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Experimental research on resistance of infrared optical windows to erosion caused by ice particle impact

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ABSTRACT

The erosion resistance of infrared optical windows was studied experimentally using ice particles of 2 mm diameter. Single ice particles were accelerated to approximately Mach 4.7 using a two-stage light gas gun. Sapphire and zinc sulfide infrared optical windows were tested. The windows were impacted repeatedly until a linear or circumferential crack was found. From the normal impact tests, it was found that uncoated and AR-coated infrared windows have similar erosion characteristics. Damage threshold curves were determined from the test data to characterize the erosion resistance of the windows. From oblique impact tests, it was found that resistance to erosion from normal and oblique impacts is related by a trigonometric function based on damage threshold velocity (DTV).

1. Introduction

IT is known that millimeter-sized ice particles and water drops are present in the atmosphere in rain or snow [1–3]. The ice particles and water drops can impact a high-speed vehicle flying through the atmosphere and may cause erosion of the vehicle material. In particular, infrared optical windows which are used to protect delicate infrared sensors are known to be particularly vulnerable to the erosive environments [4].

The erosion of optical windows in an erosive environment is due to stress waves generated from the impact. The stress waves interact with pre-existing flaws and open micro-cracks in the material. When the cracks reach critical sizes, failure occurs abruptly. [4–7]

A considerable amount of research has been carried out on the erosion of optical windows by water drop impacts [4–11], but there is no reported research in the open literature on the resistance of optical windows to erosion by ice particle impact.

Ice particle impact phenomena have, however, been studied in other contexts. Ice impact experiments have, for instance, been performed on turbofan aeroengine' hail ingestion problems [12–15]. Simulated ice particles were fired at solid plates to study post-impact ice fragment' behavior. From that research, basic ice impact characteristics were obtained.

Erosion studies have also been carried out on materials other than window material. Kato et al. [16] and Arakawa et al. [17] studied impacts of cylindrical ice particles, of a diameter of tens of mm, on an ice block. Kim et al. [18,19] studied erosion on composite materials using an ice particle with a diameter larger than 25 mm at velocities below 200 m/s. Hong et al. [20,21] studied erosion on composite materials and aluminum alloys with mm-sized ice particles

In the present research, the impact tests on infrared optical windows were performed to understand the erosion resistance characteristics. Zinc sulfide (ZnS) and sapphire windows were considered. A two-stage light gas gun was used to accelerate the spherical ice particles of 2 mm diameter to approximately Mach 4.7.

In a flight vehicle, the window has a certain angle in relation to the direction of flight, that is, the direction of impact of airborne particles. Therefore, various impact angles were considered to understand the effects of impact angle. First, normal impact tests were performed. The infrared windows were repeatedly impacted until a linear or circumferential crack was found. A damage threshold curve (DTC) [7] was derived from the test data to characterize the erosion resistance of the window material. For oblique impact tests, impact tests with angles of 45° and 60° were performed. Test data were compared to the DTC derived from the normal impact cases using a simple trigonometric scaling relationship.

2. Experimental facility

A two-stage light gas gun was developed to launch an ice particle. Detailed information on the experimental facility is presented in Ref. [21].

A spherical ice particle with a diameter of 2 mm and a density of 918 kg/m^3 was prepared using a silicone mold in the form of a sphere

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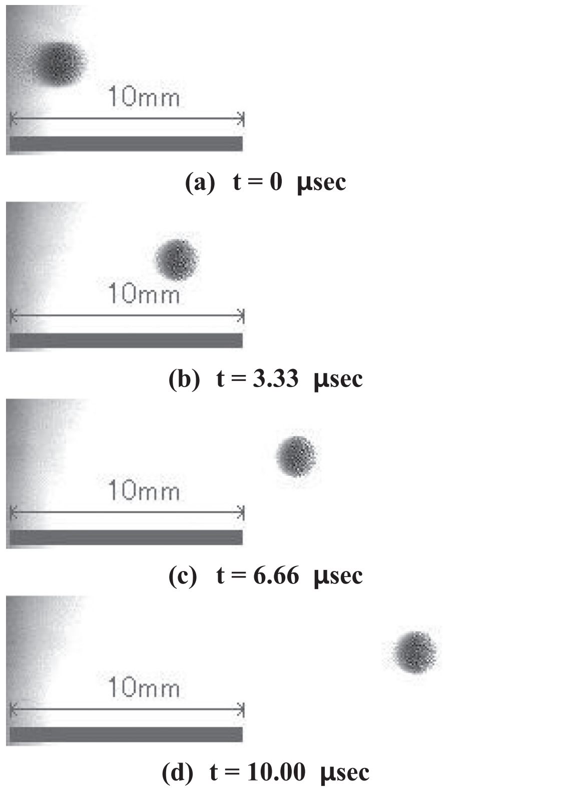

Fig. 1. Successive high-speed camera images of an ice particle with a velocity of 1429 m/s.

with a diameter of 2 mm. The mold was filled with water and frozen to 258 K. The frozen ice particle was then accelerated to the designated speed using a two-stage light gas gun.

A high-speed camera (FASTCAM SA-X2) was used to capture images with a resolution of 256 × 80 at 3.33 µs intervals. The exposure time was 293 ns. Fig. 1 shows successive images taken when the velocity of the ice particle was 1429 m/s. From the figure, it is clear that the ice particle remains intact.

Zinc sulfide (ZnS) and sapphire windows were considered as infrared optical window specimen. The physical properties are listed in Table 1. The specimens were fixed in a specimen holder as shown in Fig. 2. The distance between the gun and specimen was 50 mm. The specimen was impacted at its center with an impact angle defined as shown in Fig. 2.

3. Erosion resistance tests: normal impact cases

Erosion resistance tests of the infrared optical windows were performed for normal impact cases, with an impact angle of 90° (See Fig. 2).

First, a chemically vapor deposited (CVD) ZnS window with

Table 1
Physical properties of tested optical windows.

	ZnS	Sapphire
Density, g/cm^3	4.09	3.98
Harness (Knoop, kg/mm^2)	220	2000
Tensile strength (MPa)	104	400
Flexural strength (MPa)	68.9	650
Fracture toughness (MPa)	84	420
Young's modulus (GPa)	74.5	345
Poisson ratio	0.29	0.25
Thickness (mm)	4	3

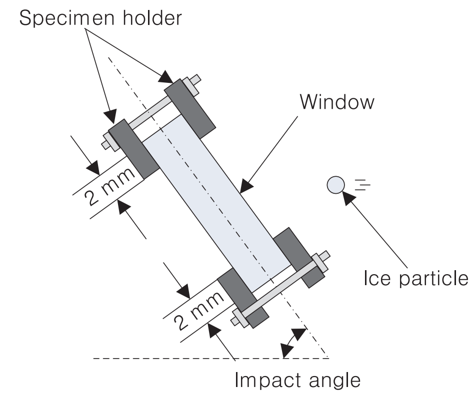

Fig. 2. Schematic of optical window and specimen holder.

dimensions of 30 × 30 × 4 mm (thickness) was tested. Both uncoated and anti-reflection (AR) coated ZnS windows with 1.34 µm coating thickness were tested. Repeated impact tests were conducted until the window had a linear or circumferential crack. The window was inspected using a microscope with 60 times magnification.

Fig. 3(a) and (b) show uncoated and AR-coated ZnS windows after 2 and 41 impacts, at ice particle velocities of 302 and 175 m/s, respectively. A circumferential crack was found in the uncoated ZnS window after 2 impacts. A partial circumferential crack was found in the AR-coated ZnS window after 43 impacts.

Test data for the uncoated and AR-coated ZnS windows are summarized in Table 2. For the AR-coated ZnS window with an average impact velocity of 155 m/s, no damage was found before 100 impacts.

Fig. 4 shows the erosion resistance characteristics of uncoated and AR-coated ZnS windows for the normal impact condition. A damage threshold curve (DTC) was derived from test data for the uncoated ZnS window as

$$V = 322N^{-0.1425} \tag{1}$$

where V and N represent damage threshold velocity and number of impacts, respectively. The average difference between the DTC and the test data for the AR-coated ZnS window is 3.65%. Therefore it can be concluded that there is no apparent difference between uncoated and AR-coated ZnS window. This is expected, because the AR coating is designed not to improve erosion resistance but to improve transmittance by reducing reflection [4].

Damage threshold curves were also derived using all test data for uncoated and AR-coated ZnS windows as shown in Fig. 4 because they have no difference in their erosion characteristics. The correlation coefficient, R, between the DTC and measured data is 0.994. From this curve, the damage threshold velocity (DTV) for 1 and 100 impacts of ice particles can be determined as 323 and 159.4 m/s, respectively.

A sapphire (Al_2O_3) with C-plane (0001) window with dimensions of 30 × 30 × 3 mm was also tested. Uncoated and anti-reflection (AR) coated sapphire windows with 0.36 µm coating thickness were tested. Repeated impact tests were conducted until the window had a linear or circumferential crack. The impacted window was inspected using a microscope with 60 times magnification.

Fig. 3(c) and (d) show the uncoated and AR-coated sapphire windows after 13 and 59 impacts at ice particle velocities of 864 and 681 m/s, respectively. The figure shows partial circumferential cracks. The test data for sapphire windows are summarized in Table 3. There is no damage to the AR-coated sapphire window, even after 100 impacts of the ice particle with an average velocity of 606 m/s.

Fig. 4 shows the results of the impact tests. A damage threshold curve (DTC) was derived from test data for uncoated sapphire window as

$$V = 1150N^{-0.1176}. \tag{2}$$

The average difference between the DTC and test data for AR-coated