JOURNAL OF PROPULSION AND POWER
Vol. 25, No. 5, September–October 2009

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Comparative Study of Plastics as Propellants for Laser Ablation Plasma Thrusters

Muddassir M. S. Gualini*
Polyitecnico di Torino, 10129 Turin, Italy
Shakeel A. Khan†
Federal Urdu University of Arts, Sciences and Technology, Islamabad 44000, Pakistan
and
Salman Iqbal‡
International Islamic University, Islamabad 44000, Pakistan

DOI: 10.2514/1.40318

Nomenclature

C_m = coupling coefficient
$F(t)$ = produced thrust
I_{SP} = specific impulse
$\overset{*}{Q}$ = energy of ablation per unit mass
v_E = exhaust velocity
v_T = target velocity

I. Introduction

A NEW analysis and comparison of laser ablation propulsion (LAP) parameters like specific impulse and coupling coefficient obtained while ablating different prospective plastic materials is presented in view of selecting the most suitable of them. The tests involved a medium–low energy pulsed laser along with a free-moving ballistic pendulum with a target pasted on it. In a novel application of 2-D position-sensitive detectors (PSDs) in LAP, the displacement measurements were taken by the noncontact optical triangulation with a laser. Their use gave the advantages of detecting any unwanted lateral movement of the pendulum. The study should have high utilization for the future LAP applications.

Laser ablation propulsion technique, introduced by Arthur Kantrowitz in 1972, depends upon the characteristics of laser source as well as those of the target material, as the momentum of the target is produced in reaction to the generated momentum of the ejecting particles [1–3]. Specific impulse values up to several thousand seconds are possible by properly choosing the propellant, that is, target material and the laser pulse characteristics. The momentum of the object may well also depend on the coupling coefficient of material–laser interaction. Earlier works include ablation with some of the materials included in this study, but here a list of three commonly available plastics is analyzed and compared [3–6]. Additionally, most researchers have employed mechanical force sensing for thrust measurement or charge-coupled device imager for displacement measurement [5], whereas others have used electromagnetic coils for sensing torque on the suspended target [3]. On the other hand, here a noncontact optical triangulation method is being employed using a precision PSD with 1 μm resolution and a stable He-Ne laser. This yields direct measurement and better accuracy along with lateral-shift error reduction, and thus useful output curves have been obtained.

II. Mathematical Model

Defining the coupling coefficient Cm as $m\Delta v/W$, the energy to ablate unit mass ($\overset{*}{Q}$) as $W/\Delta m$ [4,5,7] and applying the law of conservation of momentum on LAP apparatus, the following can be written:

$$\Delta v_T = C_m\left(\frac{w}{m_T}\right) \tag{1}$$

Specific impulse, commonly defined as the impulse (change in momentum) per unit mass of propellant, is commonly denoted by I_{SP} and can be approximated as $I_{SP} \sim m\Delta v/\Delta m$. It can be related to v_E by dimensional analysis as follows. Here the thrust produced by the laser energy is given by $F(t) =$ Thrust $F(t) = PC_m$ [4,5,7]

$$C_m\overset{*}{Q} \;=\; v_E = g\, I_{SP} \tag{2}$$

If the material is mounted over a pendulum as shown in Fig. 1, the angular displacement for low values of θ may be given as follows:

$$\theta \approx \tan\theta = \frac{X}{2D} \tag{3}$$

Here, X is the displacement of the reflected laser beam spot and D is the distance from the pendulum to the plane of measurement. The coupling coefficient derived from this measurement is given by Pakhomov and Gregory [4]

$$C_m = \frac{mgrT}{2\pi WL}\sqrt{2(1-\cos\theta)} \tag{4}$$

Here m is the pendulum's total mass, r is the pivot point to center of mass distance, T is the oscillation period, L is the pivot to target point length, θ is the angular displacement, and W is the energy per pulse of the laser.

III. Experimental Setup

The schematic diagram of the experiment is shown in Fig. 2. An Nd:YAG laser of 50 mJ/pulse energy at 1064 nm wavelength was used with a pulse duration of 8 ns, and it was operated in single shots mode. The focusing lens used is a biconvex lens that can focus the laser beam at its focal point to about 0.5 mm diameter of beam spot.

Received 8 August 2008; revision received 28 April 2009; accepted for publication 4 May 2009.

*Research Fellow, Department of Electronics Engineering. Member AIAA.

†Doctoral Student, Department of Applied Physics.

‡Doctoral Student, Department of Electronics Engineering, currently, Government of Pakistan.

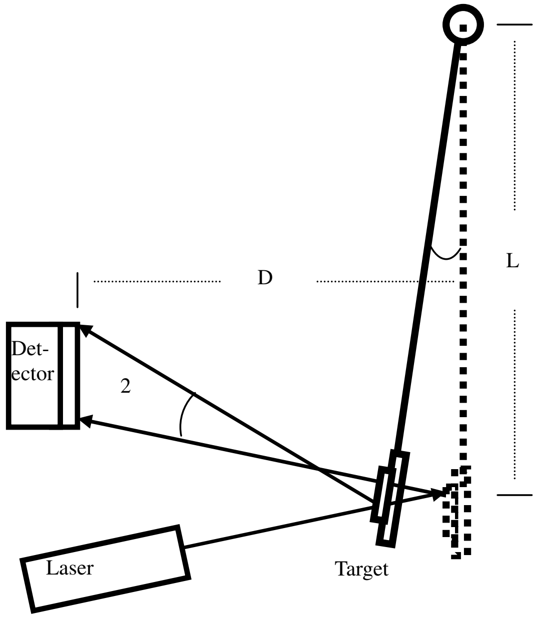

Fig. 1 Pendulum displacement measurement by optical triangulation method.

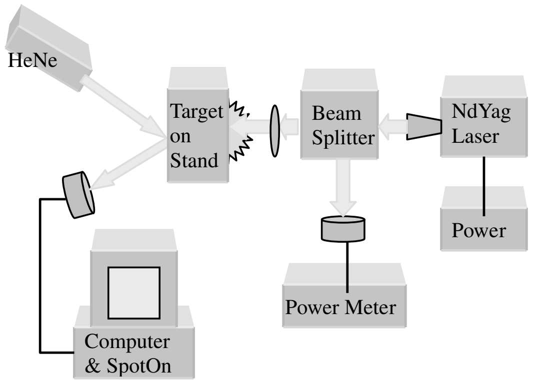

Fig. 2 System components' layout.

This makes the fluence of the shot about 250 mJ/mm^2. The pendulum had a mass of 14.15 g.

The pendulum displacements were measured using a dual-axis lateral effect position-sensitive detector combined with a low-power He-Ne laser unit, for the noncontact measurements with the additional advantage of lateral movement sensing. This setup is implemented by a commercial calibrated system known as Spot-On. The system has full-length linearity and position resolution of ± 1 μm in the spectral range of 350–1050 nm band. Extending the work done earlier on polymers and plastics [7,8], three standard plastic materials were used in the experimentation to compare their performance for laser ablation propulsion, including 1) black-coloured vinyl insulation tape, which is commonly used for electrical assemblies; 2) white-coloured Delrin (with generic name of acetal), which is a thermoplastic polymer; and 3) grey-coloured PVC (a polymer of vinyl-chloride), which is a widely used plastic.

Table 1 Comparison of parameters for different plastic materials

Parameter/material	Vinyl tape	Delrin	PVC
Maximum displacement X, cm	0.0177	0.0197	0.0238
First interval displacement, μm	86	103	128
Time interval, s	0.05	0.05	0.06
v_T, cm/s	0.172	0.206	0.213
D, cm	36	36	36
Angular displacement θ, mrad	0.2458	0.2736	0.3306
I_{SP} for 3 μg/pulse, s	850	1018	1054
Cm, dynes-s/J	5.05	5.62	6.79
Thrust per pulse, N	315	351	424

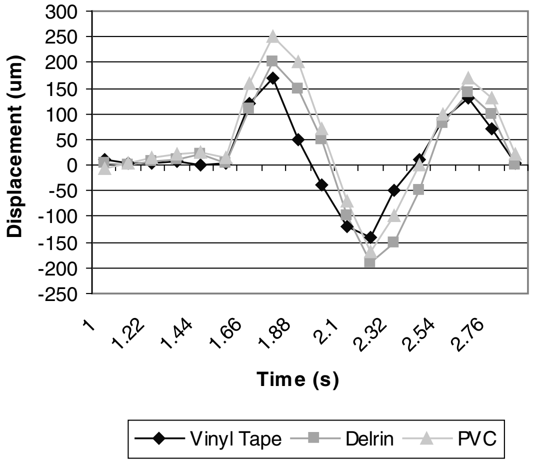

Fig. 3 Comparison of pendulum displacement curves for single ablation pulse.

IV. Results

Figure 3 shows the individual displacements produced by the three different materials and subsequent pendulum oscillations. Data analysis showed that ablation of PVC has produced the maximum deflections. In Table 1 the major parameters obtained from the experiment are reported.

Displacements were measured in small intervals, and the velocity of the pendulum was estimated. Because of the apparatus limitations, the ablated mass could not be directly measured and, rather, was calculated from the data of the movement of the pendulum to be about 3.0 μg for each pulse. Using this information, the velocity of species (i.e., ions) of the plume was estimated, which comes in the range of hypersonic velocities even for small energies per pulse as in our case [9]. The mathematical formulation discussed earlier can be used to find the necessary parameters like C_m, initial velocity of the pendulum, and I_{SP}. These are compared in Fig. 4, with PVC giving better performance.

Comparing our results with the earlier works, even with low laser fluence used, I_{SP} values compare well with the values obtained by Phipps et al. [3] or Sterling et al. [5] with the earlier showing much

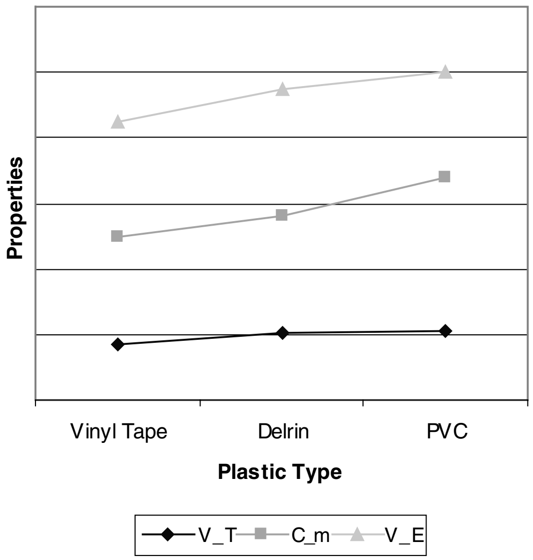

Fig. 4 Graphical comparison of v_T, C_m, and v_E for the different materials.

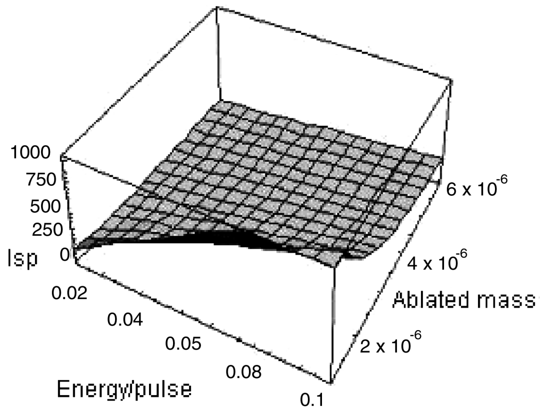

Fig. 5 Change in values of I_{SP} for different values of energy/pulse and ablated mass of gray PVC.

wider measured range. Performance of PVC is shown better here than contending materials when compared with earlier works. The C_m values match very well with those given by Phipps, whereas Pakhomov obtained much different values [3,5]. For our sample and the used data, the expected values of I_{SP} for PVC are shown in a surface graph in Fig. 5 by simulating different ablated masses and different energies per pulse. It may be viewed as a more regular form of some of the earlier data depictions [3].

V. Conclusions

A new and useful comparative analysis of laser ablation propulsion parameters like specific impulse and coupling coefficient obtained while using different standard plastics (PVC, Delrin, and vinyl tape) is presented. A novel application of optical triangulation was adapted for the displacement measurement while using a 2-D position-sensitive detector, which also showed any unwanted lateral movement of the pendulum. Acquired values compare well with the results of earlier works with some differences. Among the tested samples, PVC showed better performance in terms of critical propulsion parameters like C_m and I_{SP}, and its detailed analysis was also shown.

Acknowledgments

Authors are thankful to the Higher Education Commission, Pakistan, for funds; John Sinko, University of Alabama in Huntsville, for encouragement; and the Institute of Industrial Control System for support.

References

[1] Kantrowitz, A., “Propulsion to Orbit by Ground-Based Lasers,” *Astronautics and Aeronautics*, Vol. 10, No. 5, 1972, pp. 74–75.

[2] Phipps, C., Luke, J., Lippert, T., Hauer, M., and Wokaun, A., “Micropropulsion Using a Laser Ablation Jet,” *Journal of Propulsion and Power*, Vol. 20, No. 6, 2004, pp. 1000–1011. doi:10.2514/1.2710

[3] Phipps, C. R., Luke, J. R., McDuff, G. G., and Lippert, T., “Laser Ablation Powered Mini-Thruster,” *SPIE Conference Proceedings*, Vol. 4760, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 2002, pp. 833–842.

[4] Pakhomov, A. V., and Gregory, D. A., “Ablative Laser Propulsion: An Advanced Concept for Space Transportation,” *Young Faculty Research Proceedings*, University of Alabama in Huntsville, Huntsville, AL, 2000, pp. 63–72.

[5] Sterling, E., Lin, J., Sinko, J., Kodgis, L., Porter, S., Pakhomov, A., Larson, C., and Mead, F., “Laser-Driven Mini-Thrusters,” *AIP Conference Proceedings*, Vol. 830, American Institute of Physics, Melville, NY, 2006, pp. 247–258.

[6] Bennett, L. S., Lippert, T., Furutani, H., Fukumura, H., and Masuhara, H., “Laser Induced Microexplosions Of A Photosensitive Polymer,” *Applied Physics A: Materials Science & Processing* , Vol. 63, No. 4, 1996, pp. 327–332.

[7] Pakhomov, A. V., Thompson, M. S., and Gregory, D. A., “Ablative Laser Propulsion: A Study of Specific Impulse, Thrust and Efficiency,” *AIP Conference Proceedings*, Vol. 664, American Institute of Physics, Melville, NY, 2003, pp. 194–205.

[8] Bityurin, N., Lukyanchuk, B. S., Hong, M. H., and Chong, T. C., “Models for Laser Ablation of Polymers,” *Chemical Reviews (Washington, DC)*, Vol. 103, No. 2, 2003, pp. 519–552. doi:10.1021/cr010426b

[9] Gualini, M. M., Khan, S. A., and Zulfiqar, K., “Development of Laser Propelled Semi-Perpetual Rotary Machine,” *AIP Conference Proceedings*, Vol. 830, American Institute of Physics, Melville, NY, 2006, pp. 591–599.

G. Spanjers
Associate Editor