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High velocity impact characterization of Al alloys for oblique impacts

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ABSTRACT

This paper describes the experimental and computational analyses of a high velocity aluminum projectile impact on an Al6061-T6 spacecraft inner wall at different oblique angles. Al2017-T4 spherical projectiles of 5.56 mm in diameter and 0.25 g in weight were chosen within the velocity range of 1000 ± 200 m/s due to the limitation of the light gas gun. The energy absorbed was calculated by measuring the velocities before and after impact on the inner wall. The energy absorbed by the wall and the remaining energy carried by the projectile helped to estimate the severity of further damage to inner components. Afterwards, validation was done by using the commercially available software LS-DYNA with a dedicated SPH. On average, a 10% energy absorption difference between experimentation and simulation was found. By using C-SCAN, the damage area proportion of the total inner wall to impact penetration hole area was found to be on average 6%, 26% and 53% greater than the projectile cross sectional area for the oblique angle impacts of 30°, 45°, and 60°, respectively. These findings helped to understand the relationship between the oblique impact event and the damage area on a spacecraft inner wall along with space debris cloud propagation and comparison with experimental results using LS-DYNA.

1. Introduction

With the launch of Sputnik in October 4, 1957, the race for space exploration began. Numerous satellites were launched without considering the space debris problem surrounding Earth. In the beginning, the main sources of space debris were, among other items, old launch vehicle upper stages and residual propellants. In 2007, the planned destruction of the Fengyun-1C weather satellite by China, followed by an accidental collision of communication satellites in 2009, exponentially increased the space debris count. All these incidents increased the threat to operational spacecraft, making the issue of space debris increasingly important. Along with the development of advance spacecraft shielding systems, the phenomenon of impact also has to be understood experimentally and numerically.

In the Low Earth Orbit (LEO) environment, factors which affect the spacecraft include high vacuum, atomic Oxygen (AO), Ultraviolet (UV) radiations, thermal cycling and space debris attacks. However, for the structural application of aluminum alloys, the main devastation effect is caused by space debris attacks, which damage the satellites partly or sometimes completely. The data from NASA shows that, up until now, around 4900 space missions have been conducted; out of these, only 6% of the spacecraft are currently operational, while the rest more or less lie within the category of space junk. This junk includes the remains of rocket bodies, inactive payloads, mission related bodies, anomalous debris

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bodies and breakup debris components. More than 21,000 orbital pieces of debris larger than 10 cm are known to exist, while there are approximately 500,000 particles having a size between 1 and 10 cm in diameter. The number of particles smaller than 1 cm exceeds 100 million [1,2]. Evidence from NASA's experimental study of space debris showed that only 10–20% of space debris impacts on spacecraft are normal to the surface while the rest are oblique in nature. These oblique impacts destroy the spacecraft partly or completely depending on the obliquity and size of the debris. The normal impact event is totally different from that of oblique impact in terms of debris clouds and their propagation during and immediately after the impact. Researchers explained that in the case of a normal impact event, ejecta clouds and in-line debris clouds are the main resulting types of cloud. While for the case of oblique impacts, the debris clouds are mainly classified as ricochet, in-line, and normal debris clouds [3].

In the case of an impact event on spacecraft shielding, the outermost components absorb most of the impact energy while the rest of the impact energy is absorbed by the inner part of the shielding system. The risk and failure criterion has to be defined independently for every surface because of the complex impact phenomenon [4]. In ballistic limit equations and their curves, in the region where projectile velocity was found to be less than 3 km/s, the projectile was more damaging when remaining intact even after impact [5].

At the impact event, the pressures generated in the projectile and bumper are functions projectile velocity, impact obliquity angle, projectile and shield thickness and material properties, along with a few others [4]. The standoff distance between the bumpers in spacecraft shielding configurations always plays a critical role towards space debris propagation, especially the blast loading in the rear wall is a function of shield standoff. This space debris cloud expands while moving across the standoff, resulting in the impactor momentum being distributed over a wide area of the rear wall. A key factor governing the performance of spaced shields is the state of the debris cloud projected from the bumper toward the rear wall.

Another factor which affects the dynamics of a projectile is if the inner wall is part of a fluid filled tank. In the case of an impact on a fluid filled tank, catastrophic damage occurred and increased with the increase of internal fluid pressure [6]. This is different from highly compressed gas which deformed the wall inside, while in the case of a fluid filled tank, the hole edges bulged out because pressure and drag forces played an important role in slowing down the debris cloud.

The research conducted in this paper aims to experiment and validate the shielding response of the inner wall when the speed of the projectile has already been decreased by different components of shields. Also, after impact on intermediate bumpers, fragments dispersed in different directions within the shielding system causing damage to the spacecraft inner wall which might lead to shielding failure and failure of spacecraft subcomponents.

With the recent advancement in computational techniques, it has become quite effective to utilize them for the better understanding of the space debris phenomenon on spacecraft. Different software is being used for the prediction and calculation of impact phenomenon. Because the impact phenomenon involves high mesh deformation in a very short duration of time regular FE software cannot handle mesh entangling easily but the smooth particle hydrodynamics (SPH) technique was found to be effective in this case. Initially, SPH was developed by Lucy, Gingold, and Monaghan [7,8] for astrophysical problems where large deformation was the norm. Afterwards, this technique received the attention of other researchers and was implemented to other engineering fields. Nowadays, the SPH technique is found to be effective for space debris simulations. Different software and hydrocodes used by different space agencies and commercial organizations include EXOS, EPIC, MAGI, PAM-SHOCK, and LS-DYNA [9]. However, the last one is commercially available and found to be fitting when the problem is to be solved commercially. In the case of LS-DYNA, the dedicated SPH module is found to be more effective for the simulation of the space debris impact event.

In this research, innermost Al6061-T6 walls of shielding system have been tested and validated experimentally and computationally for space debris impact, especially when the angle of attack is oblique in nature and most of the velocity has already been absorbed by earlier structural components of the shielding system. The velocity range of 1000 ± 200 m/s was used in the experimentations to effectively demonstrate the impact event on the structural inner wall of the shielding system. LS-DYNA analyses were conducted to assist the experiments and to extrapolate the results to higher velocities.

2. Methods and procedure

2.1. Experimental setup

The Al6061-T6 specimens were prepared with 120×120 mm^2 dimensions having average areal density of 0.250 g/cm^2. Afterwards, the specimens were impacted by Al2017-T4 projectiles which had been used previously as space debris [10–13]. For their attack, a two stage light gas gun (LGG) was used. The working fluids used were Helium and Argon, with working pressures of 6–12 bars and 100–130 bars, respectively. The projectile used was Al2017-T4 having 0.25 g in weight and 5.56 mm in diameter. The specimen was placed 880 mm from the launch of the projectile in different angle variations as shown in Fig. 1.

The energy absorption was calculated by measuring the velocity before and after the impact on the specimen. For initial experiments, chronographs were utilized for velocity measurement but afterwards magnetic and laser intervalometers were used. As the mass of the projectile is known, Eq. (1) was utilized for the energy calculation:

$$E_{absr} = \frac{1}{2} m (V_{initial}^2 - V_{residual}^2) - E_{air} \quad [\text{Joules}] \tag{1}$$

where E_{absr} is the energy absorbed in Joules by the specimen, while $V_{initial}$ and $V_{residual}$ are the velocities of the projectile before and after impact in m/s, respectively, and E_{air} is the energy absorbed by air in Joules. Initial impact