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Numerical Simulation on Laser Propulsion Capability of Polymer Target

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ABSTRACT

A computational model of laser ablated polymer was established. Set the ablation criterion based on threshold energy. Put forward the polymer ablation criterion in the numerical model. It established the energy distribution equation to describe the laser ablation process. When the ablation products ejected, the target gained recoil impulse from ejection process. Get the ejection energy and the recoil momentum of target based on momentum conservation law. The numerical analysis model can reflect the propulsion capability of different polymer propellant, revealed the law of propulsion parameters in laser ablation process.

Keywords: Laser Propulsion; Laser Ablation; Polymer Target

1. Introduction

Laser propulsion as a new concept propulsion technology, it is given more and more extensive concern by the main astronautic powers. As one of the practical application achievements, laser ablation micro thruster is one of thefocus[1,2]. With its high specific impulse, wide dynamic range of impulse, small minimum impulse bit, low power and easy to realized the lightweight and digital control etc, laser ablation micro thruster has wide application prospects on high-precision task of satellite attitude adjustment, orbit maintain and networking formation control. Based on these applications, the generation of micro thrust using a middle or low intensity laser ablation was studied. The principle of laser ablation micro thruster is that using small portable laser ablated target can generate micro thrust. Due to low thermal conduction, low ablation threshold, polymer material was easily ablated to generate thrust[3,4]. Based on the summary of domestic and international laser micro propulsion development, this paper studied the polymer propulsion properties through establishing the theoretical calculation model.

Simulated the micro-thruster working vacuum environment, a computational model of low intensity laser ablated polymer was established. Put forward the polymer ablation criterion based on the experimental phenomena. The polymer doesn't have fixed fusion point, so building the ablation criterion based on threshold energy, which has observed in many experiments of reference. In the numerical model, the target ablation phenomenon happens when inner deposited energy achieves the threshold value. Along with inner deposited energy increasing, ablation phenomenon continually happened and ablation depth rose. It established the energy distribution model to describe the ablation process of temperature rise, phase change and the influence of chemical exothermic process. When ablation phenomenon happened the ablation products would ejected, and the target gained recoil impulse from ejection process. Based on the conservation law, assumed that in the ablation process the laser deposited energy consume in such aspects: fusion and vaporization process, target inner energy which made temperature rose, the exothermic energy in chemical reaction, product ejection energy. According to energy distribution equations we can get the ejection energy, and then get the recoil momentum of target based on momentum conservation law. Propulsion capability of laser ablated polymer was studied through the numerical analyse model. The generation law of impulse, thrust, impulse coupling coefficient, specific impulse, ejection velocity and ablation efficiency was calculated. And it analyzed the propulsion capability of different polymer targets.

The conclusions showed that, the numerical analysed model can reflect the propulsion capability of different polymer propellant, revealed the law of propulsion parameters in laser ablation process. The results for propellant selection, micro-thruster design and improvement of propulsion performance are valuable.

2. Numerical Modeling

Laser ablated a target can caused micro-thrust, the direction is showed in **Figure 1**. Based on the physical process of interaction between laser and polymer material, a numerical model was set up to simulate the ablation thrust and momentum coupling coefficient.

2.1. Thermal Conduction Equation

The first equation for interaction between laser and polymer is thermal conduction energy conservation equations for column symmetric case.

$$\rho C\frac{\partial T}{\partial t}=K\left[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T}{\partial r})+\frac{\partial}{\partial z}(\frac{\partial T}{\partial z})\right]+q_i \quad (1)$$

where ρ, C and K are the target density, specific heat and thermal conductivity, q_i is target inner deposited power when laser is heating.

$$q_i=\begin{cases}\alpha I_0(1-R)\exp(-\frac{r^2}{b^2}-\alpha z), & 0\le r\le b\\ 0, & r>b\end{cases} \quad (2)$$

where I_0 and b are laser power and radius, R is target reflectivity, α is laser absorption coefficient in target.

2.2. Ablation Threshold Energy

Summarizing laser ablated polymers experiment results, the ablation process is described by the following equation[5,6]

$$d(F)=\frac{1}{\alpha}\ln(\frac{F}{F_t}) \quad (3)$$

where F and F_t are laser fluence and ablation threshold fluence; $d(F)$ is the ablation rate; α is the laser absorption coefficient. In the process of laser ablation, The polymer don't have fixed fusion point, so in this paper we build the ablation criterion based on threshold energy, which has observed in the experiment. In our numerical model, the target ablation phenomenon happens when inner deposited energy achieve the threshold value. Along with inner deposited energy increasing, ablation phenomenon continually happened and ablation depth rose. According to Eq.(3), the ablation threshold energy is

$$E_{th}=\alpha F_t\exp(\alpha z) \quad (4)$$

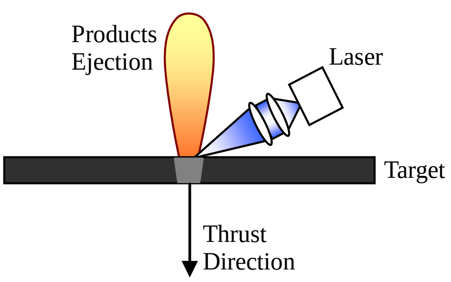

Figure 1. Sketch of laser ablated polymer target.

After laser irradiation last time t, the target inner deposited energy is

$$E_i=\alpha I_0(1-R)\exp(-\alpha z)t \quad (5)$$

When inner deposited energy is larger than ablation threshold energy, the ablation phenomenon happened, so the ablation criterion is

$$E_i\ge E_{th} \quad (6)$$

2.3. Energy Distribution Equation

When Eq.(6) achieves, it means the ablation phenomenon happened, and the ablation products would ejected, the target gained recoil impulse from ejection process. Based on the conservation law, we assume that in the ablation process the laser deposited energy consume in such aspects: fusion and vaporization process, target inner energy which made temperature rose, the exothermic energy in chemical reaction, product ejection energy. the distribution equation of energy E_i is

$$E_i=\rho[h_f+h_v-h_c+C(T_a-T_0)]+E_{ej} \quad (7)$$

where h_f,h_v and h_c are fusion heat, vaporization heat and exothermic energy; T_a and T_0 are ablation temperature and initial temperature; E_{ej} is ejection energy. According to all above equations we can get the ejection energy E_{ej}, so the momentum P_{ej} is

$$P_{ej}=\sqrt{2m_aE_{ej}} \quad (8)$$

where m_a is ablation mass. Based on momentum conservation law, P_{ej} is equal to the recoil momentum P of target.

2.4. Simulation Setting

Considering the symmetry configuration of laser and target, planar symmetric column coordinate is used in simulation model. In actual ablation process, the ablated products would eject form target and dissipated, so in the simulation model we set a ablation moving boundary, see **Figure 2**.

In this paper, chose PVC (Poly vinylchloride), POM (Polyoxymethylene), GAP (Glycidylacide polymer) as targets in computation example, the parameters[7,8] of polymer in **Table 1**. It analyzed the propulsion capability of different polymers.

3. Numerical Results and Analysis

3.1. Momentum Coupling Coefficient

Figure 2 shows the relation of momentum coupling coefficientwith laser power. When ablation begin, the momentum coupling coefficient increased rapidly and reach the peak then fall slowly, the reason is plasma screening effect weakened reaction of laser and target.

The exothermic polymer GAP has the maximal momentum coupling coefficient48dyn/W, because released chemical energy in the ablation process, but PVC and POM don't have additional energy in ablation.

3.2. Specific Impulse

Figure 3 shows the relation of specific impulse with laser power. When ablation begins, the exothermic polymer GAPreleased chemical energy in the ablation progress so has the maximalspecific impulse200s. The PVC and POMincreased slowly, the stabilization are 120s and 50s.

3.3. Compare with Experiment

The **Figure 4** shows the comparison between experiment and numerical model. According to literature description, using our numerical model to calculate the experiment results, lines represent experiment data and dots represent simulation results [9,10]. The simulation results are basically accord with the experiment data. But there is a little different, the simulation results are less than the experiment data in short laser pulse width. The reason maybe in short width the mechanismis more complex, and the model can't simulatevery well.

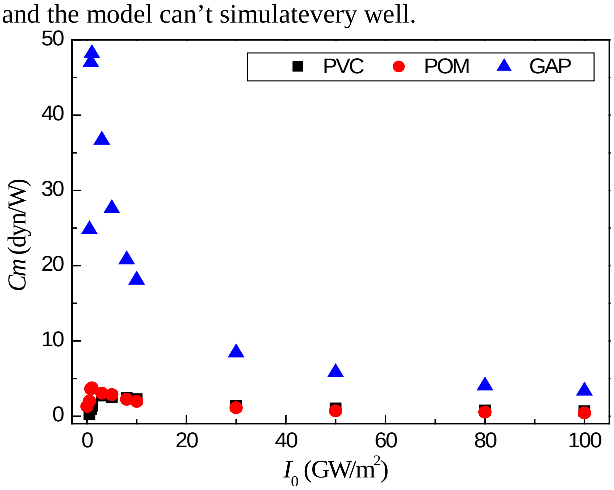

Figure 2. Momentum coupling coefficient of polymers.

Table 1. Parameters of polymer target.

	PVC	POM	GAP
Densityρ Kg/m^3	1439	1410	1290
Thermal conductivity$K$ W/(mK)	0.15	0.36	0.40
Specific heat$C$ J/(kgK)	1700	1450	1800
Reflectivity$R$	0.2	0.2	0.2
Absorptioncoefficientα 1/m	1.7×10^5	1.0×10^5	2.0×10^4
Vaporization heath_v J/kg	2.8×10^5	5.0×10^5	1.9×10^6
Chemical heath_c J/kg	0	0	3.0×10^6
Ablation thresholdF_t J/m^2	9.0×10^3	1.0×10^4	3.1×10^4

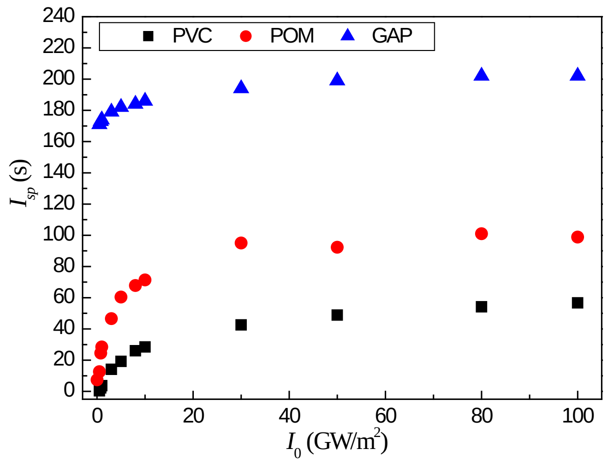

Figure 3. Specific impulse of polymers.

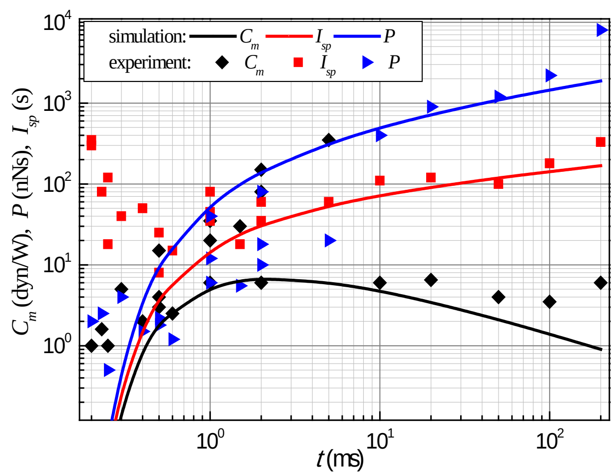

Figure 4. Compare simulation with experiment.

4. Conclusions

Numerical model of laser ablated polymer was founded to analyzed the propulsion capability of PVC, POM, GAP. The results show that, the exothermic polymer GAP has great propulsion capability because released chemical energy in the laser ablation process. Its maximalmomentum coupling coefficient and specific impulse are 48 dyn/W and 200s, more than PVC and POM. Polymer GAP is an excellent propellant in laser ablation propulsion.

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