APPORTS OF 3D SEM TO THE CARACTERISATION OF MICROMETEOROIDS CRATERS

Benoît Viallet[(1)], Guy Perez, Christian Durin, Jean-Michel Desmares [(2)], Dorine Lauverjat [(3)] Hélène Chauvin [(4)]

[(1)] INSA-université de Toulouse, 135 Avenue de Rangueil, 31400 Toulouse, France, benoit.viallet@insa-toulouse.fr
[(2)] CNES, 18 Avenue Edouard Belin, 31400 Toulouse, France

[(3)] ELEMCA, 425 rue Jean Rostand - IOT Valley 31670 Labège, France

[(4)] TCS, 3 avenue de l'Europe, 31400 Toulouse, France

ABSTRACT

The damages and the density of micrometeoroids and orbital debris (M&D) are important parameters for the space environment and for structures integrity. They are created by high velocity impacts with spacecraft's and can lead to defects (perforation, surface damages) and creation of new micro-particles. They could be of serious concern for the operation of long-lived space structures and for man operations in space.
Some elements return to the earth have been used in past years to understand these phenomena. Now new ground expertise allows us to better understand damages and also to better evaluate the quantity of new micro-particles create. We propose here two complementary methods to obtain a 3D representation of the impacts craters of micrometeoroids: by optical confocal profilometry and by scanning electron microscopy. The methods are compared and the interest of those methods are outlined. This study is completed by chemical information obtained by Energy-dispersive X-ray spectroscopy

INTRODUCTION

There is a current need for a better knowledge of solid particle environment in low earth orbits. This is crucial for the design and the survival of space missions, especially when human security is concerned. Indeed, surface damage resulting from the impact of small particles (less than 1 mm) which separately is not lethal for a spacecraft, may become one of the major concerns for sensitive devices used in space. For example an aluminium sphere ϕ = 1 mm at 10 km/s can pass through a 4 mm thin aluminium wall.

During the recent years, several spacecraft missions have flown with sensors devoted to the monitoring of this specific environment. Furthermore, many aspects of the damages are documented from material retrieved after exposure to space[1-3]: Long Duration Exposure Facility (LDEF) satellite, ISS, Hubble Space Telescope (HST)…We present here a set of ground expertise methods in order to better understand damages and also to better evaluate the quantity of new micro-particles create.

The importance of this expertise approach is justified by several factors:
· Improve our knowledge of our close environment
· To increase our knowledge of real damage
· To provide useful help to retrieve particles origins
· To understand particles/debris creation
· To supply entries for models of environment and design

This presentation will describe new technologies used and the principal scientific results.

EXPERIMENTAL APPROACH

1.1. Samples

The samples analysed here came from dedicated missions and from analysis of part of satellites.
Aluminium samples were collected from structure plates and form flight shields of LDEF/FRECOPA (Long Duration Exposure Facility/French Cooperative passive Payload) witch stayed 69 months in space. Glass craters were sampled from integrated solar cells of Hubble.

1.2. 2D and 3D Scanning Electron Microscopy (SEM)

SEM characterisations were carried out with a Philips XL 30 conventional SEM equipped with a Bruker Energy-dispersive X-ray spectroscopy (EDS) detector. 3D geometry of craters were reconstructed from 2D SEM images by a flow process using optical photogrammetry software[4-6].

First a set of SEM images were obtained of one crater with different angle of view (Fig. 1). A minimum of two images is theoretically necessary[7]. But in order to increase the quality of final reconstruction and to observe some hidden parts, an average of 15 images/crater were used. 61 images were taken for the most complex geometries.

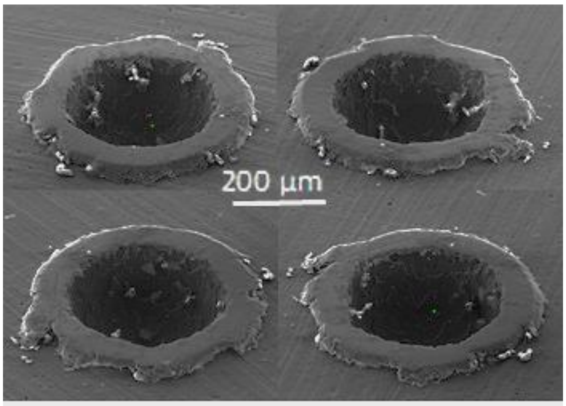

Fig. 1 : 4 images extracted from the set of SEM pictures of crater (A) (aluminium alloy)

Secondly a 3D point cloud was computed from the 2D images with Regard 3D software. Regard 3D is an open source program witch convert optical photos of an object, taken from different angles, into a 3D model of this object. Regard 3D detects features (sometimes also called keypoints) for each image, matches features between each images and then compute a 3D point cloud by triangulation.

Third a complete mesh is created and analysed using MeshLab software (Fig. 2). The originality of this work is to compute 3D images with open source programmes normally dedicated to optical photogrammetry.

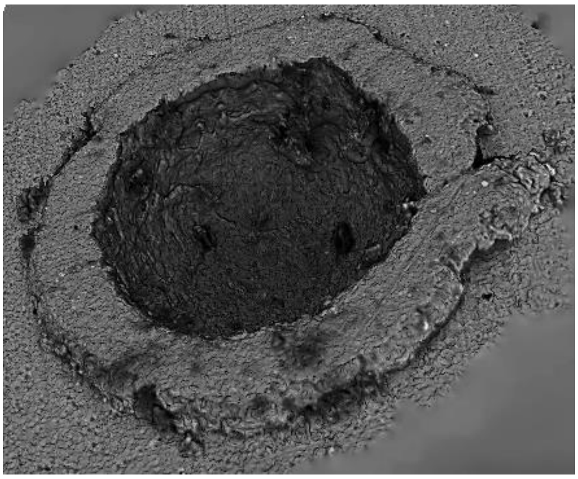

Fig. 2 : 3D representation of crater (A) after reconstruction. Obtained by SEM images in BSE mode

1.3. Confocal profilometry

3D images were also acquired by optical confocal surface profiler from SENSOFAR. The workflow to obtain a 3D model from a crater is much simpler with the confocal profiler. The optical profiler produce directly a 3D point cloud. That point cloud is then converted into a mesh with MeshLab software Fig. 3.

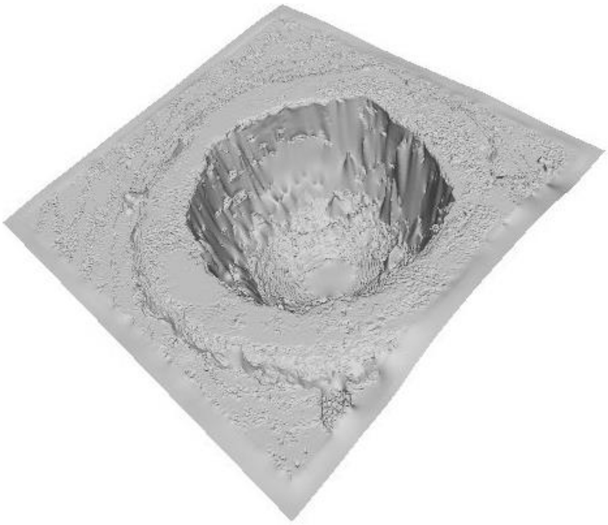

Fig. 3 : 3D representation of crater (A) obtained by confocal optical profiler

RESULTS

1.4. Geometry of metallic craters

The geometry of craters created in aluminium alloy substrates were obtained analysed and compared. With craters presenting a simple geometry like crater (A) presented in Fig. 2 and Fig. 3, both methods gives same reconstructions although more details are present with 3D SEM. The colour of the 3D SEM image is a combination of shading computed by MeshLab and of colour of SEM images. That colour is an additional visual information enhancing the texture of the surface.

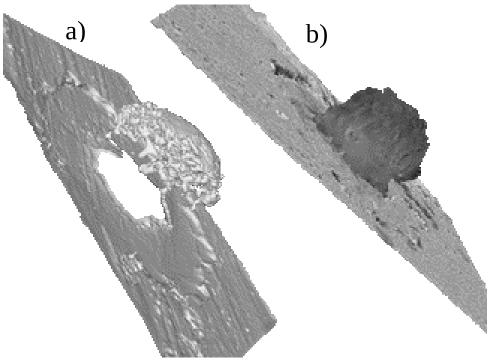

Fig. 4 : Backside 3D representation of crater (B) after reconstruction by confocal optical profiler (a) and 3D SEM (b)

Some craters like the crater (B) presented in this paper present a large undercut. The maximum diameter of the hole is larger than the inside diameter of the collet. With optical confocal profiler, the sample is scanned from an optical axis quasi perpendicular to the plane of the sample. Therefore, some inside parts of the crater are hidden and cannot been observed. Fig. 5 shows profiles cut of crater (B) obtained by 3B SEM and optical profiler. The optical profiler fails to describe the undercut whereas 3D SEM describes correctly the shape of the crater. Comparing the 3D representations Fig. 2 and Fig. 3 shows that the confocal profiler gives very low information about the fine structure of nearly vertical surfaces whereas small reliefs are visible on 3D SEM reconstructions vertical surfaces.

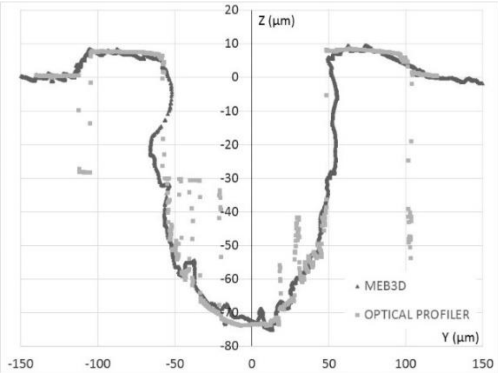

Fig. 5 : profiles of crater (B) presented Fig. 4.

3D SEM offers more flexibility and also more resolution than optical confocal profiler in order to characterize complex geometries with nearly vertical surfaces or undercuts.

1.5. Chemistry of metallic craters

3D SEM reconstructions can be completed with chemical information with small effort[8].

The SEM images taken to compute the reconstruction presented Fig. 2 were taken with BackScattered Electrons (BSE) detector in composition mode. The grey levels of those images represent the average atomic number. The colour applied to the 3D representation also correspond to the chemistry of the sample, bright pixels correspond to heavier elements than dark ones.

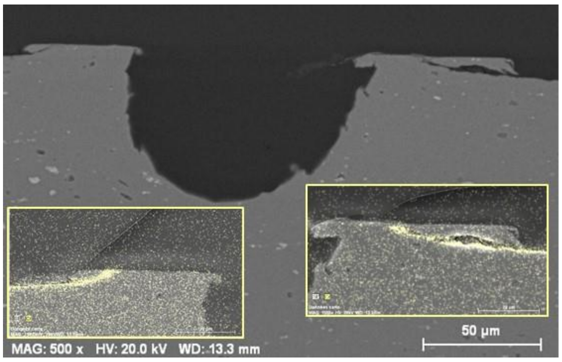

Fig. 6 : SEM image with EDS mappings of a metallographic section of crater (B)

In order to have more information on the chemistry, crater (B) has been crossed-sectioned and observed by SEM. Fig. 6 shows this metallic cross-section witch confirms the presence of an undercut in the crater (B). Chemistry of the crater was analysed by EDS inside the SEM. That analyse reveals the presence of magnesium and iron with the aluminium alloy and the presence of traces of chlorine and sulphur. It reveals also that a 200 nm thin chromium layer has been deposited on the aluminium surface as a protective layer. No tentative has been made to retrieve traces of the micrometeoroid since this sample is not a fresh sample and may be contaminated with different earthen particles.

Fig. 6 inserts present EDS mappings of chromium. Close to the crater, there is a zone of 32µm on the left and 16 µm on the right without chromium. It means that during the impact with the micrometeoroid, the liquid aluminium had flowed from the crater and had blowed the chromium layer who was ejected.

1.6. Glass craters

Craters created in glass materials[9] present different morphologies than in metallic materials. They present a melt pit at the centre with a smooth surface, and a conchoidal spallation.

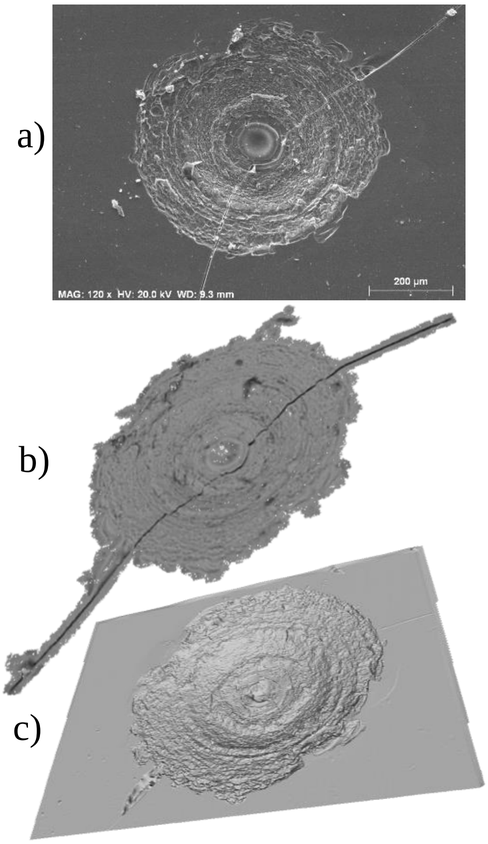

Fig. 7 : Characterization of a crater into a coverglass: SEM image a) 3D SEM reconstruction b) and confocal profiler representation

During the operation of 3D reconstruction from SEM images regard3D software has to find the same characteristic points on different images and to compute the 3D representation. Unfortunately, the centre pit of the glass crater and the bare surface of the glass are very smooth and lead to a uniform contrast zones in SEM images (Fig. 7 a)). Therefore the reconstruction software cannot find characteristic point in those areas which are not reconstructed or badly reconstructed with some missing or bad points (Fig. 7 b)). Contrary to 3D SEM, confocal profiler has no difficulty to represents smooth areas (Fig. 7 c)). Optical confocal profiler is then more adapted than 3D SEM in order to characterize craters from glass substrates.

APPORT OF THE DIFFERENT TECHNICS TO MICROMETEORITES CRATERS ANALISYS

All the characterizations of this paper allows to a good comprehension of crater geometry and chemistry. It enable also to better understand the crater formation. For example:

- Most of measured craters have an asymmetric shape due to the angle of incidence of the micrometeoroids with the surface. By analyzing the geometry of the 3D reconstruction of the crater, it is possible to retrieve that incidence angle.
- The volume of craters can be precisely estimated from 3D reconstructions. By measuring both the volume of the inner crater and of the outer rim, one can estimates the volume of material that has been ejected from the crater and the volume of material that has been displaced to form the rim. In case of craters presenting an undercut, a more precise estimation will be obtained with 3D SEM reconstructions.
- Fig. 6 highlights that a flux of aluminum has driven away the chromium layer. The comparison between that observation and a model of the metal flux during the impact can help to precise the model in order to improve his accuracy.
- In order to retrieve the morphology of craters on big objects or systems, without cutting a piece of the system, it is possible to make a polymer molding (replica) of the crater and to reconstruct the geometry. This technology becomes then nondestructive.

ACKNOLEGEMENTS

We thanks Alisson Vanheule and Patrick Nguyen for the work they made during this project.

REFERENCES

1. J. C. Mandeville, “Orbital debris and meteoroids: results from retrieved spacecraft surfaces”, *Adv. Space Res*., 13, No.8 (1993) 123-127.
2. L. Berthoud, J.C. Mandeville, “analysis of remnants found in LDEF and MIR impact craters”, *AIP Conference Proceedings*, 310 (1994) 313-328.
3. C. A. Sapp, T. H. See, M. E. Zolensky, “3-D crater analysis of LDEF impact features from stereo imagery”, *69 Months in Space Second LDEF Post-Retrieval Symposium*, Part2 (1993) 339-345.
4. M. Eulitz, G. Reiss, “3D reconstruction of SEM images by use of optical photogrammetry software”, *Journal of Structural Biology*, 191 (2015) 190–196.
5. L. C.Gontard, R. Schierholz, S. Yu, J. Cintas, R. E. Dunin-Borkowski, “Photogrammetry of the three-dimensional shape and texture of a nanoscale particle using scanning electron microscopy and free software”, *Ultramicroscopy*, 169 (2016) 80–88
6. A.D. Ball, P.A. Job, A.E.L. Walker, “SEM-microphotogrammetry, a new take on an old method for generating high-resolution 3D models from SEM images”, *Journal of Microscopy*, 267-2 2017, 214–226
7. J. L. Pouchou, D. Boivin, P. Beauchene, G. L. Besnerais, F. Vignon, “3D reconstruction of Rough Surfaces by SEM stereo imaging”, *Mikrochim Acta*, 139 (2002) 135–144.
8. L. C. Gontard, M. Batista, J. Salguero, J. J. Calvino, “Three-dimensional chemical mapping using non-destructive SEM and photogrammetry”, *Scientific Reports* (2018) 8:11000 DOI:10.1038/s41598-018-29458-8
9. A.T. Kearsley, G.A. Graham, J.A.M. McDonnell, E.A. Taylor, G. Drolshagen, R.J. Chater, D. McPhail, M.J. Burchell, “The chemical composition of micrometeoroids impacting upon the solar arrays of the Hubble Space Telescope”, *Advances in Space Research*, 39 (2007) 590–604