NORMAL AND 45° HYPERVELOCITY IMPACT TESTS TO EVALUATE SPACECRAFT MATEIAL EJECTA

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ABSTRACT

Until September 2012 and the adoption of ISO11227, no standardized test procedure existed to evaluate ejecta from spacecraft material. Kyushu Institute of Technology is carrying out hypervelocity impact tests to contribute to the standard database enrichment and standard improvement. This paper reports 1) a review of the normal impact tests results, 2) the first results for oblique impact tests, and 3) the future studies to be carried out. Ejecta size distribution for normal impact tests showed that ejecta tend to impact in smaller concentric circle as their size increases, whereas ejecta smaller than 75 µm seem to impact uniformly the witness plate. Preliminary results of oblique impact tests showed that ejecta form a trail along the central axis of the witness plate. The authors also observed that the impact of the biggest fragments, 100 ~ 750 µm, were concentrated in two distinct areas showing that these fragments were cone-ejected at about 50°.

1 INTRODUCTION

1.1 Ejecta

Many types of debris can be found in space that can range from a few micrometers to a few meters. In this paper, the authors focus on ejecta, a major contributor to the small space debris population in low Earth orbit.

Ejecta are secondary space debris emitted upon the impact of a primary debris on a spacecraft surface. The smallest ejecta are a few micrometers large, whereas the largest can reach a few millimetres in diameter. Ejecta cannot be tracked by ground observations due to their smallness [1]. Moreover, not enough data on the ejecta population were obtained from retrieved space surfaces. Therefore, there are currently two main methods for estimating ejecta population and assessing the risk ejecta represent:

1. in-situ measurements;
2. on-ground hypervelocity impact experiments.

One of the in-situ measurements methods, the educational debris sensor, was developed at Kyushu Institute of Technology (KIT) from an original idea of the Japan Aerospace Exploration Agency and the Institute of Q-shu Pioneers of Space. Since the sensor developed has already been described in the literature [2-4], it will not be expanded further in this paper. However, KIT's on-ground hypervelocity impact facilities will be described in further details in the next sections.

There are three types of ejection that have been identified upon hypervelocity impact [5] as shown in Fig. 1. Jetting consists in the ejection of small and fast liquid particles at grazing angles. Jetting represents less than 1 percent of the total ejected mass and can therefore be neglected. Cone consists in the ejection of small and fast solid particles at an angle of about 60°. Spall consists in the ejection of large fragments at low velocities perpendicularly to the surface. Spall ejection only occurs for brittle targets.

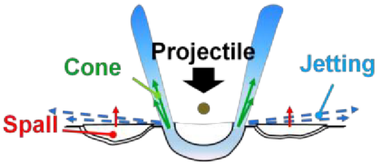


Figure 1. The three types of ejection upon hypervelocity impact

1.2 Standardization for the Ejecta Evaluation

Since several decades, different organizations through the world are carrying out hypervelocity impact testing to evaluate ejecta. However, each facility applies its own set of parameters when carrying out experiments. The results are thus not comparable and can vary greatly from one place to another, which can lead to significant mismatch between ejecta population simulation models such as between the European Space Agency's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) and the National Aeronautics and Space Administration's Orbital Debris Engineering Model (ORDEM) (Fig. 2).

As a countermeasure to the lack of data and discrepancies between results on the ejecta population, a standard has been developed since 2007 and has finally been adopted by the International Organization for Standardization (ISO) in September 2012 as *ISO11227: Space systems – Test procedure to evaluate spacecraft*

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

material ejecta upon hypervelocity impact. The International Standard ISO11227 details the procedure to comply with when performing ejecta evaluation tests such as target and projectile material, size, thickness as well as impact velocity and incident angle. ISO11227's objective is to create a database easily accessible to spacecraft designers that will be able to choose space-friendly outer materials to mitigate the risk of space debris [6].

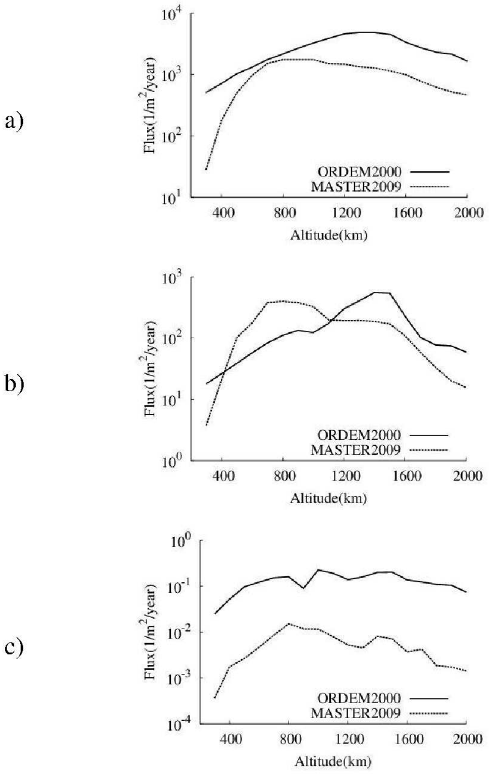


Figure 2. ORDEM2000 and MASTER-2009 debris flux vs. altitude for different size of space debris. a) 10 µm. b) 100 µm. c) 1 mm [7]

Three years after its adoption, ISO11227 has to be revised. In its current version, the International Standard gives only a few details regarding oblique impact experiments. To improve the standard with regards to oblique impact, KIT is currently carrying out oblique hypervelocity impact tests on different target materials.

2 EXPERIMENTAL SETUP

To perform the different tests, the two-stage light gas gun installed at the Laboratory of Spacecraft Environmental Interaction Engineering, KIT was used (Fig. 3). The ambient pressure in the sabot separation section is about 7.0 kPa, the pressure in the test chamber is about 10 Pa, and the measured impact velocity is about 5.0 km/s.

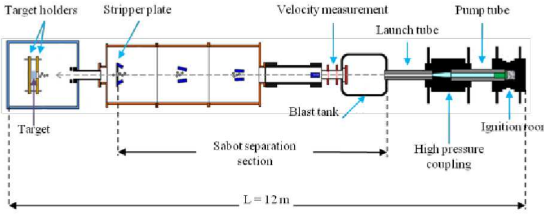


Figure 3. Kyushu Institute of Technology's two-stage light gas gun

2.1 Normal Impact Tests

Normal impact tests were carried out from 2009 to 2011 and based on clauses 5 and 6 from the ISO11227, four types of materials were used as target:

1. synthetic fused silica (calibration tests);
2. solar array coupon;
3. carbon fibres reinforced plastic (CFRP)/aluminium honeycomb;
4. aluminium honeycomb.

Except for calibration tests for which only one witness plate was used (Fig. 4a), two witness plates were used to capture the ejecta. One plate was placed in front of the target with a 30 mm hole in the centre, and one plate was set behind the target without hole. Both witness plates were placed at a distance of 100 mm from the target (Fig. 4b).

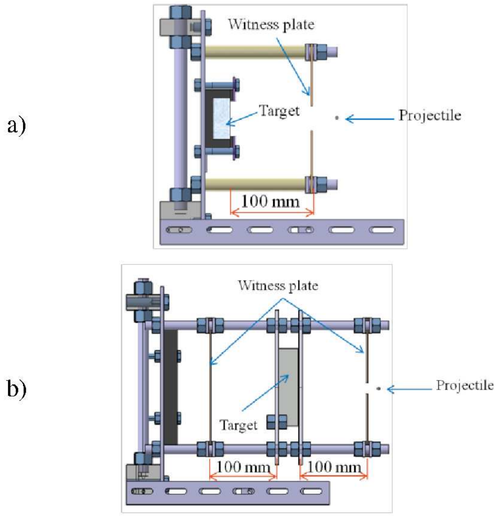


Figure 4. Target and witness plates setup for normal impact tests. a) Calibrations. b) Spacecraft materials

2.1.1 Calibration tests

The 2009 study had for objective to verify the feasibility of the test procedure as defined in the future ISO11227. Therefore, a series of tests was conducted in 2009. Tab. 1 shows the difference between the parameters as defined in the CD/C11227 (future ISO11227) and the parameters used during the 2009 study.

Table 1. Comparison between the experimental parameters as given in CD/C11227 and the experimental parameters used during the 2009 study

		CD/C11227[a]	2009 Study
Projectile	Material	Al alloy	A1050
	Size [mm] and shape	1 ± 0.1 sphere	Same
	Impact velocity [km.s^{-1}]	5 ± 0.1	4 ~ 5
Target	Material	Fused silica	Same
	Size [mm]	50×50×20	Same
Witness Plate	Material	Cu or a ductile material	Cu
	Size [mm]	250×150×2	180×150×2
	Distance to the target [mm]	50 ~ 100	50 and 100
	Position angle to the target	Parallel	Same
	Surface treatment	Not defined	Buffing, chemical polishing or none

[a]Future ISO11227

2.1.2 Spacecraft materials tests

The 2010 and 2011 studies had for objective to evaluate ejecta emitted from spacecraft materials upon normal hypervelocity impact. As projectile, a 1 mm A2017 sphere with a mass of 1.7 mg was used.

2.2 45° Impact Tests

In 2012, 45° calibration impact tests were carried out. Based on clause 5 from ISO11227, 20 mm thick synthetic fused silica was used as target material. To capture the ejecta, one witness plate was placed at a distance of 100 mm above the target and at an angle of 90° with regard to the projectile flight direction. Target and witness plate setup for the 45° calibration impact tests is shown in Fig. 5. As projectile, a 1 mm A2017 sphere with a mass of 1. 7 mg was used.

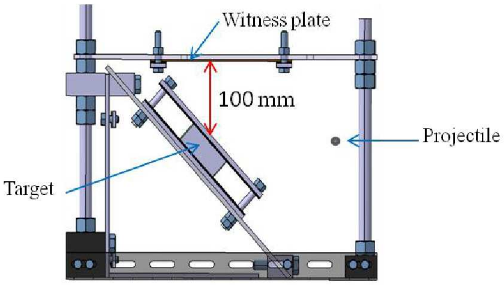


Figure 5. Set up of the target and witness plates for the 45° calibration impact tests

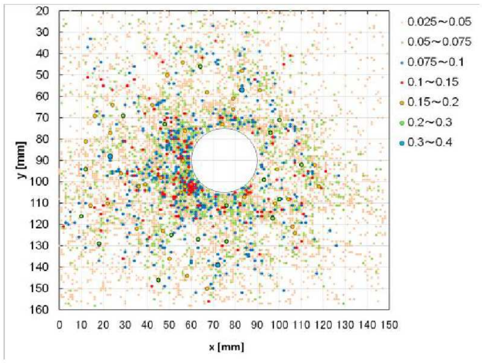
3 RESULTS

3.1 Normal Impact Tests

3.1.1 Calibration tests

The 2009 study demonstrated the feasibility of the test procedure as established in the future ISO11227. Moreover, during the study, different witness plate treatments have been tested and a mirror finished surface seems to be the most suitable for counting impact craters. Tab. 2 gives the number of ejecta and the ratio of the ejecta mass over the projectile mass. The different witness plate microscope scans are presented in Fig. 6. From Fig. 6b, for the case with a distance target-witness plate of 50 mm, it can be noticed that most of the ejecta are concentrated around the central hole and a large part of these ejecta probably went through the hole making their capture impossible. On the other hand, for the other cases with a 100 mm target-witness plate distance, it can be noticed that the ejecta are more uniformly distributed over the plate, which 1) makes impacts easier to distinguish from one another, and 2) seems to lead to a lesser loss of ejecta through the central hole.

a)



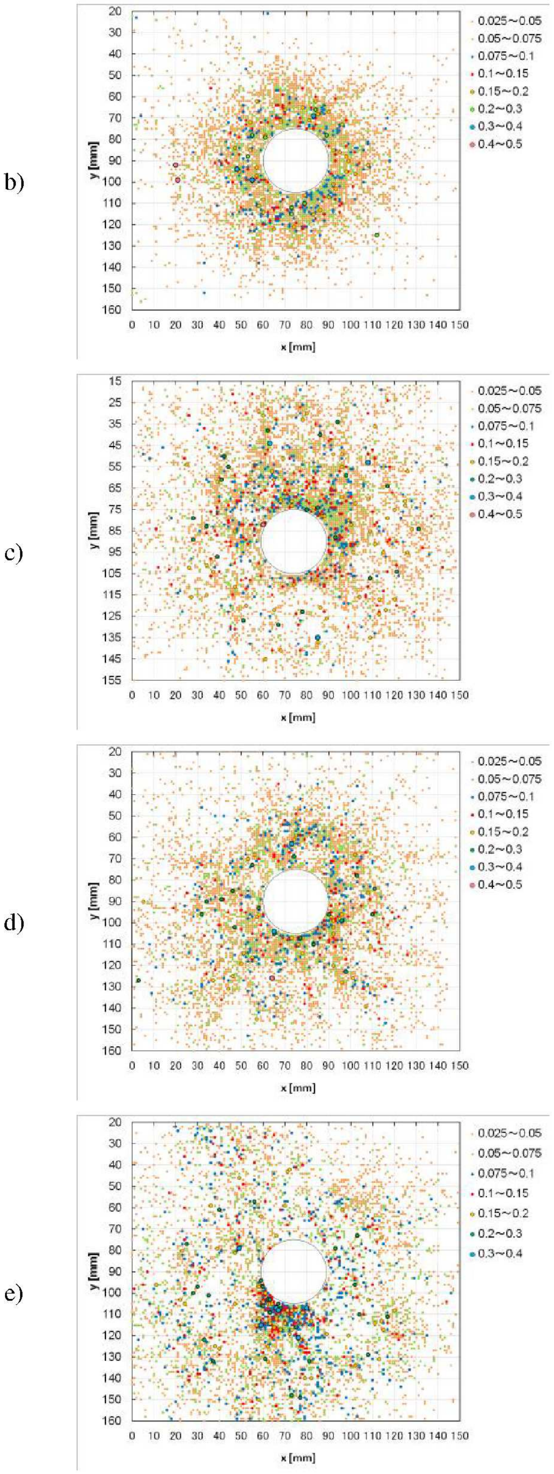


Figure 6. Microscope scans of the different 2009 tests. a) 09-101. b) 09-102. c) 09-117. d) 09-119. e) 09-120

Table 2. 2009 study experimental parameters

Test	WP[a] Material (treatment)	Distance T-WP[b]	Ejecta Mass [mg]	R[c]	Ejecta Number
09-101	Cu (chemical polishing)	100	88.5	46.6	22,013
09-102	Cu (buffing)	50	80.4	42.3	28,603
09-117	Cu (buffing)	100	70.2	36,9	37,064
09-119	Cu (buffing)	100	84.9	44.7	8,024
09-120	Cu (none)	100	83.2	43.8	6,522

[a] WP: witness plate; [b] T-WP: target-witness plate; [c] R: ratio of ejecta total mass to projectile mass

3.1.2 Spacecraft material tests

Tab. 3 and 4 show for the spacecraft materials the number of ejecta and the ratio of the ejecta total mass to the projectile mass, respectively.

Table 3. 2010 and 2011 tests results

Test	Impact Velocity [km.s^{-1}]	Target	Ejecta Front WP	Ejecta Rear WP
10-77	5.37	SAC[a] (front)	65,851	61,410
11-180	5.48	SAC (front)	16,431	10,821
11-15	4.62	SAC (rear)	-	-
11-185	5.23	SAC (rear)	2,208	1,160
10-115	4.97	CFRP/Al	3,910	-
11-186	5.18	CFRP/Al	1,241	20,381
10-131	4.79	Al	2,427	24,374
11-195	5.56	Al	4,677	10,502

[a] SAC: solar array coupon

Table 4. Ratio of the ejecta total mass to the projectile masse for the 2010 and 2011 studies

	10-77	**11-180**	**11-15**	**11-185**
Me[a] [mg]	68.8	62.8	98.6	70.9
R	40.5	36.9	58.0	41.7
	10-115	**11-186**	**10-131**	**11-195**
Me[a] [mg]	41.1	19.6	10.3	30.1
R	24.2	11.5	6.0	17.7

[a]M_{ej}: ejecta total mass

As expected, the front of the solar array coupon emits the largest number of ejecta upon hypervelocity impact due to the cover glass on its surface. However, the mass of ejecta is the largest in the case of the rear solar array coupon tests, which indicates that despite the smaller amount of ejecta, their size is larger than with any of the other materials tested. Regarding CFRP/Al honeycomb and Al honeycomb, they emit on average the same number of ejecta but these ejecta are larger in the case of CFRP/Al honeycomb. Finally, it is worth notice that for the case of an impact on a solar array coupon, front or rear surface, the largest number of ejecta is emitted toward space. On the other hand, in the case of CFRP/Al honeycomb or Al honeycomb, the number of ejecta detected is the largest on the rear witness plate. This indicates that upon a hypervelocity impact in actual space, most of the ejecta will be emitted inward the spacecraft body, which could lead to a catastrophic chain reaction for the components inside the spacecraft.

Overall, the ejecta mass is 6 to nearly 60 times the mass of the projectile.

From Fig. 7 front witness plate scans, it appears that in the case of the impact on the front solar array coupon (Fig. 7a), i.e., fragile material, the matter is ejected in a narrower manner, 40° ejection angle, than for the ductile material cases (Figs. 7b and d), 60° ejection angle. Moreover, for the case of impact on CFRP/Al honeycomb (Fig. 7c), the matter seems to be randomly ejected and widely spread all over the front witness plate.

From Fig. 7 rear witness plate scans, it appears that the ejected matter impacts in a narrow circular-like manner on the rear witness plate for front solar array coupon and Al honeycomb cases, 40° ejection angle (Figs. 7a and d). For the CFRP/Al honeycomb case (Fig. 7c), the ejecta seems to be distributed in a more scattered way with some extremities extending outward the impact centre, in a star-like shape, 50° ejection angle. For the rear solar array coupon (Fig. 7b), the ejecta impacted in a random manner all over the rear witness plate.

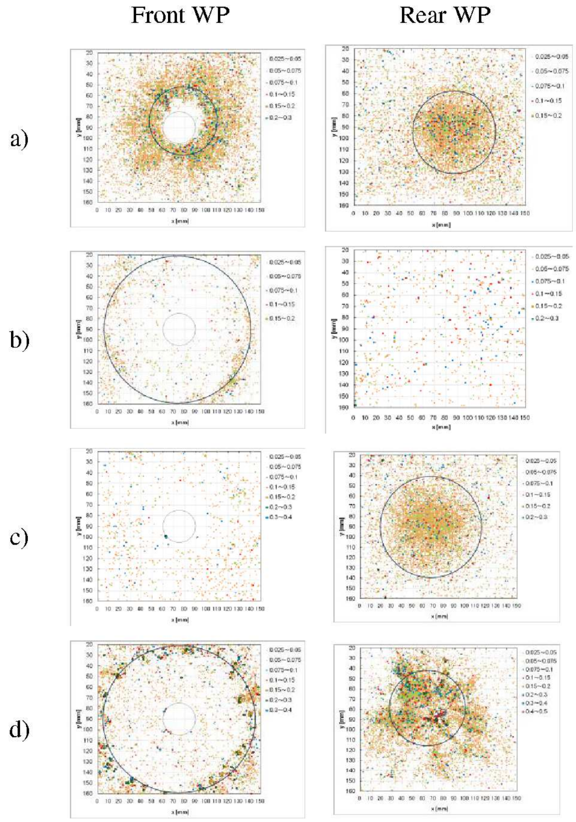


Figure 7. Microscope scans of the spacecraft material tests. The blue circle represents the average ejection diameter. a) 11-180, SAC front. b) 11-185, SAC rear. c) 11-186, CFRP/Al honeycomb. d) 11-195, Al honeycomb

Tab. 5 gives, when applicable, the average ejection diameters and corresponding angles for the different spacecraft materials tested.

When decomposing the scan for each size range, it can be noticed that for the case of brittle material, the ejecta slightly impact in smaller circle when their size increases (Figs. 8a-d). However, for the case of impact on a ductile material like Al honeycomb, the ejecta seem to impact within the same area independently of their size (Figs. 8e-j).

3.2 45° Impact Tests

From the 2012's 45° calibration impact tests, three main conclusions can be made.

1. The ejecta impacts form a trail along the y axis with two main centres at the lower and upper part of the trail (Fig. 9).
2. Ejecta impacted at the bottom of the witness plate,

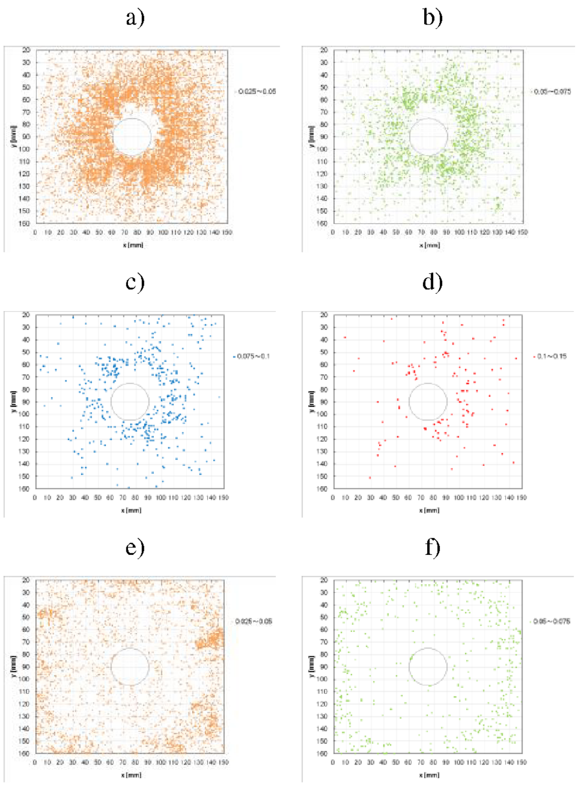
perpendicularly to the previously described ejecta trail (Fig. 9).

3. The number of ejecta is about 10 times higher for the 45° calibration tests than for the 90° calibration tests (Tab. 6).

Overall, the ejecta mass is 91 to nearly 160 times the mass of the projectile for the 45° impact tests, and 62 to nearly 90 times the mass of the projectile for the normal impact tests.

Table 5. Ejection diameter and ejection angle for the different spacecraft material tested

Test	**Front WP**		**Rear WP**	
	Ejection Ø [mm]	**Ejection Angle [°]**	**Ejection Ø [mm]**	**Ejection Angle [°]**
11-180	65	36	75	40.1
11-185	140	70	-	-
11-186	-	-	100	52.1
11-195	145	71.9	75	40.1


a) b) c) d) e) f)

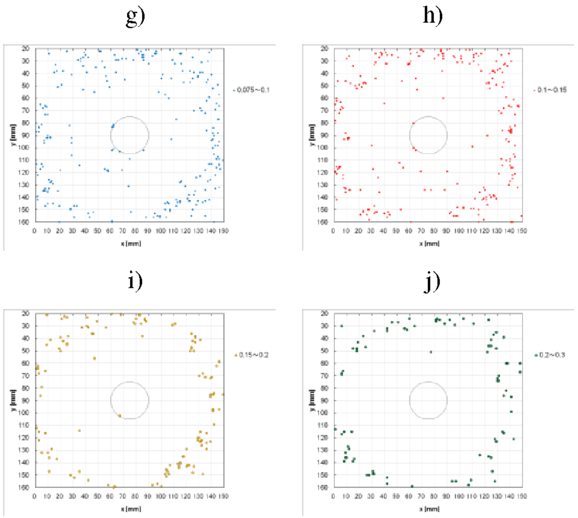

g) h) i) j)

Figure 8. Ejecta distribution for each size range. a-d) Test 11-180, front solar array coupon. a) 0.025-0.05 mm. b) 0.05-0.075 mm. c) 0.075-0.1 mm. d) 0.1-0.15 mm.. e-j) Test 11-195, Al honeycomb. e) 0.025-0.05 mm. f) 0.05-0.075 mm. g) 0.075-0.1 mm. h) 0.1-0.15 mm. i) 0.15-0.2 mm. j) 0.2-0.3 mm

Table 6. Comparison of normal and 45° calibration impact tests

Test	**Impact Velocity [km.s^{-1}]**	**Impact Angle [°]**	**Ejecta WP**	**Ejecta Mass [mg]**	**R**
12-72	5.01	45	43,970	167.7	98.6
12-74	5.09		41,919	154.4	90.8
12-75	5.16		43,711	265.2	156
11-72	4.83	90	3,783	156.6	92.1
11-73	4.93		4,555	105.6	62.1
11-82	4.97		4,184	144.5	85

The two centres are mainly formed by the largest ejecta with a size ranging from 75 µm to 400 µm, whereas the smallest ejecta, up to 75 µm, are more widely distributed all over the witness plate. Tab. 7 gives the ejection angle corresponding to the two centres for each test. The values presented have however to be taken carefully since a significant number of ejecta seems to have been emitted outside the witness plate.

For the ejecta distribution, the witness plates were separated into 15 sections with a width of 10 mm along the x axis (Fig. 10a). The ejecta distribution follows a Gaussian function and is presented in Fig. 10b.

As noticed for the test on the front solar array coupon, the ejecta seems to impact in smaller concentrated area with their size increasing (Fig. 11).

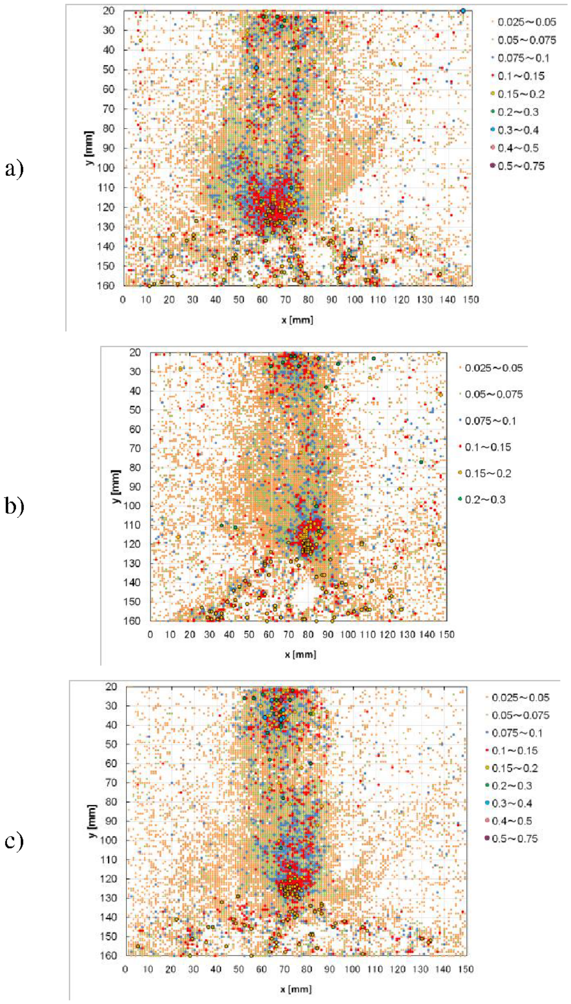


Figure 9. Microscope scans of the 45° calibration tests. a) 12-72. b) 12-74. c) 12-75

4 OUTLOOK

The calibration tests for the 45° impact tests were successful. The next step is thus to perform 45° impact tests on spacecraft materials. Moreover, oblique impact tests at different impact angles will be carried out.

From these data, the author would like to improve the current ISO11227 with regard to oblique impact evaluation procedure, and contribute to the ejecta database.

Table 7. Ejection centres characteristics

Test	Ejection Ø Lower Centre [mm]	Ejection Ø Upper Centre [mm]	Ejection Angle [°]
12-72	30	-	53.6
12-74	35	35	49.0
12-75	30	30	42.3

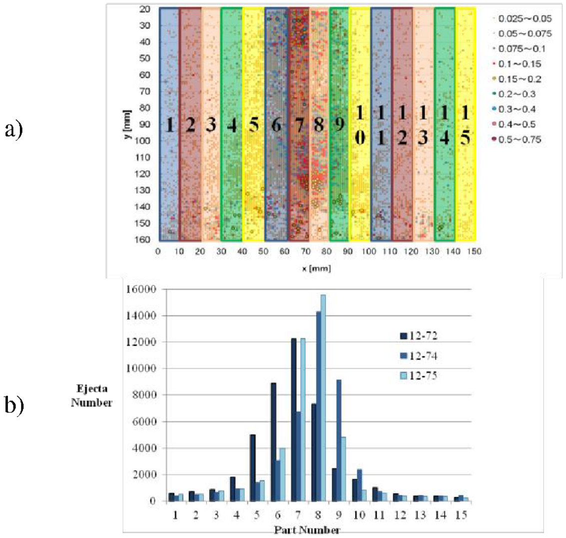
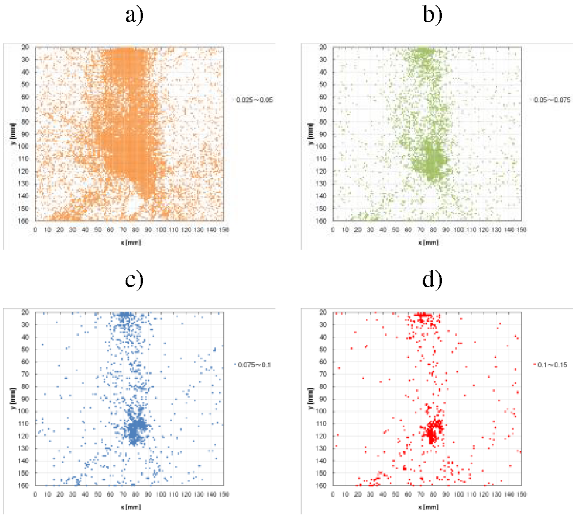


Figure 10. Ejecta distribution of the 45° calibration impact tests. a) Witness plate sections. b) Ejecta distribution



e)

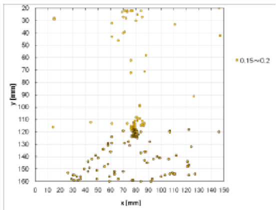


Figure 11. Ejecta distribution for each size range for the 45° calibration test, 12-74. a) 0.025-0.05 mm. b) 0.05-0.075 mm. c) 0.075-0.1 mm. d) 0.1-0.15 mm. e) 0.15-0.2 mm

5 CONCLUSION

In the paper, a review of the normal hypervelocity impact tests carried out at Kyushu Institute of Technology from 2009 to 2011 was first presented and several points were established:

1. the feasibility of the test procedure as defined by ISO11227 has been demonstrated;
2. the front of the solar array coupon emits the largest number of ejecta due to the cover glass on its surface;
3. CFRP/Al honeycomb and Al honeycomb emit on average the same number of ejecta but these ejecta are larger in the case of CFRP/Al honeycomb;
4. in case of an impact on a solar array coupon, the largest number of ejecta is emitted toward space;
5. in the case of CFRP/Al honeycomb or Al honeycomb, most of the ejecta will be emitted inward the spacecraft body;
6. for tests on spacecraft materials the ejecta mass is 6 to nearly 60 times the mass of the projectile;
7. ejecta impact in a narrower manner for brittle material case, 40° ejection angle, than for ductile materials case, 60° ejection angle.

Second, the first results of the ejecta distribution for the 45° calibration impact tests were given:

1. ejecta impacted forming a trail along the y axis;
2. ejecta impacted at the bottom of the witness plate, perpendicularly to the previously described ejecta trail;
3. two main ejection centres were identified that correspond to an average ejection angle of 48°;
4. the number of ejecta is about 10 times higher for the 45° calibration tests than for the 90° calibration tests;
5. the ejecta mass is 90 to nearly 160 times the mass of the projectile;
6. the ejecta seem to impact in smaller concentrated area with their size increasing;
7. the ejecta distribution can be represented by a Gaussian function.

Finally, in future studies, the authors planned on carrying on further oblique tests at different incident angles and on targets representative of materials used on-board of spacecraft.

ACKNOWLEDGMENTS

This work was partially supported by the JAXA and IHI. The authors thank Mr. H. Matsumoto and Mr. H. Kato (JAXA), and Dr. Y. Kitazawa (IHI) for their efforts. It also was partially supported by the JSPS Grant-in-Aid for Scientific Research (B) (Grant Number:24360351) and (C) (Grant Number:21560819).

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