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Paper

Polybenzimidazole (PBI) Coated CFRP Composite as a Front Bumper Shield for Hypervelocity Impact Resistance in Low Earth Orbit (LEO) Environment

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ABSTRACT: An object in the Low Earth Orbit (LEO) is affected by many environmental conditions unlike earth's surface such as, Atomic oxygen (AO), Ultraviolet Radiation (UV), thermal cycling, High Vacuum and Micrometeoroids and Orbital Debris (MMOD) impacts. The effect of all these parameters have to be carefully considered when designing a space structure, as it could be very critical for a space mission. Polybenzimidazole (PBI) is a high performance thermoplastic polymer that could be a suitable material for space missions because of its excellent resistance to these environmental factors. A thin coating of PBI polymer on the carbon epoxy composite laminate (referred as CFRP) was found to improve the energy absorption capability of the laminate in event of a hypervelocity impact. However, the overall efficiency of the shield also depends on other factors like placement and orientation of the laminates, standoff distances and the number of shielding layers. This paper studies the effectiveness of using a PBI coating on the front bumper in a multi-shock shield design for enhanced hypervelocity impact resistance. A thin PBI coating of 43 micron was observed to improve the shielding efficiency of the CFRP laminate by 22.06% when exposed to LEO environment conditions in a simulation chamber. To study the effectiveness of PBI coating in a hypervelocity impact situation, experiments were conducted on the CFRP and the PBI coated CFRP laminates with projectile velocities between 2.2 to 3.2 km/s. It was observed that the mass loss of the CFRP laminates decreased 7% when coated by a thin layer of PBI. However, the study of mass loss and damage area on a witness plate showed CFRP case to have better shielding efficiency than PBI coated CFRP laminate case. Therefore, it is recommended that PBI coating on the front bumper is not so effective in improving the overall hypervelocity impact resistance of the space structure.

Key Words: Polybenzimidazole (PBI), Hypervelocity impact, Front bumper, CFRP

1. INTRODUCTION

Polymer composites especially carbon-epoxy composites (referred as CFRP) with its lightweight, high specific strength and stiffness could serve as a potential material for spacecraft structures. The main parameters that affect the material performance in the Low Earth Orbit (LEO) environment are Atomic oxygen, High Vacuum, thermal cycling, Ultraviolet radiation and MMOD impacts [1]. A material in the LEO environment is generally exposed to 2×10^9 to 8×10^9 atoms/cm^3 of AO, 10^{-6} to 10^{-7} torr of high vacuum, 200-400 nm wavelength of UV radiation and ±150°C thermal cycling. These LEO environment parameters causes surface erosion, outgassing, contamination of surfaces and formation of volatile substances in the carbon epoxy composites, and lead to degradation of material properties of the structure. Hence, spacecraft materials should be designed to withstand the effects of these parameters for its entire lifespan and provide acceptable levels of protection throughout its service life. Moreover, the increasing amount of space debris in the LEO poses a serious threat to the spacecraft in space [2]. More than 24000 objects in space are actively monitored by various space agencies and

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millions of micro debris that are not trackable also exists. These debris objects generally collide with the spacecraft at hypervelocity speeds of 7-15 km/s and it could potentially destroy the entire structure if the object is a few centimeters large [3]. Orbital diversion is performed for objects greater than 10 cm. However, these diversions are not possible for smaller debris objects. Hence, it is essential to design structures that withstand these hypervelocity impacts.

There has been studies that report various approaches to achieve the required level of debris impact, such as Whipple shield designs, multi shock shields, surface modification, surface coatings, high energy absorption fabrics, etc [4-7]. Parameters like laminate thickness, standoff distance and number of shielding layers affect the performance of shielding design in hypervelocity impact conditions [8]. Moreover, the location of materials on a spacecraft structure also affects its shielding efficiency [9]. Hence, it is very essential to evaluate the performance of composite materials in different configurations to obtain the most optimal configuration.

Polybenzimidazole (PBI) is a thermoplastic polymer that has excellent thermo-mechanical properties also at cryogenic conditions, high thermal stability and fire resistance, low coefficient of thermal expansion, excellent AO resistance and radiation shielding properties [10]. Their high fracture toughness and ductile fracture mechanism is expected to improve the shielding efficiency in the event of a hypervelocity impact. It was reported earlier that a thin PBI coating on a CFRP laminate helps in improving the surface erosion and mass loss in a LEO environment and also energy absorption capability of the structure at hypervelocity speeds [11]. This paper discusses about the efficiency of a PBI coating on a CFRP specimen to be utilized as a front bumper for a spacecraft structure in improving the surface erosion resistance and enhancing the impact resistance at hypervelocity speeds.

2. METHODS AND PROCEDURE

CU125NS, a carbon-epoxy prepreg system, purchased from Hankuk Fiber Glass Cooperation (South Korea) was considered as the reference composite laminate for the present study. The CFRPs were manufactured using a stacking sequence of $[0/\pm45/90]_{2s}$ in a vacuum bag by autoclave molding. Fig. 1 shows the vacuum and temperature conditions for this manufacturing process.

The CFRP specimens was later taken through an Atmospheric Pressure Plasma Treatment (APPT) surface treatment process to improve the adhesion for the coating process [12]. Firstly, the samples were surface cleaned using ethanol solution to remove the impurities on the surface of CFRPs. After surface cleaning, the samples were exposed to plasma with a power of 200 watts for 10 minutes in a vacuum dried chamber with oxygen flow of 10 sccm. The samples were purged with nitrogen to atmospheric pressure. The treated samples were then dried in vacuum for 4 hours in a vacuum oven.

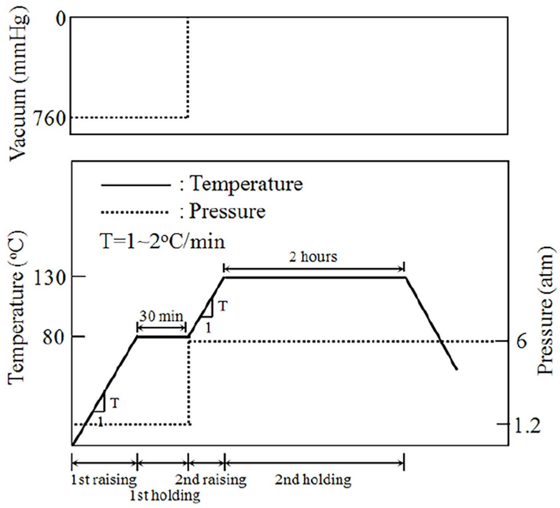

Fig. 1. Curing cycle of CU125NS by Autoclave molding

PBI coating on the CFRPs is implemented using a doctor blade. The PBI material is diluted to the required concentration (12%) needed by the user using N, N-Dimethylacetamide (DMAc) as the solvent. The PBI solution added is homogenized using a sonicator for one hour and magnetic stirrer at 60°C and 250 rpm for one hour. This solution is then applied using a doctor blade (500 μm thickness) on the CFRP samples and then dried in a vacuum oven for 12 hours (1 hr at 70°C, 2 hrs at 80°C and 9 hrs at 120°C). The sample is then allowed to cool down in vacuum environment. The average thickness of the specimen is measured to find the PBI coating thickness.

The CFRP and PBI coated CFRP (PBI/CFRP) samples were used for LEO exposure to study mass loss and surface erosion in a LEO environment simulation chamber with parameters like AO, high Vacuum, thermal cycling and UV. The chamber was calibrated using a Kapton film to find the closest real time mission. The environmental conditions simulated in the LEO chamber are described in Table 1. It was found that the atomic oxygen fluence of the chamber was 2.29×10^{20} atoms/cm^{2}s what was very close to the EOIM-III mission with AO fluence 2.3×10^{20} atoms/cm^{2}s. The LEO exposure study of the CFRP and PBI/CFRP specimens were also conducted with the simulation conditions mentioned in Table 1. The experiment was performed for approximately 9 hours that corresponded to 5

Table 1. LEO simulation facility environment conditions

LEO Simulation Environment	
UV radiation (UV)	UV radiation with 200 nm
Atomic Oxygen (AO)	RF power plasma with oxygen mass flow of 10 sccm (AO flux of 6.93×10^{15} atoms/cm^2·s)
High Vacuum	10^{-6} torr
Thermal Cycle	-70°C to 170°C (5 cycles (9 hours))

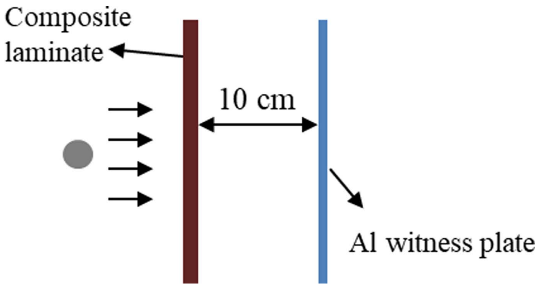

Fig. 2. Schematic Diagram for test setup

cycles of thermal cycling in the simulation chamber.

The CFRP and the PBI/CFRP samples were tested for hypervelocity impact resistance as a front bumper shield in a dual wall structure using an Aluminum projectile (Al2017-T4) of 5.56 ϕ mm and 0.25 g weight. A schematic diagram of the experimental setup is showed in Fig. 2. The hypervelocity impact tests are performed at speeds of 2.2 to 3.2 km/s with the help of a 2 stage light gas gun (LGG) in a vacuum environment. An Al 6061-T6 Aluminum witness plate of 3 mm thickness is placed 100 mm behind the front bumper to study the debris cloud and the mass loss. The velocity of the projectile is measured with the help of a laser intervalometer as shown in Fig. 3.

3. RESULTS AND DISCUSSION

LEO exposure study is a very essential study for a composite laminate as front bumper as the rate of erosion is a very critical parameter to the structural stability of the spacecraft. PBI has excellent AO resistance, outgassing properties, high thermal stability and strength retention in cryogenic temperatures. Thus, adding a PBI coating on the outer bumper could help improve the shielding efficiency in the LEO environment. The CFRP and PBI/CFRP samples were exposed to LEO environment as described in Table 1. The LEO environment exposure in the simulation chamber resulted in a mass loss decrease of 5.13% and 3.85% for the CFRP and the PBI/CFRP samples respectively. The mass loss density reduced 22% as a result of PBI coating on the CFRP. Erosion yield values calculated for the CFRP and PBI/CFRP composites (Fig. 4) showed a 22.06% improvement from 3.84×10^{-23} to 2.99×10^{-23} cm^3/atom by coating a 43 micron (±3 μm) PBI on the CFRP composite. Moreover, the performance of the material could

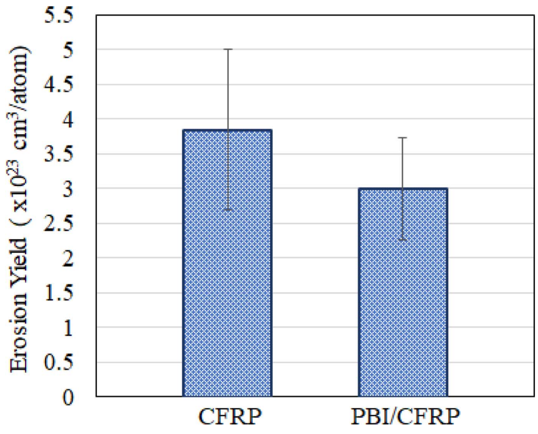

Fig. 4. Erosion Yield of composite after LEO exposure

be possibly improved with an increase in thickness. However, This particular thickness was decided to achieve uniform coating with the least increase in areal density as it a very important design criterion for space structures.

Fig. 5 shows the CFRP and PBI/CFRP samples and their respective witness plates after hypervelocity impact with test setup shown in Fig. 2. It was observed that both the CFRP and the PBI/CFRP samples showed similar fracture mechanism at all the velocity ranges tested. Moreover, The shape of the debris cloud in the witness plate for both the CFRPs and the PBI/CFRPs were also indistinguishable on visual analysis except for the projectile velocity range ~3.14 km/s. Below the 3 km/s velocity range there was possibly no fragmentation of the projectile and hence a similar debris cloud shape was visualized in witness plates for both the CFRP and PBI/CFRP samples. However, above 3 km/s the difference in debris shape could be attributed to the defragmentation of the projectile after impact with the bumper shield. It was noticed that the debris cloud is more spread in the case of the CFRP specimens more than the PBI/CFRP case.

Fig. 6 shows the mass loss of CFRP and PBI/CFRP composite bumper shields after hypervelocity impact experiments. Firstly, mass loss of both the CFRP and PBI/CFRP specimens were observed to increase with increase in projectile velocity. In addition, the mass loss of CFRP laminates were noticed to be higher than the mass loss of PBI/CFRP laminates. The average mass loss of the CFRP samples was about 7.19% more than in the PBI/CFRP samples. This decrement in mass loss in the

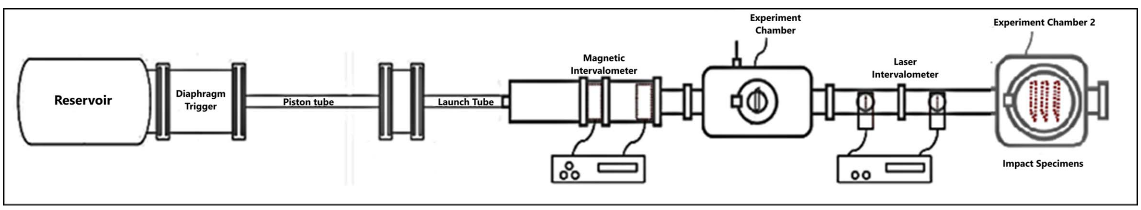

Fig. 3. Schematic Diagram of the two stage Light Gas Gun

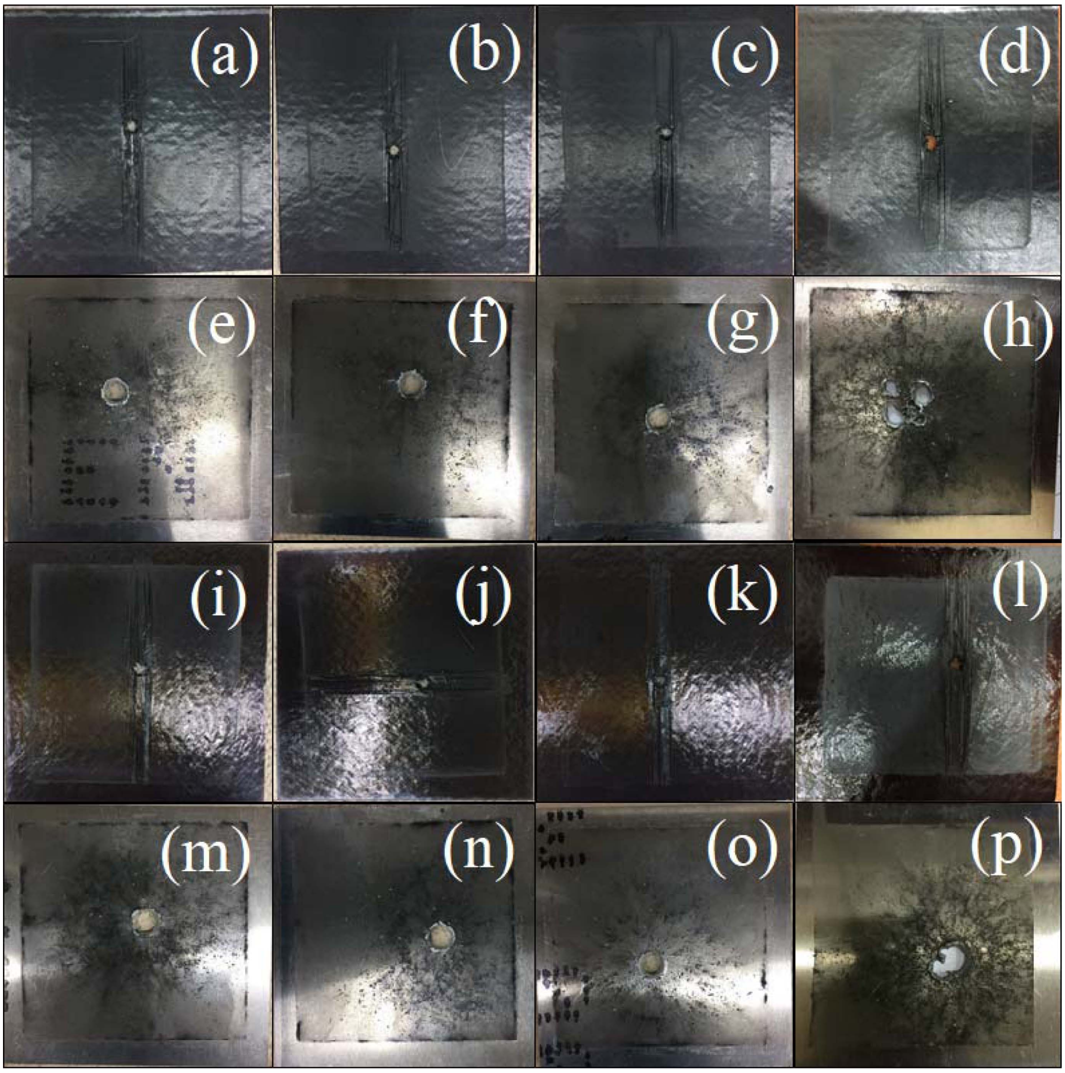

Fig. 5. (a),(b),(c) and (d) are CFRP Front bumper shield at 2.27 km/s, 2.45 km/s, 2.25 km/s and 3.18 km/s; (e), (f), (g) and (h) are respective Al witness plate to (a),(b),(c) and (d). (i),(j),(k) and (l) are PBI/CFRP front bumper shield at 2.67 km/s, 2.51 km/s, 2.27 km/s and 3.14 km/s; (m), (n), (o) and (p) are respective Al witness plate to (i),(j),(k) and (l)

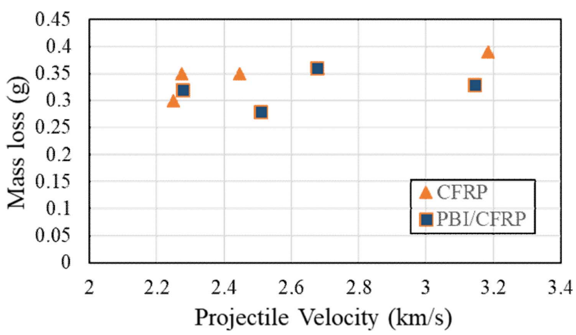

Fig. 6. Mass loss of the laminate after impact

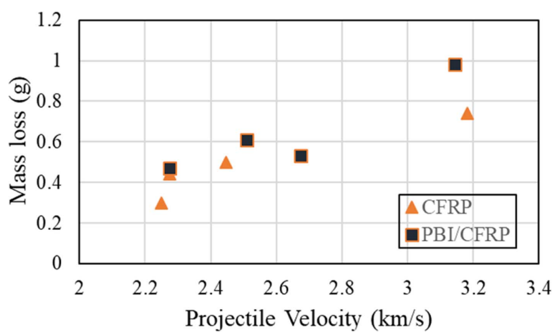

Fig. 7. Mass loss of the Witness plate after impact

PBI/CFRP samples could be attributed to the efficiency of the PBI coating to improve the hypervelocity impact resistance of the composite laminate. This result is in agreement with the observations of a previous study evaluating the effectiveness of a PBI coating on a composite laminate [10]. However, the improved hypervelocity impact resistance of the composite laminate is not sufficient to verify the effectiveness of the PBI coating on the front bumper as there are many factors like

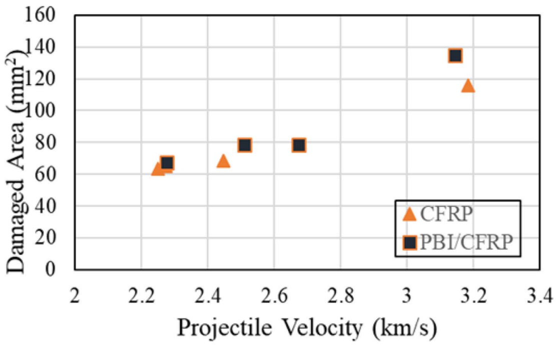

Fig. 8. Damaged Area of the witness plate after impact

debris shape that affect the shielding efficiency of the entire system.

Fig. 7 shows the mass loss of witness plates for both the CFRP and the PBI/CFRP cases. It could be noticed from the figure that the mass loss of witness plates for both CFRP and PBI/CFRP cases increases with increase in projectile velocity. However, unlike the observations of the bumper shield, the mass loss of the witness plates was found to be higher in the case of PBI/CFRP rather than CFRP. Thus, it could be assumed that the PBI coating on the bumper shield actually reduces the shielding effectiveness of the whipple shield. However, an alternative analysis of damage area in the witness plate is also essential to affirm this observation from the mass loss study.

The damaged area on the witness plates were calculated with a scanned image of the witness plate utilizing an image processing software. Fig. 8 shows the damaged area of witness plates for both the CFRP and PBI/CFRP samples described in Fig. 5. It can be observed from the figure that the average damaged area of the witness plate with PBI/CFRP composites was higher in all cases than the CFRP laminates. It could thus be implied that PBI/CFRP samples were not so effective in scattering the debris upon impact as much as the CFRP bumper. This results in an increased number of concentrated high-energy particles which as a consequence leads to increased damage area. This result affirms the results observed from the mass loss study.

4. CONCLUSIONS

PBI coated CFRP specimens showed to be more efficient than CFRP specimens in protection with LEO environment parameters like AO, UV, thermal cycling and high vacuum. In the event of a hypervelocity impact, PBI coating serves as a protecting material in reducing the mass loss of the specimen. Whereas, the high mass loss and damaged area of the witness plates in the case of PBI coated CFRP composites makes PBI a less favorable material to considered as a coating for front bumper. However, the reduction of mass loss in the PBI coated composite laminate cannot be neglected and hence it can be recommended as good material to be used as a back bumper.

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