An investigation into cold weld adhesion for spacecraft repair after a space debris impact using space education based sub-orbital sounding rocket platform.

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Abstract

It has been observed that similar metallic materials, when in contact and undergoing relative displacements, can fuse or weld. In standard atmospheric conditions it is not common but in the space environment the inability of the surface interfaces to re-oxide after abrasive contact is hindered, atomic diffusion of the metal occurs, and this can lead to fusion. Oscillatory motion and Hertzian contact stress between the two surfaces plays a major role in the strength of the cold welded joint. It has been shown that the action of a low fretting load can almost double the adhesion force under cyclic loading even in terrestrial atmospheric conditions. In space, cold welding was first identified in the 1960's as an adverse reaction. It has been attributed to anomalies and failures of deployable mechanisms. Other research has alluded to the potential of this phenomena for use in spacecraft repair in space. Examples where this may hold promise is repair of a spacecraft hull breach after hypervelocity impacts due to micrometeoroids or orbital debris. This research proposes an investigation into cold welding for use in spacecraft hull repair. The research intends to qualify an experimental apparatus to TRL 4 using a sub-orbital sounding rocket platform. A joint research effort between the Aerospace, Mechanical and Electronic Department at I.T. Carlow, Ireland, the Department of Aviation at Malta College of Arts, Science, and Technology, Malta is underway. The project aims at developing a test apparatus to apply a number of custom patches to simulated hypervelocity spacecraft hull breaches and investigate the adhesion properties during re-entry for a range of mechanical application conditions. A number of chambers may be tested and monitored using pressure transducers. After Phase 1 (terrestrial development and validation using a vacuum chamber), there will be an application to education based space programmes such as the one offered by the European Space Agency (REXUS). The core of the activity will be the design and testing of the experimental payload, simulating hull breaches, deployment the repair patch and monitoring of its performance during re-entry (Phase 2). The recovery of the payload will allow further metallurgical analysis of the cold welded joint (Phase 3). A conceptual 3-D model of the payload has been developed and is presented here. The data acquired from the sub-orbital flight experiment will test the validity of the hypothesis for use of cold welding for spacecraft hull repair but will also detail the development and implementation of mock hypervelocity impacts to rocket skin for the purposes of simulating hull breaches in the space environment.

Keywords

Cold welding adhesion, Hypervelocity impacts, Space debris, Spacecraft repair, Sub-orbital flight

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Acronyms/Abbreviations

CPU Central Processing Unit

DRAMA Debris Risk Assessment and Mitigation Analysis

EM Engineering Model

ESA European Space Agency

EVA Extra Vehicular Activity

FM Flight Model

HGA High Gain Antenna

HVI Hypervelocity impact

ISS International Space Station

LEO Low Earth Orbit

LGG Light-Gas Gun

LVDT Linear Variable Differential Transformer

MASTER Meteoroid And Space debris Terrestrial Environment Reference

MCAST Malta College of Arts, Science and Technology

MRS Mini Research Module

MMOD Micrometeoroids and Orbital Debris

NASA National Aeronautics and Space Administration

ODEM Orbital Debris Engineering Models

RSC Rocket and Space Corporation

SSEA Symposium on Space Educational Activities

1. Introduction

Orbital artificial habitat satellites such as the International Space Station (ISS) have experienced loss of atmosphere due to perforation of the spacecraft hull. This can occur from engineering failures, manufacturing defects or Hypervelocity Impacts (HVIs) from space debris and micrometeoroids [1]. The frequency of the space debris impacts can be predicted using Orbital Debris Engineering Models (ODEM currently v 3.1). The Metroid impact flux can be estimated using NASAs ODPO SSP-30425 specification or European Space Agency's (ESAs) Meteoroid And Space debris Terrestrial Environment Reference (MASTER-8) and DRAMA (Debris Risk Assessment and Mitigation Analysis) [2]. One estimation based on early models predict that in a 30-year period more than 35,000 secondary debris particle impacts will occur to the ISS and will be at energy levels high enough to perforate the solar arrays [1].

By the end of 2020, the ISS has carried out 26 collision avoidance manoeuvres to escape impact with space debris [3]. If a collision is unavoidable, the ISS is equipped with a bumper structure known as a Whipple/Advanced Stuffed Whipple plate and this is designed to absorb the impact energy. However, secondary ejecta and collision with unprotected areas can, and do, lead to perforation of the ISS hull. If there is a hull perforation, the ISS benefits from its Low Earth Orbit (LEO) and ease of access to resupply any lost oxygen. Longer manned missions, also susceptible to hull perforations, do not have this option and it is a necessary precaution to consider how hulls would be repaired in space. There is a paucity of detailed information in the literature on how these leaks/perforations are repaired and no standards published but recently a description of a successful repair of 2.0 mm diameter hole in the Soyuz crew vehicle which was docked to the Mini Research Module (MRM-1) or Rassvet module was released [4]. It was stated that the perforation was repaired by using a medical gauze soaked in epoxy [5]. The adhesive is known as Germetall-1 and packaged as the GERMETIC leak repair kit. This repair kit includes Germetall-1 and Anaterm-1u sealant [6]. The most recent loss in atmosphere was identified in the Zvezda Service Module in 2020. A 22 mm long crack was detected in the module. It was reported that the leak was causing a pressure drop of 1 mm of mercury every 8 hours [7]. The crack was repaired using an undisclosed sealant. It is obvious that there is a conscious effort towards finding a viable solution. It is proposed to investigate the intentional cold welding of metals for spacecraft hull repair during a sub-orbital flight and monitor the performance of such repair during re-entry. This will also involve characterising and replicating perforations from HVIs. The aim of this project is to use an education-based sounding rocket platform and student team to investigate this phenomenon. The goal is to form a pan-European collaboration between third-level institutes and award an MSc in Space Systems Engineering. Project Team Lead, Materials Engineer, Mechanical Engineer, Aerospace Engineer and Electronics/ Communications Engineer are some of the student positions required. 5-10 team members are required. With that said, there are both educational and technical objectives for the proposed programme. This includes the identification of educational space-based opportunities through programme outreach. Recruitment of a student team and application to an education-based sounding rocket programme. As part of the technical objectives, an Engineering Model (EM) (Phase 1) along with HVIs perforations will be developed for terrestrial experimentation and validation. It is envisaged that the experiments will examine several material candidates, surface finishes and a range of impact forces and interactions (fretting and galling). The Flight Model (FM) (Phase 2) will re-design this experimental set up within the confines of a sounding rocket module. It will require the high vacuum conditions, re-entry pressurisation and acceleration forces/temperatures to validate the experiments. The micro-gravity environment in this phase may also play a role in the evolution of the joint adhesion. The experiment will introduce mock hull perforations and the experiment will operate autonomously during the flight profile. Further metallurgical analysis of the retrieved samples will form Phase 3 of this research.

2. HVIs and Cold Weld Adhesion

2.1. HVI effects

In hypervelocity impacts, the projectile velocity exceeds the speed of sound within the target material. The resulting shock wave that propagates across the material is reflected by the surfaces of the target, and reverses its direction of travel. The superimposition of progressing and reflected waves can lead to local stress levels that exceed the material's strength, thus causing cracks and/or the separation of spalls at significant velocities. With decreasing target thickness, the effects range from cratering, via internal cracks, to spall detachment, and finally to clear hole perforations. It has been shown that MMOD impacts on spacecraft, according to the debris' dimensions can generate [8]:

- Small surface pits due to micrometre-size impactors;
- Clear hole penetrations for millimetre-size objects;
- Mission-critical damage for projectiles larger than 1 cm

Any impact of a 10 cm catalogue object on a spacecraft or orbital stage will most likely imply a catastrophic disintegration of the target. This destructive energy is a consequence of high impact velocities. The effects of hypervelocity impacts are a function of projectile and target material, impact velocity, incident angle and the mass and shape of the projectile. At low velocities, plastic deformation normally prevails. With increasing velocities, the impactor will leave a crater on the target. Beyond 4 km/s, depending on the materials, an impact will lead to a complete break-up and melting of the projectile, and an ejection of crater material to a depth of typically two to five times the diameter of the projectile. Usually when the impact risk from meteoroids and orbital debris is assessed the main concern is usually structural damage. In this context, the proposed research targets the preliminary assessment of a repair to a damaged spacecraft hull shields. For this purpose, a range of mock hull perforation configurations will be evaluated and tested. An example perforation hole created by an Aluminium sphere projectile of 2.3 mm diameter at a speed of 4.8 km/s is shown in Figure 1 [9].

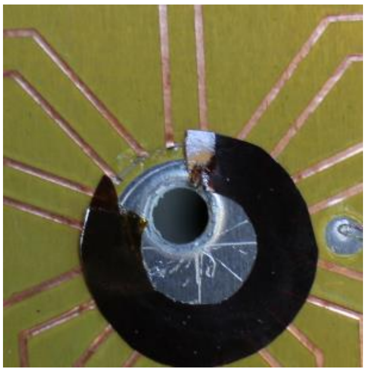


Figure 1. HVI impact example on an Aluminium plate.

2.2. Cold weld adhesion

Cold welding is the fusion of two metals at low temperature. Theoretically, adhesion of two metal samples of the same material will occur in contact providing the surfaces were smooth (microscopic scale), free from contaminants and the crystal lattice of the opposing surfaces have the same orientation [10]. There are two schools of thought on the mechanisms behind this phenomena and they are based on the film theory and energy barrier theory (mismatch of crystal lattice and recrystallization theory). In space, the absence of atmosphere provides necessary conditions favourable for cold weld adhesion. Furthermore, evaporation of lubricants in high vacuum and intimate contact of metal, causing disruption of the oxide film will further promote this fusion. In 1966 NASA published a state-of-the-art survey in the field of metal-to-metal adhesion or cold welding in space. This investigation examined both positive and negative effects of cold welding in space citing that it may be used someday to fabricate or repair structures in space [10].

This was followed in 1969, when NASA initiated a cold welding program to determine the proper test environment for qualifying spacecraft mechanisms. This research investigated the effects of cycles, and lubricated versus non-lubricated contact. In 1989, it was proffered that cold welding was shown to be a credible cause of the failure of the Galileo High Gain Antenna (HGA) to deploy [11]. The bond strength of cold welding in high vacuum has been shown to be significant, at least an adhesion strength equal to the load applied [12]. Adhesion forces in the vicinity of 10s of Newtons are reported and, in certain conditions, as high as 100 N under high vacuum launch environment using silver mating pairs [13]. Other soft metals, such as Indium, are excellent candidates for deliberate fusion as they have been shown to readily fuse in atmospheric conditions [14]. In general, along with metal surface conditions, the adhesion force is a function of the relative motion and magnitude of the applied contact force. In a study carried out by ESA in 2009 on the effects of fretting and metal adhesion, the maximum adhesion force (9.5 N) was found to be 2.5 times the applied load (4 N) [15].

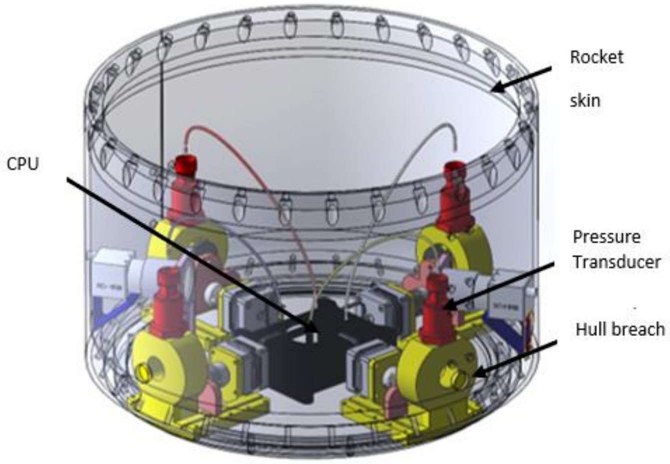
3. Operational framework

In November 2021, Institute of Technology Carlow, Ireland, initiated a collaboration with the Malta College of Arts, Science, and Technology (MCAST), which is currently developing the first hypervelocity impact facility of Malta. This joint research effort aims at attracting and involving post and undergraduate graduate students to a space based project while boosting the competences of these research centres. The two Institutions also initiated a collaboration with Luleå University of Technology, in Sweden. The focus is on studying the payload integration of the previously described experiment on a rocket for a sub-orbital flight. The space research centre of this University has world-class facilities and partners with Esrange, a rocket range and research centre located near Kiruna in northern Sweden. Currently a Memorandum of Understanding is being finalised.

4. Results

4.1. *Preliminary design*

A conceptual design of an experimental layout has begun. This includes four Aluminum alloy chambers (7075-T651), hermitically sealed and mounted to the rocket skin at the location of a simulated hull breach. Space qualified bonding agent, such as Kryptos may be used to form the seal. Each unit will investigate a set of experimental parameters established through Phase 1 testing. This may include, material type, surface finish and surface contact conditions. At apogee the experiment will commence. Signals from either ground station (SOD/SOE) or timers will initiate the experiment after Yo-Yo stabilisation. A breach in the rocket skin is introduced to each chamber and the material samples will be actuated by stepper motors or piezoelectric actuators. The performance of the sealed chamber will be monitored using welded stainless steel temperature compensated differential pressure transducers located in each chamber and will be monitored during re-entry. Some chambers may be pressurized prior to re-entry to examine the joint integrity in space (against a vacuum alone). A PC104 embedded CPU will be used to acquire the data. It will be stored locally, and an onboard Service Module (SM) and transmitter will be used to transit live data to ground station (sensors and housekeeping). Load cells or Linear Variable Differential Transformer (LVDT) may be used to verify the position of the sealing patch and the applied and reaction forces. Video data may also be acquired and stored locally as a means of anomaly detection. A preliminary outline and design of the experiment has been created. A potential configuration for multiple test chambers is offered but not fixed. It is intended for use as a guide or template for students to develop further into a proposal for a space-based educational research program. The preliminary design of the test rig is shown in Figure 2. This experiment is designed within 356 mm diameter and 237.5 mm in height, a standard REXUS sounding rocket module. Expected mass (excluding rocket skin and baseplate) is less than 4.5 kg.



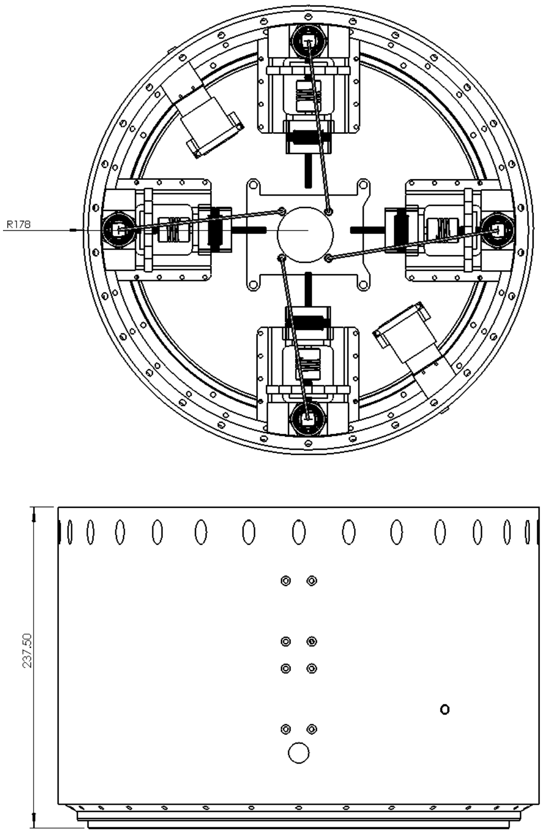


Figure 2. Conceptual design of sounding rocket experiment (mm).

This paper also details the basis of the technical objectives required for the student experiment. The general theme of the research is presented but the intention is that the student team will develop this project in more detail.

5. Conclusions

This publication forms the first collaborative effort towards achieving the academic objectives. It is designed as an impetus for students to develop this programme. There are a number of funded student positions available. Expressions of interest can be emailed to either of the authors before November 1st 2022. This effort was conceived as a means to combine expertise and resources from multiple third-level institutes with limited space flight heritage, to bolster their space research capabilities and to promote European collaborations.

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