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Dependence of *Cm* on the composition of solid binary propellants in ablative laser propulsion

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ABSTRACT

Propulsion pellets of different metal/salt ($Zn/CaCO_3$) composition have been prepared. The impulse imparted to the pellet by the laser has been measured using two different methods: a torsion pendulum and a piezoelectric sensor. The dependence of the coupling coefficient, C_m, on the composition of the solid binary propellants in ablative laser propulsion has been investigated under different experimental conditions: in vacuum and at atmospheric pressure as well as with two different wavelengths, IR and UV. The composition of the $Zn/CaCO_3$ propellant mixture that optimizes the coupling coefficient, C_m, has been determined.

1. Introduction

Ablative laser propulsion has demonstrated to be better than other propulsion schemes in terms of specific impulse, that is, of the efficiency of energy conversion to mass–power ratio. In this sense, the most recent experimental results in which micro-spheres of metallic and non-metallic elements have been used show that the coupling efficiency, C_m (momentum transfer per unit incident laser energy) [1] is to a large extent dependent on the diameter and material of the spheres as well as on the laser pulse width. In consequence, the dependence of ablative laser propulsion on the different parameters needs to be further investigated.

Many works on laser ablation have been published in the literature [2]. Most of them have focused on the physical processes that dominate this phenomenon. However, in the literature consulted by these authors, no studies relating these processes to ablative laser propulsion have been found. On the other hand, a lot of research has been carried out using the Laser induced breakdown spectroscopy (LIBS) technique, particularly in the analytical chemistry area [3]. These studies could provide very useful information to enhance the laser propulsion yield. The LIBS technique uses matrices doped with analytes which emit light following ablation. It has been demonstrated in different works in this area that the minor component (analyte) dominates the laser energy absorption process while the major component (matrix) controls the physical behavior (structure, ductility, etc.). These features have enabled the development of stable matrices for metal determination in soils by means of LIBS [3]. The determination of the physical characteristics of a matrix and their relation with the emission of electronically excited particles is a basic requirement for the development of propellants for laser ablation. On the other hand, as it has been demonstrated by Villagrán-Muniz and co-workers [4], it is also possible to determine the energy distribution in the laser ablation processes by using piezoelectric sensors. The opto-acustic signals obtained with this method can be used to characterize the laser propulsion processes.

The measurement of the velocities of the particles ejected during the ablation process cannot be used to perform a correct determination of the coupling coefficient. These measurements constitute a very important topic in the studies of chemical dynamics since the LIBS technique has been used to produce molecular beams with hyper-thermal velocities [5]. In these studies Rossa et al. [6] have determined that the atoms and ions excited in different electronic states possess different velocities. These velocities differ as well from those of the same species in their fundamental states. Therefore, these features hinder a correct measurement

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of the coupling coefficient, C_m, from the velocities of the ejected particles.

Bearing in mind the precedent information, the concepts of ablation matrix for analytical purposes [3] and utilization of piezoelectric sensors [4] have been applied in this paper to the development of solid propellants composed of metal/salt mixtures and to the optimization of the coupling coefficient. Propellant pellets of different Zn/$CaCO_3$ composition have been prepared. The impulse imparted to the pellet by the laser has been measured using two different methods: a pendulum of torsion and a piezoelectric sensor. Then, ablation of the pellets has been performed in an evacuated system in order to uncouple the impulse imparted by the plasma expansion produced by air breakdown from that transferred by the momentum transmitted by the ablated material. The propellant samples have been irradiated both with IR and UV laser radiation. The composition of the binary propellant mixture that optimizes the coupling coefficient, C_m, has been determined from the results obtained.

2. Experimental

In this section the procedure used to prepare the propellant pellets is presented. In addition, two experimental methods used to measure the coupling coefficient, *Cm*, are described.

2.1. Propellant pellets preparation

In order to determine the composition of the propellant pellet it was necessary to carry out a study to enable the selection of the matrix as well as of the ablation conditions (wavelength, laser fluence). A preliminary analysis was undertaken taking into account that the ablation process is mainly governed and characterized by the matrix composition. As a result the use of Zn as ablation matrix was defined [3]. This selection was performed on the basis that Zn favors the ablation process due to its physical and thermal properties: low ionization potential and high electronic density [7]. It also improves the homogeneity and cohesion of the sample, resists the mechanical shock and allows the vaporization of the surface target avoiding the crumbling effect [8]. On the other hand, there is experimental evidence that a small amount of salt ($CaCO_3$) can produce large effects on the processes of emission of light and particles during the ablation of a Zn matrix [3].

Therefore, in order to determine the coupling coefficient, C_m, and its relation to the propellant composition (metal/salt), pellets with different (Zn/$CaCO_3$) concentration ratio has been prepared.

The pellets of 0.5 g and 10 mm of diameter per 1.5 mm of thickness, were prepared by mixing Zn metal powder (Mallinckrodt, 99.99%) and $CaCO_3$ (Aldrich powder, 99.99%) in a mortar, which were subsequently powdered using a mill and then pressed in two stages. In the first stage, a pressure of 36 kpsi was applied for 10 min and, in a second stage; the pellets were additionally pressed with 54 kpsi during 5 min. This pressure reduces strongly the effects of the size of the particle in the ablation process, increasing the homogeneity of the surface of the sample and reducing its humidity content. The grain size of the powder of the pellets was not determined. Even though it might have an influence on the ablation efficiency, the experiments were performed at laser fluences above the threshold for massive ejection of material [9] and in this condition any effect of grain size should be negligible [10]. The composition of the propellant pellets was also controlled by infrared spectrometry. FTIR spectra of 100% Zn pellets show ZnO and carbonates impurities as expected from exposition to air. Table 1 shows the composition of the propellant pellets.

Table 1
Composition of the propellant pellets.

Pellets	Zn (% w/w)	$CaCO_3$ (% w/w)
1	0	100.00 ± 0.01
2	29.89 ± 0.01	70.10 ± 0.01
3	49.81 ± 0.01	50.19 ± 0.01
4	70.34 ± 0.01	29.66 ± 0.01
5	89.87 ± 0.01	10.13 ± 0.01
6	94.98 ± 0.01	5.02 ± 0.01
7	100.00 ± 0.01	0

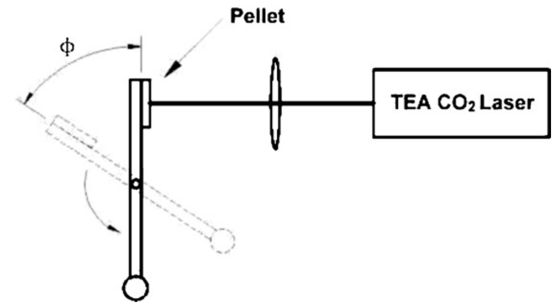

Fig. 1. Experimental set-up for pendulum of torsion measurements.

2.2. Measurement of the impulse with a pendulum of torsion

The pellets were placed in the set-up shown in Fig. 1 which consists of a pendulum of torsion implemented in the laboratory. A pulsed homemade TEA CO_2 laser tuned to the 10P(20), 10.59 μm, emission line was used to produce ablation on the pellet. The laser output energy was 2.5 J *per* pulse and the pulse width was 80 ns. The laser beam was focused on the center of the target, with a flat–convex lens of 12.7 cm focal length and a spot size of 1 mm was obtained in the ablation point on the pellet. The laser fluence, ϕ, was thus estimated in 320 J/cm^2.

The entire procedure was recorded by a video camera operating at 24 fps. The angular velocity was then measured using a program for digital images processing (ImageJ) that allows to process movies [11]. A set of five movies was filmed for each pellet (for statistical propose) in order to measure the C_m as a function of the pellet composition. Then each movie was analyzed with a plug-in incorporated in the ImageJ software. A typical data set obtained after using the ImageJ processing software is shown in Fig. 2.

Fig. 3 shows a diagram of a pendulum of torsion. Its movement can be described by Eq. (1) with the initial conditions given

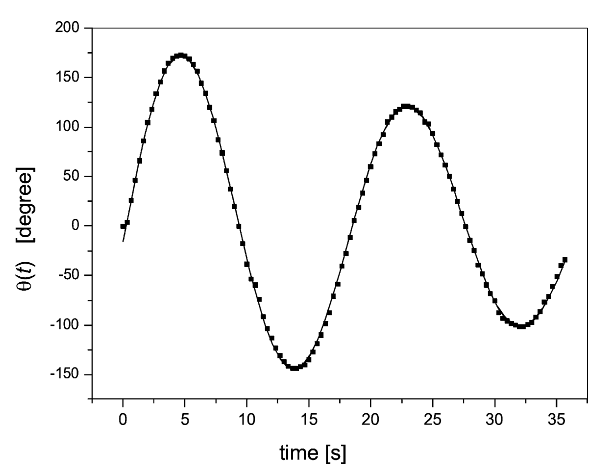

Fig. 2. Typical time-dependent data set obtained after processing the movies.