Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 204 (2017) 270–275

Procedia Engineering

www.elsevier.com/locate/procedia

14th Hypervelocity Impact Symposium 2017, HVIS2017, 24-28 April 2017, Canterbury, Kent, UK

# Ejecta From LPSO-Type Magnesium Alloy Targets in Hypervelocity Impact Experiments

Masahiro Nishida[a,]*, Fumiya Kodama[a], Koichi Hayashi[b],
Yasuhiro Akahoshi[c], Kazuyuki Hokamoto[d], Yoshihito Kawamura[d]

[a]*Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, Aichi 466-8555, Japan*
[b]*National Institute of Technology, Toba College, 1-1, Ikegami-cho,Toba City, Mie, 517-8501, Japan*
[c]*Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu-shi, Fukuoka, 804-8550, Japan*
[d]*Kumamoto University, 2-39-1 Kurokami, Chuo-ku, Kumamoto 860-8555, Japan*

---

## Abstract

Because long period stacking ordered (LPSO) type magnesium alloys have the low density, excellent mechanical strength and ignition resistance, LPSO-type magnesium alloys have a great potential as structural materials of satellites. Ejecta size and crater shape were examined when spherical projectiles struck targets made of LPSO-type magnesium alloy at hypervelocities of 2 km/s and 5 km/s. After impact experiments, crater surfaces and lips near craters were observed X-ray computed cosmography (CT) in detail. Ejecta collected from test chamber were measured. Results of LPSO-type magnesium alloy targets were compared with those of aluminum alloy (A6061-T6). Fracture behavior of LPSO-type magnesium alloy targets seemed to be brittle and many small ejecta from LPSO-type magnesium alloy were observed.

Peer-review under responsibility of the scientific committee of the 14th Hypervelocity Impact Symposium 2017.

*Keywords:* Hypervelocity, Ejecta, Magnesium alloy, Size distribution, Space debris;

---

## 1. Introduction

Launching costs of satellites are roughly proportional to payload weight. Therefore, decreasing weight of satellites brings reduction of launching costs. Many types of aluminum alloys have been widely employed for spacecraft and launch vehicles. Among many prospective materials, magnesium alloys have several advantages

---

* Corresponding author. Tel.: +81-52-735-5349
*E-mail address:* nishida.masahiro@nitech.ac.jp

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the 14th Hypervelocity Impact Symposium 2017.
10.1016/j.proeng.2017.09.735

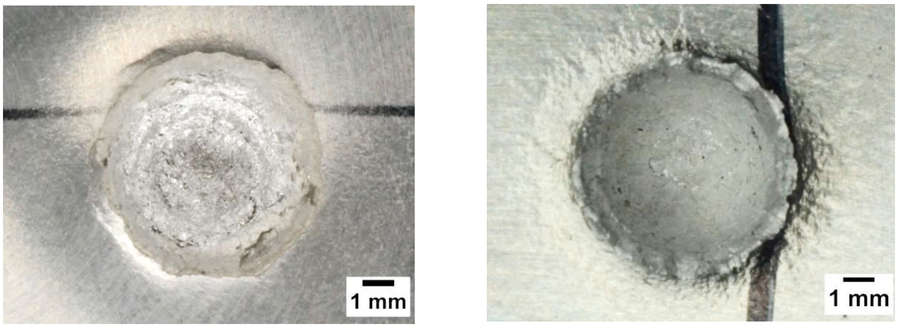
such as low density, high vibration absorption, electromagnetic shielding and dimension stability. New-types of magnesium alloys using rare metals overcame longtime disadvantages of conventional magnesium alloys such as fire hazard and low strength. Among them, Professor Kawamura of Kumamoto University developed magnesium alloys with long period stacking order (LPSO) phase and alpha phase (dual phase) with high strength and thermal resistance [1]. Many industrial applications such as automobiles, aircraft and spacecraft are being considered. In the case of space application, environment resistance such as the defense against and suppression of space debris, atomic oxygen (AO), electron beam (EB) and vacuum ultraviolet radiation is crucial.

Space debris often strikes space stations and spacecraft at hypervelocities over 10 km/s. The International Space Station (ISS) employs bumper shields, such as the Whipple shield and the stuffed Whipple shield, which consists of thin plates to protect itself from space debris. Even though small space debris strikes satellites, mission failure might be triggered. Therefore many hypervelocity impact experiments have been carried out to understand the mechanism of space debris impact. The authors are interested in ejecta from targets when projectiles struck targets in hypervelocities [2, 3]. New types magnesium alloys have been developing. Many researchers have been studying shock behaviour of magnesium alloys [4-6]

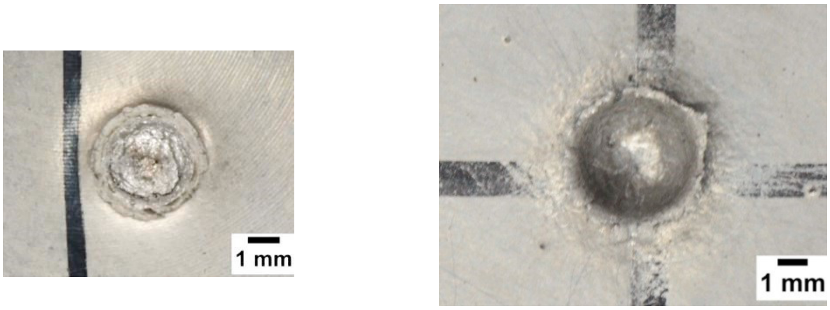
In this study, a high strength magnesium alloy of LPSO-type magnesium alloy (hereinafter referred to as LPSO-Mg) was used for the targets of impact experiments. Ejecta from LPSO-Type magnesium alloy targets were examined. Crater shape of LPSO-Mg was also compared with that of aluminum alloy.

## 2. Experimental Methods

Projectiles were made of aluminum alloy 2017-T4 with a diameter of 1.6 mm. Two-stage light gas guns at Japan Aerospace Exploration Agency, (JAXA) [7] and Nagoya Institute of Technology was used for impact test. The impact velocity was fixed at 2 km/s and 5 km/s. Thick plates of LPSO-type magnesium alloy, $Mg_{95.65}Zn_2Y_2La_{0.1}Al_{0.25}$ (at. %) (Fuji Light Metal Co.) [8-10], were used as targets. In order to compare results, aluminum alloy, A6061-T6, was also used as target materials. Table 1 lists the values of the mechanical properties of the target materials. After impact experiments, the length of ejecta collected from test chamber was measured using image analysis software (ImageJ).



(a) LPSO magnesium alloy (5.5 km/s) (b) Aluminum alloy 6061-T6 (5.3 km/s) [11]



(c) LPSO magnesium alloy (2.0 km/s) (d) Aluminum alloy 6061-T6 (2.1 km/s)

Fig. 1. Photographs of craters after impact experiments.

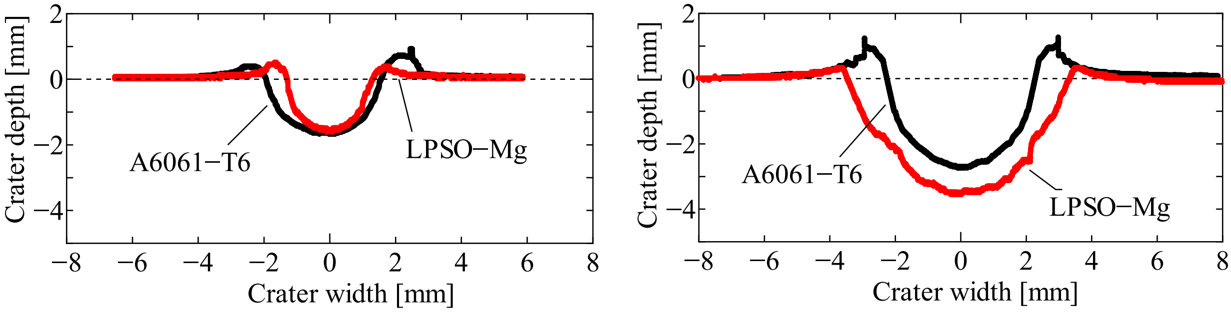
Table 1. Mechanical properties of target materials.

| | LPSO-Mg<br>Mg96Zn2Y2 | Aluminum alloy<br>A6061-T6 [12] |
|---|---|---|
| 0.2% proof stress [MPa] | 340 | 275 |
| Tensile strength [MPa] | 376 | 310 |
| Elongation at break [%] | 5 | 12 |
| Density [g/cm$^3$] | 1.89 | 2.70 |

## 3. Results and Discussion

### 3.1. Observation of targets

Figure 1 show photographs of the LPSO-type magnesium alloy target and aluminum alloy target after projectile impact of 1.6 mm in diameter at 2 km/s and 5 km/s. Enlarged images of the targets from directly above were shown in the figures. Regardless of impact velocity, the crater surfaces of aluminum alloy were smooth, whereas those of LPSO-Mg were relatively rough. The crater surfaces of LPSO-Mg seemed to be multilayers. Crater lips of aluminum alloys were clearly developed, whereas those of LPSO-Mg were not long. LPSO-Mg seemed to be brittle compared with aluminum alloy.



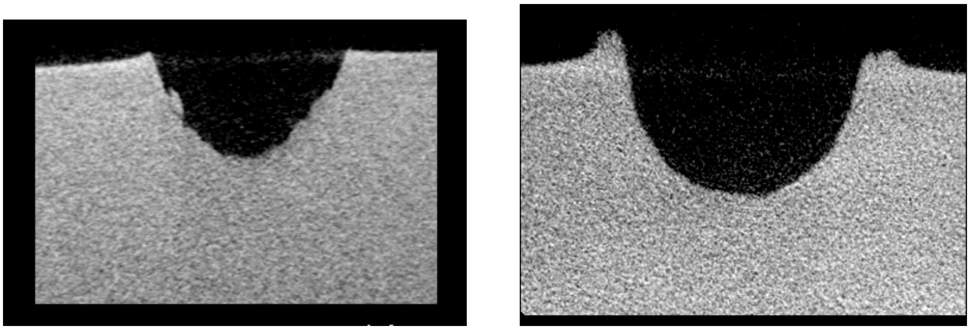
(a) 2 km/s (b) 5 km/s

Fig. 2. Comparison of crater shapes.

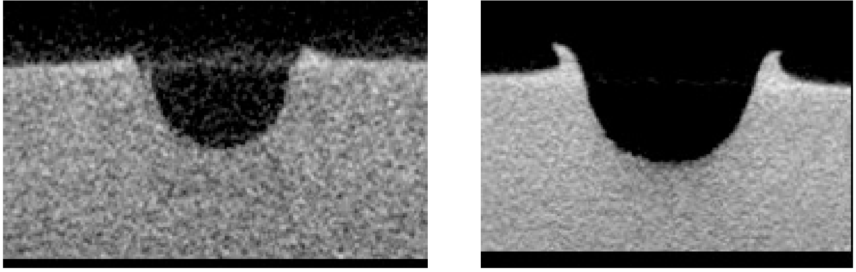
After the experiments, the crater shape was measured using a contour measuring instrument (Tokyo Seimitsu Co., 600B). Fig. 2 shows the comparison of the crater shape profiles between the LPSO magnesium and the aluminum alloy. At the impact velocity of 2 km/s, the crater diameter of LPSO-Mg was smaller than that of aluminum alloy. The crater depth of LPSO-Mg and aluminum alloy was almost the same. At the impact velocity of 5 km/s, the crater depth and crater diameter of LPSO-Mg was clearly larger than that of aluminum alloy.

Fig. 3 shows cross-sectional views using X-ray computed tomography (X-ray CT, Shimadzu inspeXio SMX-100CT). Regardless of impact velocity, we can observe many cracks on the crater surfaces of LPSO-Mg and cannot observe any cracks of aluminum alloy targets. The crater surfaces of aluminum alloy were smooth. The cross-sectional views by X-ray CT show that crater lips of aluminum alloys were largely developed, whereas those of LPSO-Mg were not observed as shown in Fig. 1. The shape of aluminum alloy was hemisphere regardless of impact velocity. The crater shape of LPSO-Mg at the impact velocity of 2 km/s was slightly circular cone rather than hemisphere, whereas that at 5 km/s was hemisphere.

Fig. 4 shows photographs of fragments collected from test chamber after impact experiments. Many large fragments were collected in the case of LPSO-Mg and aluminum alloy. There was no special feature. In both cases, the fragment shapes were similar. After taking images, size of fragments collected from test chamber was measured using image analysis software (ImageJ) as shown in Fig. 5. The length, *a*, width, *b*, and thickness, *c*, of fragments was defined as shown in Fig. 6. We measured only the fragments having length over 0.5 mm.



(a) LPSO magnesium alloy (5.5 km/s) (b) Aluminum alloy 6061-T6 (5.3 km/s) [11]

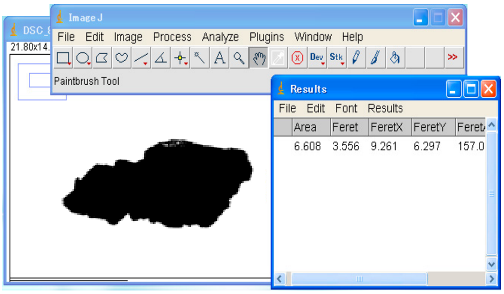


(c) LPSO magnesium alloy (2.0 km/s) (d) Aluminum alloy 6061-T6 (2.1 km/s)

Fig. 3. Cross-sectional images by X-rays computed tomography (CT).

(a) LPSO-Mg (b) A6061-T6

Fig. 4. Photographs of fragments collected from test chamber (5 km/s).



| Area | Feret | FeretX | FeretY | Feret |
|---|---|---|---|---|
| 6.608 | 3.556 | 9.261 | 6.297 | 157.0 |

Fig. 5. Analysis image of ImageJ.

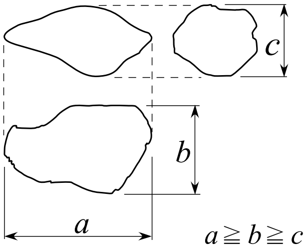
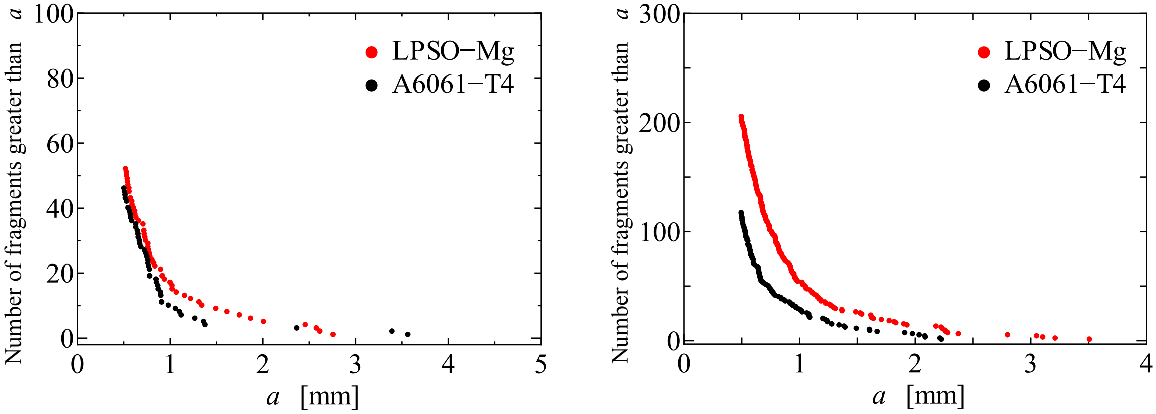


Fig. 6. Definition of fragment size.



(a) 2 km/s

(b) 5 km/s

Fig. 7. Comparison of crater shapes.

Fig. 7 shows the cumulative number distribution of the maximum length *a*. At the impact velocity of 2 km/s, the cumulative number distribution of LPSO-Mg was almost the same as that of aluminum alloy in a length range less than 0.7 mm. At the impact velocity of 5 km/s, the cumulative number of LPSO type magnesium alloy was always more than that of aluminum alloy. The maximum of the fragment length was 3.5 mm in the case of LPSO-Mg, whereas that of aluminum alloy was 2.2 mm which is two-thirds of LPSO-Mg.

## 4. Conclusions

Ejecta size and crater shape were examined when spherical projectiles struck targets made of LPSO-type magnesium alloy at hypervelocities of 2km/s and 5 km/s. The crater surfaces of aluminum alloy were smooth, whereas those of LPSO-Mg were relatively rough. LPSO-Mg seemed to show brittle fracture compared with aluminum alloy. At the impact velocity of 5 km/s, the crater size of LPSO-Mg was large. The number of ejecta from LPSO-Mg was higher and the maximum length of ejecta was larger.

## 5. Acknowledgments

This study was supported by ISAS, JAXA as a collaborative program with the Hypervelocity Impact Facility (the Space Plasma Laboratory) and was supported in part by JSPS KAKENHI Grant Number JP24360351, Grant-in-

Aid for Scientific Research (B). The authors would like to express the deepest appreciation to the financial support from Nagoya Institute of Technology.

## References

[1] Y. Kawamura, K. Hayashi, A. Inoue, T. Masumoto, Rapidly solidified powder metallurgy Mg97Zn1Y2 alloys with excellent tensile yield strength above 600MPa, Mater. Trans. 42 (2001) 1172-1176.
[2] M. Nishida, K. Kuzuya, K. Hayashi, S. Hasegawa, Effects of alloy type and heat treatment on ejecta and crater sizes in aluminum alloys subjected to hypervelocity impacts, Int. J. Impact Eng. 54 (2013) 161-176.
[3] M. Nishida, Y. Hiraiwa, K. Hayashi, S. Hasegawa, Ejecta cone angle and ejecta size following a non-perforating hypervelocity impact, Procedia Eng. 103 (2015) 444-449.
[4] L. Q. Ruan, Dynamic Forming of AZ91 Magnesium Alloy Using Explosive Energy, Materials Science Forum. 673 (2011) 297-300.
[5] G. V. Garkushin, I. Kanel, S. V. Razorenov, High strain rate deformation and fracture of the magnesium alloy Ma2-1 under shock wave loading, Physics of the Solid State. 54 (2012) 1079–1085.
[6] P.J. Hazell, G.J. Appleby-Thomas, E. Wielewski, C. Stennett, C. Siviour, The influence of microstructure on the shock and spall behaviour of the magnesium alloy, Elektron 675, Acta Materialia. 60 (2012) 6042-6050.
[7] N. Kawai, K. Tsurui, S. Hasegawa, E. Sato, Single microparticle launching method using two-stage light-gas gun for simulating hypervelocity impacts of micrometeoroids and space debris, Rev. Sci. Instrum. 81 (2010) 115105.
[8] E. Abe, Y. Kawamura, K. Hayashi and A. Inoue, Long-period ordered structure in a high-strength nano-crystalline Mg-1at%Zn-2at%Y alloy studied by atomic-resolution z-contrast stem, Acta. Mater. 50 (2002) 3845-3857.
[9] S. Yoshimoto, M. Yamasaki and Y. Kawamura, Microstructure and mechanical properties of extruded Mg-Zn-Y alloys with 14H long period ordered structure, Mater. Trans., 47 (2006) 959-965.
[10] Y. Kawamura and S. Yoshimoto, Magnesium Technology 2005, (ed. H.I. Kaplan), TMS, 2005, pp. 499-502.
[11] M. Nishida, K. Ishida, F. Kodama, K. Hayashi, Y. Akahoshi, K. Hokamoto, T. Mayama, M. Yamasaki, Y. Kawamura, Ejection Area from LPSO-type Magnesium Alloy Under Hypervelocity Impact, Proc. The 31st International Congress on High-speed Imaging and Photonics, (2016) 528-531.
[12] Metals Handbook, Vol.2 - Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Table 8, ASM International 10th Ed. 1990.