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Comparison of Laser Ablation Effects to Hypervelocity Impact and Debris Darkening

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Abstract

Hypervelocity impact (HVI) studies are very important for understanding space debris, and play a crucial role in current fragmentation modelling predictions. Both the number and size of orbital debris particles are inputs to different models. The interpretation of optical measurements of orbital debris and the physical sizes of the particles require information on albedo of the particles. While hypervelocity impact experiments at a gun range can offer a realistic representation of the energy of impact and fragmentation, laboratory simulation using laser ablation with a high power laser is appealing because it provides the opportunity to investigate a variety of parameters and couple these to optical albedo measurements of HVI debris in a well-controlled and repeatable environment. Most importantly, laser ablation experiments can be conducted in high-vacuum of 10^{-8} Torr, which is representative of the pressure in the Low Earth Orbit (LEO) environment, in contrast to the hypervelocity impact experiments that are typically conducted in low pressure (1-2 Torr) air. Here we compare experiments conducted with laser ablation to hypervelocity impact tests. Specifically, we compare microscopic debris from laboratory ablation with that from the 2014 hypervelocity impact test on DebriSat. Results from microstructure and size distributions of debris collected on witness plates show that laser ablations in low-pressure air offer many similarities to the hypervelocity impact experiments, while ablations in high-vacuum provide critical distinctions relevant to LEO.

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Keywords: Hypervelocity Impact, Laser Ablation, Albedo, Debris Darkening

1. Introduction

Understanding space debris relies heavily on an understanding of hypervelocity impact (HVI), which in turn plays a crucial role in current fragmentation modelling predictions. Low earth orbit (LEO) and geosynchronous orbit (GEO) are the most crowded orbits [1]. Numerous radar and optical measurements are being conducted to identify the material composition of space debris, as well as, establish their physical sizes [1-6]. A critical parameter for the interpretation of physical sizes of the space debris particles from optical measurements is the albedo of fragments [2,3]. Currently observations of debris in LEO are conducted with radar, while most

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optical observations are used to view debris in GEO [1, 4-6].

While hypervelocity impact experiments at a gun range can offer a realistic representation of the energy of impact and fragmentation, they are not typically performed at extremely low pressures of 10^{-8} Torr or lower, that are representative of the low-earth orbit (LEO) environment. In addition to field testing, there have been numerous investigations of HVI in a laboratory environment [4-11] to examine different effects. Roybal et al. reported hypervelocity damage experiments [7] performed on spacecraft materials in order to simulate micron-sized debris travelling at 3-8 km/s. They used polysulfone resin and a graphite-polysulfone composite, with a Nd-YAG laser at 1.06 um for laser ablating the targets. Mechanical damage to the surface was studied and the ejected vapour analyzed using time-of-flight mass spectrometry. Heunoske et al [8] studied the time-resolved emission spectroscopy of the impact plasma. The experiments were conducted with EMI's Space Light-Gas Gun, capable of accelerating projectiles of a few mm in diameter to 10 km/s. The target was housed in a chamber held at 10^{-4} mbar in order to eliminate plasma interactions with the residual atmosphere. According to Pirri [9], the use of laser ablation to simulate hypervelocity shock in a material could be accomplished by setting the laser spot equal to the diameter of the particles and the pulse duration equal to the particle impact duration. Arad [10] looked at the similarity between impact events in space and laser impacts by comparing crater morphology in aluminium, gold and alumina, and by discharge initiation on metal-oxide-silicon capacitor impact detectors. Tandy et al. [11] used a 2-stage light gas gun to accelerate 5 mg nylon cylinders to speeds of 5 -7 km/s. They used UV-visible emission spectroscopy and high-speed imaging to study the process.

Here we provide results of laboratory simulations of hypervelocity impact using laser ablation with a high power excimer laser at 248 nm, on 6061 Al alloy target, the same material that comprised the exterior of the satellite structure used for DebriSat. The experiments could be conducted in high-vacuum (10^{-7}-10^{-8} Torr) and offered the flexibility of selecting any gaseous ambient, at any controlled pressure, thus allowing for comparison to the hypervelocity impact experiments in low-pressure air. The setup is also appealing because it provides the opportunity to investigate the effects of various parameters in a well-controlled and repeatable environment. Another important attribute of conducting laboratory measurements is that it does not require foam catch panels (used in DebrisLV and DebriSat experiments [12] to catch fragments) that interfered with microscopic debris analyses and albedo measurements.

Experiments are coupled with optical characterizations (UV-VIS-NIR reflectance), chemical characterization, surface morphology, and particle size distributions. In-situ spectroscopic identification of atoms and ions in the plume as a function of incident laser fluence is used to correlate energetics of the ablated plume with resulting particle size distributions of ablated debris and corresponding albedo. Initial results from spectroscopic plume analysis, and the microstructure and size distributions of ablated debris collected on witness plates show that laser ablations in low-pressure air offer many similarities to the hypervelocity impact experiments, while ablations in high-vacuum provide critical distinctions.

By addressing these critical issues, this relatively low-cost laboratory approach can complement the significantly more elaborate and expensive field-testing involving a single-shot hypervelocity impact on representative satellite structures. Specifically, we are trying to understand and compare the microstructure and albedo of debris generated by laser ablation to the hypervelocity impacts on DebrisLV and DebriSat, conducted jointly by the Space and Missile Systems Center (SMC), National Aeronautics and Space Administration (NASA), The Aerospace Corporation, Arnold Engineering Development Center (AEDC), and University of Florida. The test (conducted on April 15, 2014) was aimed at simulating an on-orbit destructive collision of a modern satellite by a hypervelocity projectile. In brief, DebriSat was a 56 kg structure representative of a modern LEO spacecraft. Debris LV was representative of a booster upper stage with tanks made of Al and Ti, and tested on April 7, 2014. A 580 g, hollow nylon-Al projectile, 86 mm in diameter and 90 mm long, and with a measured velocity of 6.8 km/s, was designed by AEDC. Additional details and the results of spectroscopic measurements on the flash from the hypervelocity impact on DebriSat have been previously described [12].

Laser ablation differs from hypervelocity impact in that the laser material interaction occurs at the surface, leading to rapid heating and vaporization of the surface layer. This then results in a high pressure that creates a shock in the target. In hypervelocity impact, the projectile goes right through the bulk of the target. We have calculated the energy/unit mass of Al in the hypervelocity impact vs. laser ablation experiments. For the DebriSat test, the mass of the Al projectile was 580 g, and its velocity was 6800 m/s. This corresponds to a kinetic energy (KE) of 1.32 x 10^{7} J. Upon hitting the first surface, which was Al honeycomb (mass 8.9 g, velocity 0 km/s), the velocity of the projectile gets reduced to 6700 m/s and the corresponding KE was 1.28 x 10^{7} J. The difference in KE was 4 x 10^{5} J. This is the KE that was dispersed in 8.9 g of Al honeycomb. Hence the energy from the hypervelocity impact per unit mass of Al honeycomb was 4.5 x 10^{4} J/g. In the case of laser ablation, for a fluence of 10 J/cm^{2}, when absorbed within 100 nm of Al target, the corresponding volume is 10^{-5} cm^{3}. The mass of Al hit by the laser is this volume times its density (2.7 g/cm^{3}). Hence the laser energy per unit mass of Al is 10 J/2.7 x 10^{-5} g, or 3.5 x 10^{5} J/g. This is within a factor of 10 of the hypervelocity impact on the first surface, and is easily the same, if the absorption depth ranges from 100 nm to 1000 nm.