EXPERIMENTAL STUDY OF SPACECRAFT MATERIAL EJECTED UPON HYPERVELOCITY IMPACT

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ABSTRACT

Twenty-eight hypervelocity impact experiments were carried out at CISAS impact facility, with the aim of assessing the amount of ejecta from three different targets representative of spacecraft materials, i.e. simple aluminum-alloy plates, silicon solar cells and simple aluminum-alloy plates covered by MLI blankets. Projectiles having different size (1, 1.5 and 2.3 mm diameter) were launched at speed ranging from 4 to 5.5 km/s and impact angle from 0° to 80° (the impact angle dependence was evaluated for simple aluminium targets only). Experiments pointed out that the number of ejecta produced after HVI is significantly high (order of thousands). Moreover, it was shown that brittle materials produce more fragments than ductile ones, but the environment pollution and the damage potential of particles coming from metals are much more critical, since large and heavy fragments are prevalent in this case.

Keywords: ejecta, light-gas gun, witness plate craters

1. INTRODUCTION

Micrometeoroids and Orbital Debris (M/OD) hitting spacecraft in Earth Orbit have sufficient kinetic energy to represent a serious hazard for various subsystems and components of the vehicle. Moreover, when a hypervelocity impact (HVI) occurs, a large amount of small fragments is produced and ejected towards space: depending on the impact obliquity, such particles (ejecta) may lead to secondary impacts on other parts of the spacecraft or may add to the environment thus increasing the number of existing debris.

On one hand, sensitive surfaces like solar cells, sensors and optics can be polluted and the crater amount may be significantly increased with respect of what is calculated during the spacecraft design phase. To account for this issue, some work has already been done in the past in the US community. Stump and Christiansen [1] proposed to quantify the threat posed by secondary ejecta as an additional flux over the primary one that must be considered in the design process. In particular, they ran a series of light-gas gun (LGG) shots to determine the size, mass, velocity and spatial distribution of spall and ejecta for targets representative of Space Station elements. In a similar framework, Schonberg [2] and Schonberg and Taylor [3] developed empirical models describing secondary ejecta created by high speed impacts on spacecraft surfaces and recommendations to protect external spacecraft subsystems against damage by ricochet particles formed during primary impacts.

On the other hand, back-scattered fragments are emitted to the free space around the spacecraft and, depending on their size and orbital parameters, they can have long lifetimes on orbit or re-enter rapidly in the atmosphere. In any case, among their fate, it is currently believed that ejecta contribution to the orbital debris population cannot be neglected, being of about 2-3% in LEO and 5-6% in GEO [4].

Knowledge of the number and properties of ejecta is therefore important for both assessing the risk posed by secondary debris to spacecraft components and for predicting the debris growth into the environment.

In such a framework. the international community is putting a considerable effort to investigate ejecta production mechanisms, to better understand what are the amount and properties of fragments emitted by many types of materials which are commonly used for spacecraft surfaces. The International Organization for Standardization (ISO) is proposing a standard which defines experimental procedures for assessing the behaviour of these materials: the standard should establish the requirements for the test methods for characterizing the amount of ejecta produced, the ratio of ejecta total mass to projectile mass and the size distribution of fragments. Such information should make possible to predict the amount of impact ejecta that a surface material might release during its orbital lifetime, thereby helping to quantify its suitability for space use. In addition to ISO, the Inter-Agency Debris Coordination Committee (IADC) has promoted an international cooperation with the broader scope of considering in detail the ejecta phenomenon and its consequences for both spacecraft protection and space environment: test methodologies and analysis techniques have been defined and implemented with the aim of carrying out impact experiments to fill an ejecta database.

In summary, the ultimate objective is to provide empirical models describing the speed-mass distribution of ejecta particles within ejecta clouds, in

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function of the target (material and geometric configuration) and impact parameters (debris size, speed and trajectory obliquity). Such models should be constructed using a statistical approach and they should provide answers to both the questions for which ejecta knowledge is relevant: from the protection point of view, they could be used as input to Risk Assessment tools which predict the damage caused to spacecraft components by a given debris flux; on the other hand, they could be considered as source of new debris for inclusion into common M/OD environment models such as ESA MASTER and NASA ORDEM.

In this scenario, this paper reports the results of twenty-eight HVI experiments on three different classes of targets representative of materials for space application and the assessment of the ejecta production from such materials subjected to different impact conditions.
The remainder of this paper is therefore organized as follows: section 2 (Experimental methods) presents the targets used for the test campaign, the selected impact conditions (projectile diameter, speed and impact angle) and the experimental setup for collecting and characterizing the ejecta from each experiment. A summary of all tests is also provided. Section 3 (Witness plates analysis) describes the procedures employed for analyzing the crater patterns left on copper witness plates by the ejecta particles. Section 4 (Results) summarizes the most relevant outcomes of the experimental activity, including crater counting information for the three categories of selected target configurations. Finally, Conclusions are given in Section 5.

2. EXPERIMENTAL METHODS

The objective of the experiments is to get information on ejecta particles produced by HVI on different spacecraft materials. The minimum requirement is to count the number of fragments emitted from the target surface and then passively collected by a proper witness plate. In addition, measuring the craters diameter on the witness plate provides raw information on the size distribution of the particles in the cloud, avoiding the employment of excessively costly and complex instrumentation.

2.1. Test setup

A simple system to mount the experiment into the LGG impact chamber was realized (Figure 1), consisting in two independent supporting frames on which the target and the copper witness plates are fixed. Copper was preferred to other metal alloys since its composition is different from that of projectile and target. The choice of having two separate supports makes possible to easily change their mutual orientation and hence the impact angle.

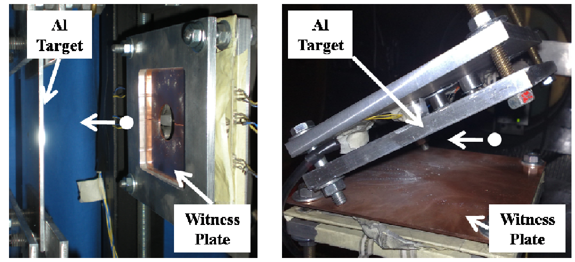

Figure 1. Target holder: normal (left) and oblique (right) impact configuration. In the normal impact configuration, a central hole is evident in the witness plate to allow the projectile pass through the plate and reach the target.

2.2. Targets and test summary

Twenty-eight hypervelocity impact tests were realized at CISAS Impact Facility, using a 4.76 mm caliber LGG capable of accelerating 0.4 – 3.2 mm spheres up to 6 km/s [4, 5, 6]. Since ejecta properties depend strongly from target material, three different classes of targets were considered to represent spacecraft surfaces commonly exposed to the orbital environment: simple aluminum-alloy plates, silicon solar cells and simple aluminum-alloy plates covered by MLI blankets. Projectiles having different size (1, 1.5 and 2.3 mm diameter) were launched at speed ranging from 4 to 5.5 km/s and the impact angle dependence was studied from 30° to 80° for simple aluminum targets.
Table 1 provides a summary of the experiments conducted within the test program. In every test, pure copper witness plates 2 mm thick were employed.

3. WITNESS PLATES ANALYSIS

For each experiment, the number and size of witness plate craters were obtained through the automatic analysis of high-resolution (1200 dpi) witness plate photographs. Clearly, this is not enough to derive speed-mass distributions for ejecta, since craters extension is not sufficient to univocally determine the velocity and size of the particles that caused the damage: a crater of given size could be both produced by large and slow particles, as well as small and fast ones. However, craters counting and measurement nevertheless gives a first idea of the extent of the ejecta phenomenon, offering also the opportunity of comparing the behaviour of different spacecraft materials in various impact conditions.
The witness plate analysis was conducted with a specific software running in Matlab environment. Craters identification, counting and measurement are based upon the detection of color variations in pictures properly treated through the application of specific color maps. Moreover, to avoid erroneous craters

identifications due to scratches or imperfections of the plate, comparisons were implemented between images of the plates before and after the experiment: damage features recognized on both pictures are labeled as "false positives" and then cancelled from the analysis results. Accepted craters are finally sorted in four bins referring to the following ranges of equivalent diameter: 0.025 to 0.05 mm, 0.05 to 0.1 mm, 0.1 to 1 mm and >1mm. Final and intermediate analysis results are made available in both graphical and in data structure format while a text report is provided with all the analysis messages.

Test ID	*Target material*	*Target thickness (mm)*	d_p *(mm)*	v_p^* *(km/s)*	α *(°)*
8621	Al6082-T6	3	1.0	5.03	0
8622	Al6082-T6	3	2.3	5.29	0
8629	Al6082-T6	3	1.5	4.71	0
8630	Al6082-T6	3	1.5	4.41	0
8631	Al6082-T6	3	1.0	4.47	0
8632	Al6082-T6	3	2.3	4.40	0
8646	Al6082-T6	10	1.5	5.20	0
8647	Al6082-T6	10	1.5	4.22	0
8648	Al6082-T6	10	2.3	5.34	0
8649	Al6082-T6	10	2.3	4.47	0
8650	Al6082-T6	10	1.0	4.42	0
8655	Al6082-T6	10	1.0	5.10	45
8656	Al6082-T6	10	2.3	5.34	45
8657	Al6082-T6	10	2.3	5.29	60
8658	Al6082-T6	10	1.0	5.29	60
8659	Al6082-T6	10	1.5	5.23	60
8660	Al6082-T6	10	1.5	5.25	45
8662	Al6082-T6	10	1.5	5.16	80
8664	Al6082-T6	10	2.3	5.29	80
8623	Al6082-T6 + MLI	3	2.3	5.29	0
8634	Al6082-T6 + MLI	3	1.5	5.36	0
8635	Al6082-T6 + MLI	3	1.5	4.39	0
8637	Al6082-T6 + MLI	3	1.0	4.35	0
8638	Al6082-T6 + MLI	3	2.3	4.46	0
8626	Si Solar cell	3**	1.0	4.97	0
8627	Si Solar cel	3**	2.3	5.16	0
8640	Si Solar cell	3**	1.0	4.20	0
8641	Si Solar cell	3**	2.3	4.23	0

* Uncertainty in speed measurement is always below or equal to 3%
** Cover glass thickness

Table 1. Test program for ejecta characterization: summary. dp, vp and α are respectively the projectile diameter, velocity and impact angle

Two examples of the witness plate analysis procedure are given in Fig. 2 and Fig. 3, referring to shots no. 8646 and 8656 respectively (see Table 1 to review the relevant test parameters). In both figures, left pictures are raw images of the witness plates after the test and right pictures highlight the "real" craters identified after "false positives" deletion. In the central pictures, green and blue symbols highlight damage features recognized on pre-shot (e.g. due to plate imperfections) and post-shot images, respectively; magenta and cyan symbols are features that are present on both pre-shot and post-shot pictures and are therefore labeled as "false positives"; red squares mark craters that come out from the post-shot image only and hence they are recognized as "real craters".

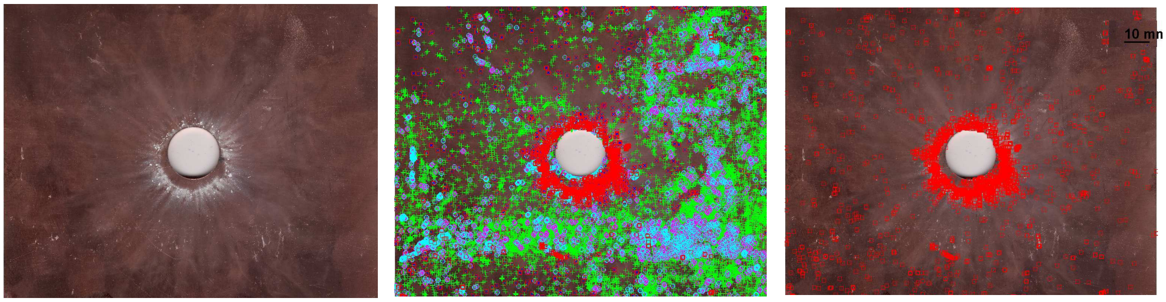

Figure 2. Witness plate analysis for shot no. 8646 (1.5 mm projectile at 5.20 km/s on a 10 mm Al6082-T6 plate, normal impact): raw image (left), damage features recognized by the analysis (center), craters identified after "false positives" subtraction (right).

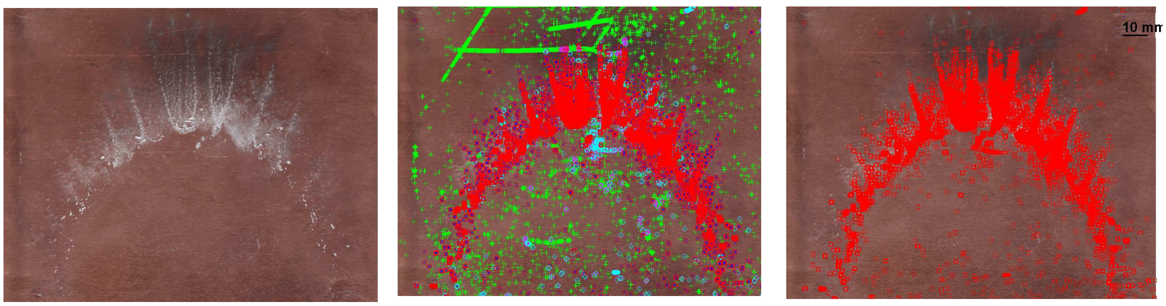

Figure 3. Witness plate analysis for shot no. 8656 (2.3 mm projectile at 5.34 km/s on a 10 mm Al6082-T6 plate, 45° impact): raw image (left), damage features recognized by the analysis (center), craters identified after "false positives" subtraction (right).

4. RESULTS

Three figures are presented in the following, each of them referring to experiments performed using projectiles having fixed size (d_p= 1mm in Fig. 4, d_p=1.5 mm in Fig. 5 and d_p=2.3 mm in Fig. 6). In the three cases, the number of craters is plotted as a function of the impact velocity range (two speed bins have been considered: 4.0-4.5 km/s and 5.0-5.5 km/s) and the crater diameter range (four size bins have been considered: 0.025-0.05 mm, 0.05-0.1 mm, 0.1-1 mm and >1 mm). The images on the left compare the behaviour of different target materials and configurations, while the images on the right evaluate the response of a single target configuration (Al 6082-T6 alloy, 10 mm thick) with different values of the impact angle.

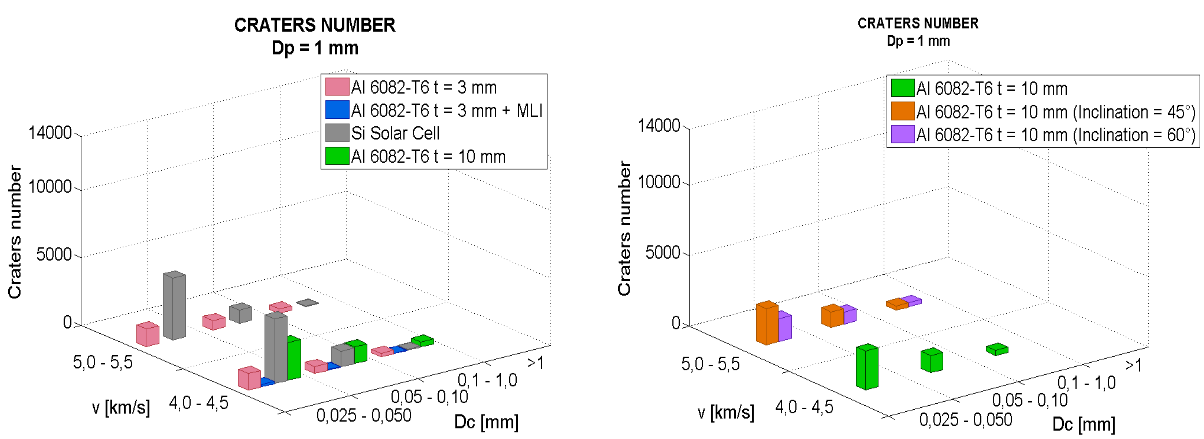

Figure 4. Number of craters for dp=1 mm.

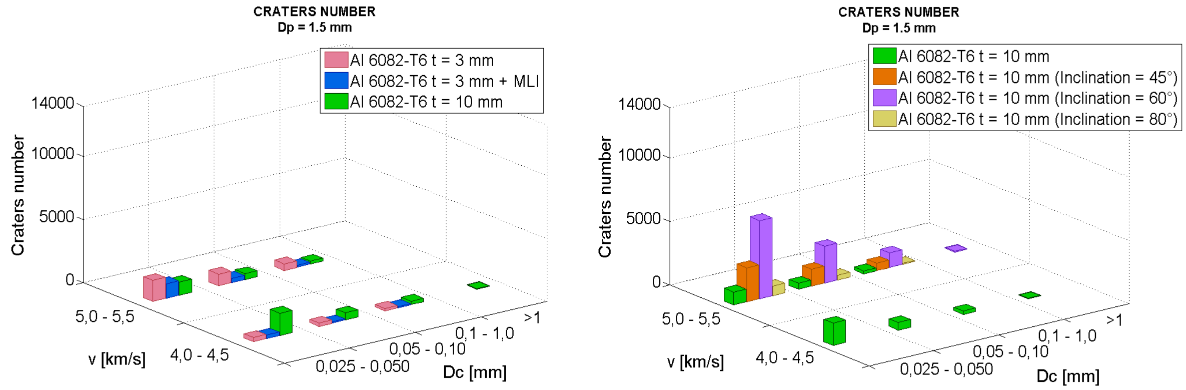

Figure 5. Number of craters for dp=1.5 mm.

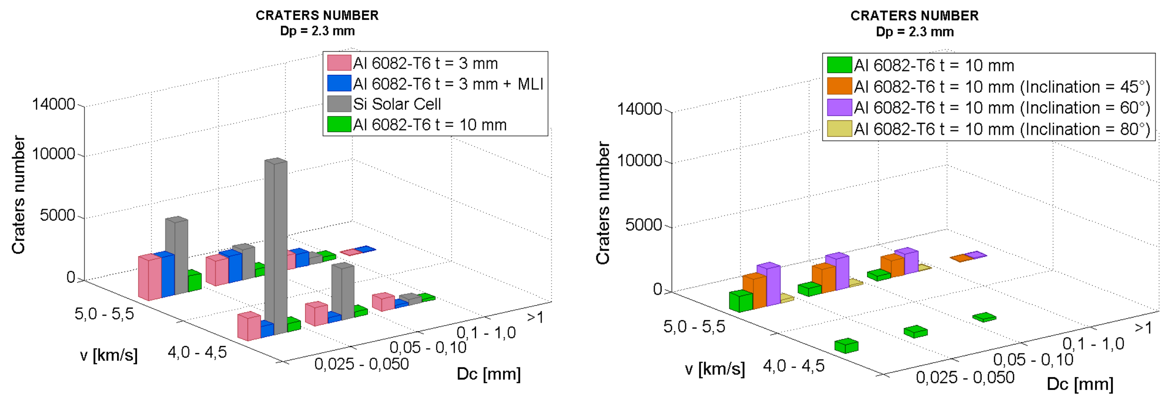

Figure 6. Number of craters for dp=2.3 mm.

Even considering the scattering of results, some important conclusion can be immediately drawn by looking at the three above figures:

- A single HVI on whatever spacecraft material produces a significantly high number of new debris (order of thousands) in a wide size range up to the magnitude of the original one;
- HVI with large debris create more ejecta than impacts with small ones and increasing the impact velocity causes a slight raise of the fragments number;
- HVI on brittle materials (e.g. solar cells cover-glass) produce more ejecta than impacts on ductile ones (e.g. metals), but the environment pollution and the damage potential of particles coming from metals are higher, since large fragments seem to be prevalent; moreover, metals covered by MLI blankets generate less fragments than similar targets without MLI;
- The impact obliquity seems to have a non-monotonous effect: the number of ejecta increase from 0° to 45°, then is almost stable up to 60° and finally falls down significantly above 60°.

5. CONCLUSION

This paper presented a summary of the work carried out at CISAS in support to the Inter-Agency Debris Coordination Committee activity for characterizing spacecraft ejecta from HVI through proper laboratory impact testing. Special focus was paid to the development of methods for laboratory analysis of ejecta, including the use of an automatic procedure to count and measure craters left on copper witness plates by secondary debris. In this framework, results of twenty-eight HVI experiments on three different classes of targets (i.e. simple aluminum-alloy plates, silicon solar cells and simple aluminum-alloy plates covered by MLI blankets) representative of materials for space application are reported. The targets were subjected to HVI with aluminum projectiles from 1 to 2.3 mm launched at speed ranging from 4 to 5.5 km/s. For simple aluminum targets, even an impact angle dependence from 0° to 80° was studied.
It was found that a single HVI on whatever spacecraft material produces a significantly high number of new debris (order of thousands) in a wide size range up to the magnitude of the original one: although the on-orbit lifetime of such fragments depends on their parameters

and most of them may rapidly re-enter the atmosphere, it's nevertheless important to realize that these particles are new debris that add to the environment.
Moreover, it was evidenced that HVI on brittle materials produce more ejecta than impacts on ductile ones, but the environment pollution and the damage potential of particles coming from metals are higher, since large fragments seem to be prevalent.
Furthermore, the effect of impact obliquity seemed to have a non-monotonous effect: the number of ejecta from simple aluminum plates increased from 0° to 45°, then was almost stable up to 60° and finally fell down significantly above 60°.

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