NUMERICAL SIMULATIONS OF IMPACT CRATERS GENERATED BY POROUS SOLID ROCKET MOTOR SLAGS

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ABSTRACT

Solid rocket motor slag, a critical debris for LEO satellites. The slags have various porosities, some exceeding 90%. The purpose of this study is to investigate the effect of porosity within projectiles on crater shape using numerical simulations. The hypervelocity impact tests were conducted at Kyushu Institute of Technology using the reversed impact method. Spherical slag particles with a diameter of approximately 1 mm was tested. Numerical simulations were performed with ANSYS Autodyn, assuming an alumina shell for the slag. The results showed that crater depth decreased at porosities of 50% and 80%. When the projectile included a void, a central bulge was generated during penetration. In the penetration process, it was observed that part of the bulge was ejected in the opposite direction to the penetration.

1 INTRODUCTION

Many satellites have used solid rocket motors for transfers to higher orbits. The solid rocket motor propellant contains aluminum particles to stabilize its combustion. These aluminum particles bind to the oxidant and then ejected as aluminum oxide particles. The size of these particles is a few micrometers. At the final phase of the combustion, on the other hand, the solid rocket motor ejects larger aluminum oxide debris. This debris is called solid rocket motor slag. As shown in the debris environment model, MASTER-8, most of the slag ranges from sub-millimeters to a few millimeters in size (Fig. 1). The slag accounts for much of the debris in orbit due to past rockets, and the possibility of impact with a spacecraft is great.

JAXA collected slags after the solid rocket motor ground combustion experiment [2, 3]. As shown in Fig. 2, the collected slags had various porosities, with porosities of some slags reaching over 90%. The purpose of this study is to investigate the effect of porosity within projectiles on the crater shape.

2 HYPERVELOCITY IMPACE TEST

2.1 Tested Slag

In the low vacuum combustion test of a small solid rocket motor, slags were collected from inside the motor case. From the collected slags, a spherical particle with a diameter of approximately 1 mm was selected as a test

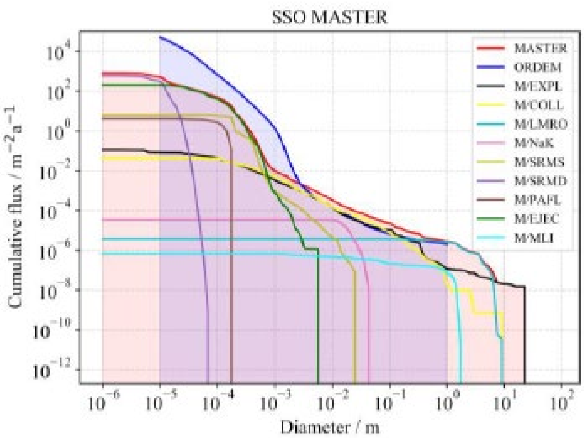


Figure 1. Debris population at 800 km altitude [1].

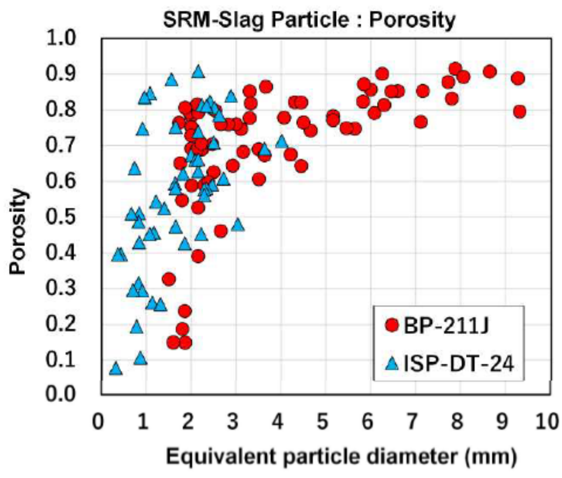


Figure 2. Porosity of Slags collected after the solid rocket motor ground combustion experiment [2].

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

sample (Fig. 3). The weight of this slag was 0.7 mg, and the representative diameter was 1.0 mm. When comparing with a 1 mm diameter sphere with aluminum density (3.95 g/cm³), the porosity was calculated to be 59.2%.

2.2 Revered Impact Test

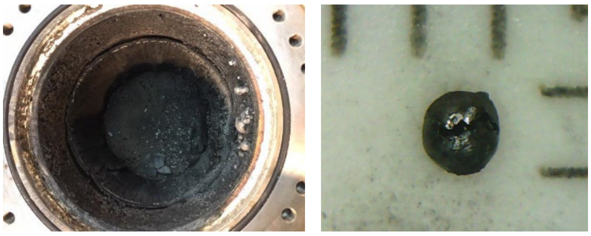
The hypervelocity impact test was conducted at Kyushu Institute of Technology. Since the slag is brittle and likely to break during acceleration, the reversed impact method was applied for the impact test.

An overview of the experiment is shown in Fig. 4. An aluminum cylinder (Fig. 5) is accelerated by a two-stage light gas gun. As shown in Fig. 5b, one side of the cylinder is machined into a concave shape. This bottom part acts as a witness plate. At the impact position shown in Fig. 4, a polystyrene supporter is placed as shown in Fig. 6 to hold the slag within the rails. Guide rails are connected to the exit of the launch tube. The cylinder accelerated by the two-stage light gas gun passes through the rail. The rails control the attitude of the cylinder and makes it impact with the slag. Downstream of the impact position, the inner diameter of the rails gradually decreases, and the cylinder is decelerated by friction. Finally, the cylinder is softly recovered in the chamber by a stack of polystyrene sheets. In this study, the speed was measured by wires installed immediately after the impact position, instead of pickup coils.

2.3 Test Result

The recovered aluminum cylinder is shown in Fig. 7. The blue circle indicates the impact mark. The impact velocity was 2.13 km/s.

The cylinder was inspected with X-ray CT. The results are shown in Fig. 8. The impact crater had a raised shape in the central part. The crater diameter was 1.40 mm, and the crater depth ranged from a maximum of 0.58 mm to a minimum of 0.28 mm, showing a difference of about 0.3 mm.



(a) Inside Rocket Motor *(b) SRM Slag Sample*

Figure 3. Tested SRM Slag.

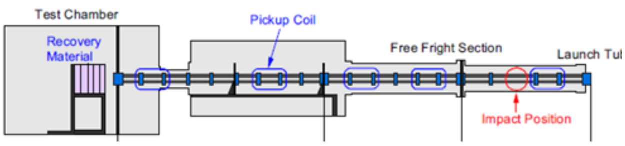
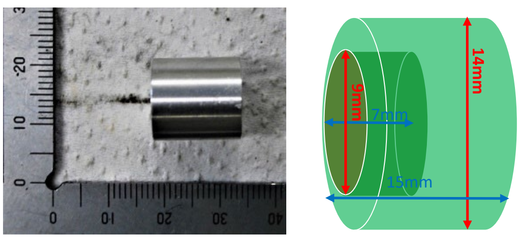


Figure 4. Reversed Impact Test [4].



(a) Outside *(b) Dimension*

Figure 5. Launched Aluminum Cylinder.

Figure 6. Slag Holder.

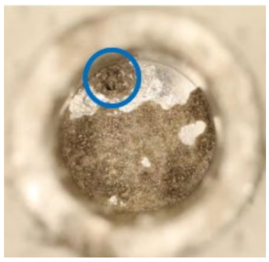


Figure 7. Crater on the Recovered Aluminum Cylinder.

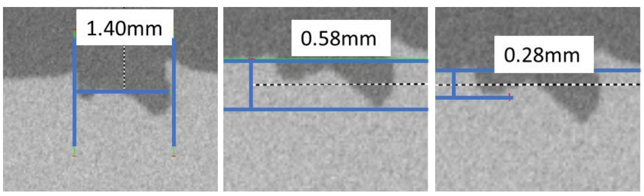


Figure 8. Xray CT Images of the Aluminum Cylinder after the Reversed Impact Test.

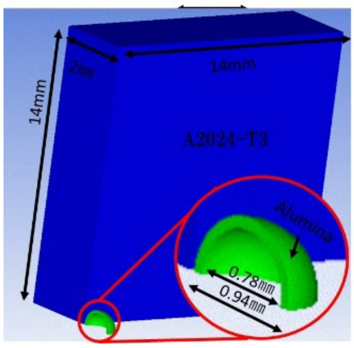


Figure 9. Numerical Simulation Model.

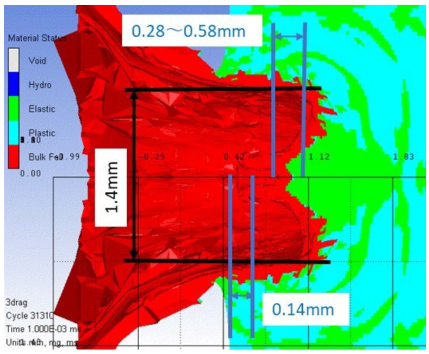


Figure 10. Numerical Simulation Result of The Impact Test.

3 COMPARISON WITH EXPERIMENT AND NUMERICAL SIMULATION

Numerical simulations were performed with ANSYS Autodyn ver.2022R2. In this study, the slag shape was assumed with an alumina shell as shown in Fig. 9. The solver was 3D Lagrange with 1/4 symmetry. The material model of alumina was imported from the Autodyn library. The equation of state was Polynomial, and the strength and failure models were Johnson Holmquist with a maximum tensile strength of 29 MPa. The aluminum cylinder was modeled as a 2 mm thick plate. The equation of state was Tillotson, the strength model was Steinberg Guinan, and the failure model was Plastic Strain of 0.4. In this simulation, the slag was accelerated to impact.

The simulation result is shown in Fig. 10. Green indicates the elastic region, light blue indicates the plastic region, and red indicates the fracture region. The arrows show the experimental values measured by the X-ray CT images. The crater diameter approximately matched between the experiment and the simulation. The depth of the crater also approximately matched, although the experimental values had a wide range. The central bulge also approximately matched the experimental values.

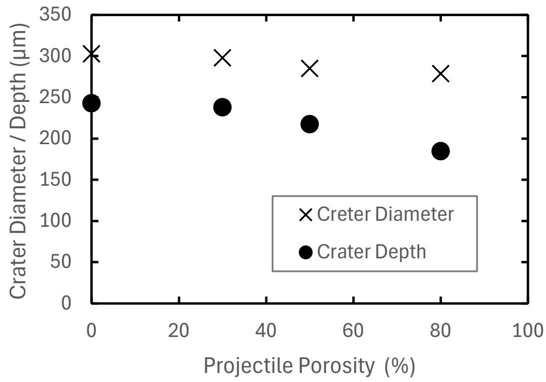


Figure 11. Porosity vs. Crater Shape.

4 EFFECT OF POROSITY

Fujii et al. conducted numerical simulations using alumina spherical shells with diameters ranging from 1 to 10 mm at impact velocity ranging between 2 and 15 km/s [5]. Their results showed that at impact velocities above 8 km/s, only the bulk density of the projectile influenced the crater depth. Therefore, this study investigates the effects of porosity on smaller particles.

For these simulations, the impact velocity was set to 10 km/s as it is a common impact velocity in low Earth orbit. To reduce computational costs, the simulations were conducted using 2D axis symmetry. The bulk density of the alumina shells was kept almost constant at 3.95 g/cm^3, and the porosities were varied by the void volumes at the center of the projectiles.

As a result of the simulations, the central bulge was not observed at the center of the crater. Therefore, the crater depths were measured from the central parts of the craters. The results are shown in Fig. 11. While the crater diameter did not change significantly, the crater depth tended to decrease at porosities of 50% and 80%. Focusing on the penetration processes, in all cases with containing void, a central bulge was formed at the center of the crater when the projectile penetrated about halfway. In the case of 30% porosity, the bulge was compressed towards the crater bottom due to the impact of the rear wall of the projectile. However, in the cases of 50% and 80% porosity, the rear walls were thin and could not compress the bulges, and part of it ejected in the opposite direction to the penetration. Therefore, it is considered that the final crater depth became shallow.

5 SUMMARY

To consider impact damage of solid rocket motor slags, this study investigated the effect of porosity within projectiles on crater formation using numerical simulations and hypervelocity impact tests with solid rocket motor slag. A hypervelocity impact test was conducted at Kyushu Institute of Technology using the reversed impact method. Numerical simulations were performed with ANSYS Autodyn, assuming an alumina shell for the slag. The simulation result showed good agreement with the experimental result. To investigate the porosity effects, the porosities of aluminum shells were varied while keeping the bulk density almost constant. The results showed that crater depth decreased at porosities of 50% and 80%, while the crater diameter remained largely unchanged. Focusing on the penetration processes, part of a central bulge of the crater was ejected in the opposite direction to the impact when the projectiles had higher porosities.

ACKNOWLEDGEMENT

This work was used computational resources of the Laboratory provided by the Research Center for Computing and Multimedia Studies, Hosei University (Project ID: LAB-842).

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