasma layer. When the laser power density comes to some strength, the density of the free-electrons in the plasma layer is high enough to absorb almost the whole laser energy, and cut off the energy coupling between the laser beam and the target, which is the so-called shielding effect of laser ablation. Because the pulse width is wide in Schall, et al. experiments, it is possible that most energy is blocked off after producing the shielding effect, so it means that the majority of the laser energy may not reach the surface of target at later times, which is probably a significant reason for the results observed in the Schall, et al. experiment. In ours, because the pulse width is short and the laser strength of the 200 ns peak is much higher than later, the blocked energy after producing a shielding effect is smaller. Therefore, in our experiments, the propulsion performance of POM seeded with Al particles is enhanced.

Table 2. Mass loss per pulse of propellant in this work comparing with Schall, et al.

	Schall, et al.	This work
The pulse width of the laser (μs)	13	5
Average power density (W/cm^2)	7.67×10^6	8.0×10^6
Laser energy per pulse (J)	202	20
Mass loss per pulse-POM (mg) 3.4	2.08	
Mass loss of unit energy-POM (mg/J)	0.0168	0.0893
Mass loss per pulse-POM+Al (mg)	3.0	0.63
Mass loss of unit energy-POM+Al (mg/J)	0.0149	0.027

Tab. 2 lists the experimental results of mass loss both for the work of Schall, et al. and this work at a similar power density (8.0×10^6 W/cm^2). The data demonstrate that: (1) The mass loss of unit laser energy for pure POM propellant is only 0.0168 mg/J in the work of Schall, et al. because of the wider pulse width and it is 0.0893 mg/J in our experiment, the latter is about 5 times of the former. It means most of the laser energy fails to achieve the surface of the POM target in the Schall, et al. experiments. (2) The mass loss of unit laser energy for POM+Al is 0.0149 mg/J in the work of Schall, et al., which is close to their result for a pure POM target. It demonstrates the Al particles seeded in the POM matrix do not give effective shielding in Shall, et al.'s work since most laser energy does not achieve the target surface. In our experiment the mass loss of unit laser energy for POM+Al is 0.027 mg/J, which is about 30% of the pure POM target. Since more laser energy achieves the target surface in this work, the shielding effect of the Al particles added into the POM can be shown clearly. The reduced mass loss per pulse causes a higher I_{sp} by seeding POM with Al powder in the present work. Consequently, we can see that the use of a shorter laser pulse with a sharp peak is conducive to the improvement of the utilization of laser energy, and also can improve the propulsion performance of polymeric propellants seeded with metallic particles.

3.4 Confirmatory Experiments

In order to verify the conclusion in Section 3.3, we selected another TEA-CO_2 laser device. Its parameters are single pulse energy of 200 J, pulse width of about 5 μs without peak separated from the main pulse profile as shown in Fig. 7.

From Fig. 1 and Fig. 7, we can see the distribution with time of the pulse energy is obviously different between the two lasers. Laser 1 produces a large spike, while the waveform of laser 2 is nearly triangular and does not produce large spikes. C_m, I_{sp}, and η are measured with the method described in Section 3.1 by using Laser 2. The results are shown in Fig. 8 and Fig. 9.

As shown in Fig. 8, with increase of the laser power density, the C_m values of both propellants increase at first and then decrease. The C_m value of POM+Al is almost the same as that of pure POM propellant at lower power density (<2.1×10^6 W/cm^2). The C_m of POM+Al decreases observably at higher power density (>2.1×10^6 W/cm^2). At 4.9×10^6 W/cm^2 the C_m values of these two propellants have maximum difference.

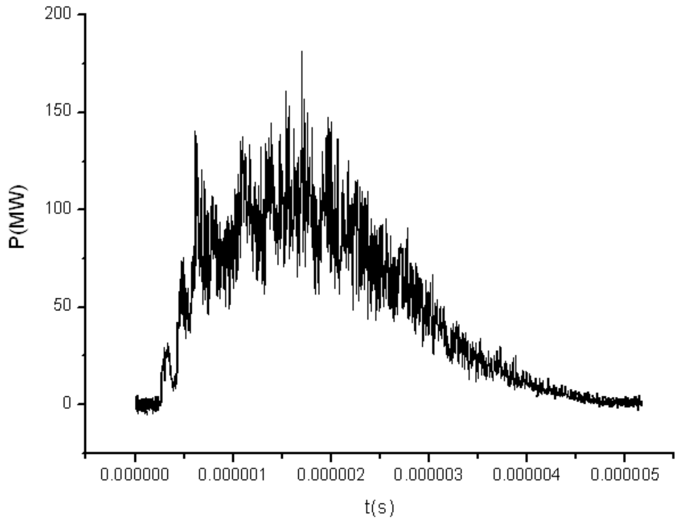

Figure 7. The laser pulse waveform in confirmatory experiments

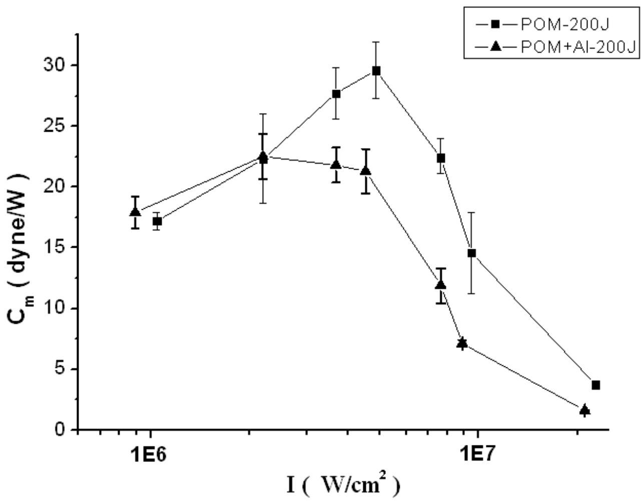

Figure 8. Experimental C_m versus laser power density curves for laser 2

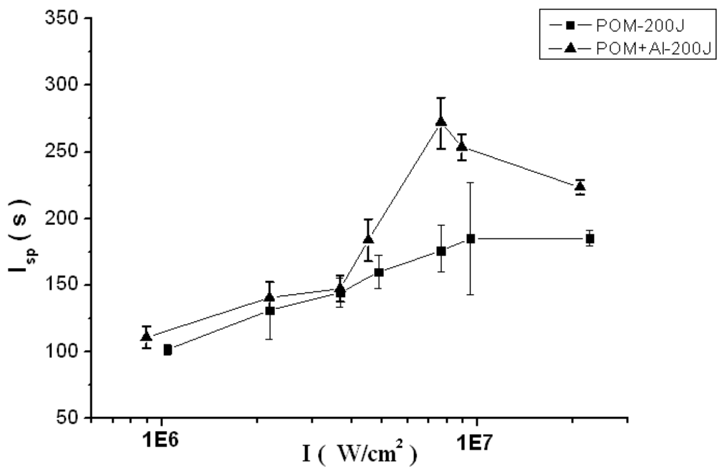

Figure 9. Experimental I_{sp} versus laser power density curves for laser 2

The experimental results in Fig. 9 show that the I_{sp} values of POM propellant seeded with Al particles are almost the same as those of pure POM at lower power density (<2.1×10^6 W/cm^2), but when the power density is larger than 2.1×10^6 W/cm^2, the I_{sp} of POM+Al increases dramatically, which is also different from the results of Schall, et al.. It shows that the shorter laser pulse width is better to improve the I_{sp} of POM with metal particles. In the present experiment, when the power density is 7.6×10^6 W/cm^2, the I_{sp} of POM+Al reaches to the maximum of 272.4s, which is about 35% higher than the I_{sp} =175s for pure POM at same power density, but is much lower than the I_{sp} increment by using laser 1 with a sharp peak. The confirmatory experimental result confirms that reducing the laser pulse duration can increase I_{sp} for POM target seeded with aluminum particles. Also it shows that a laser pulse profile with a sharp peak is beneficial to improve the propulsion performance of POM with metal powder.

4. CONCLUSIONS

Through the experimental investigation, we can make conclusions as follows:

1. With the increase of laser power density, the C_m values of all three kinds of the propellants increase at first and then decrease. The C_m value of POM+Al is nearly the same as pure POM at the low power density (<1.7×10^6 W/cm^2). The C_m value of POM+Al decreases observably at higher power density (>1.7×10^6 W/cm^2). The C_m-I curve of POM+Fe is almost parallel to the curve of POM+Al for the most part, but is underneath.
2. With increase of the power density, the I_{sp} of POM seeded with metallic particles show an obvious increase. The I_{sp} values of POM propellants seeded with metallic particles are almost the same as those of pure POM at lower power density, but when the power density is larger than 1.7×10^6 W/cm^2, the I_{sp} of POM+Al increases dramatically. When the power density is larger than 1.1×10^7 W/cm^2, the I_{sp} of POM+Fe increases dramatically, but the increased amplitude is less than that of POM+Al.
3. Laser parameters are important factors which affect the propulsion performance of propellants. Experimental results suggest that a laser with short pulse width and sharp pulse shape is conducive to the improvement of the performance of POM seeded with metallic particles.

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