

MITIGATION OF EMU CUT GLOVE HAZARD FROM MICROMETEOROID AND ORBITAL DEBRIS IMPACTS ON ISS HANDRAILS

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ABSTRACT

Recent cut damages sustained on crewmember gloves during extravehicular activity (ISS) onboard the International Space Station (ISS) have been caused by contact with sharp edges or a pinch point according to analysis of the damages. One potential source are protruding sharp edged crater lips from micrometeoroid and orbital debris (MMOD) impacts on metallic handrails along EVA translation paths. A number of hypervelocity impact tests were performed on ISS handrails, and found that mm-sized projectiles were capable of inducing crater lip heights two orders of magnitude above the minimum value for glove abrasion concerns. Two techniques were evaluated for mitigating the cut glove hazard of MMOD impacts on ISS handrails: flexible overwraps which act to limit contact between crewmember gloves and impact sites, and; alternate materials which form less hazardous impact crater profiles. In parallel with redesign efforts to increase the cut resilience of EMU gloves, the modifications to ISS handrails evaluated in this study provide the means to significantly reduce cut glove risk from MMOD impact craters.

1. INTRODUCTION

During post-flight processing of STS-116, damage to crewmember Robert Curbeam's Phase VI Glove Thermal Micrometeoroid Garment was discovered (shown in Figure 1). This damage consisted of: loss of RTV-157 palm pads on the thumb area on the right glove and a 0.75 inch cut in the Vectran adjacent to the seam and thumb pad (single event cut), constituting the worst glove damage ever recorded in "the history of going EVA for the U.S. program" [1]. The underlying bladder and restraint were found not be damaged. Evaluation of glove damage showed that the outer Vectran fibers were sliced as a result of contact with a sharp edge or pinch point rather than general wear or abrasion (commonly observed on the RTV pads). Damage to gloves was also noted on STS-118 [2] and STS-120 [3]. A potential source of EMU glove cut hazard is micrometeoroid and orbital debris (MMOD) impact craters on ISS handrails. Returned flight surfaces (see e.g. nitrogen tank assembly handrail in Figure 2) have demonstrated the susceptibility of these structures to regular MMOD impacts.



Figure 1. Damage to crewmember Curbeam's Phase IV glove following EVA 3 of STS-116

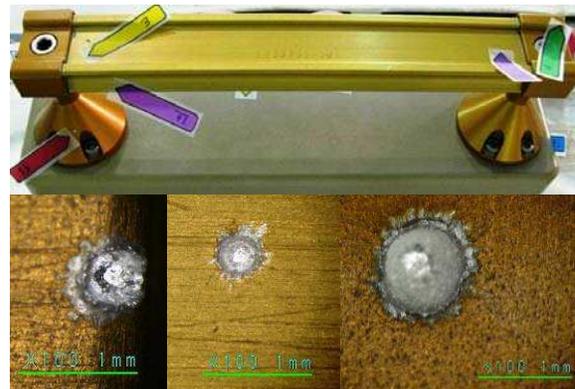


Figure 2. MMOD impacts on the returned nitrogen tank assembly handrail. Top: location of impacts; Below: impact craters 4, 5, 15 (left-to-right)

Redesign efforts are currently underway to enhance the resiliency of EMU gloves to cut hazards. In the meantime, temporary reinforcements (TurtleSkin® patches) have been added to high wear areas (lower part of thumb and upper part of index finger). Parallel efforts have been made to characterize MMOD impact damage profiles on representative and actual ISS flight hardware and mitigate the cut hazard posed by these profiles on crewmember EMU gloves. In this paper, the results of these characterization and mitigation impact test studies are presented and suggestions for modifications to ground equipment yet to be flown are made.

2. HYPERVELOCITY IMPACT TESTING OF ISS HANDRAILS

Two handrail configurations were selected for characterization of MMOD impact damage features on ISS handrails: a rectangular handrail with channelled edges (NASA part no. SDD33107728-073), and a tubular handrail (part number SDD39122635-001), both of which are shown in Figure 3.



Figure 3: ISS handrail target configuration. Left: rectangular handrail; Right: tube handrail

The rectangular handrail configuration has a nominal thickness of 1.27 mm (0.05") which is reinforced to 4.445 mm (0.175") at the corners. The tubular handrail has a nominal thickness of 1.57 mm (0.62"). Dimensions of the handrails are provided in Figure 4. Both handrails are manufactured from Al 6061-T6.

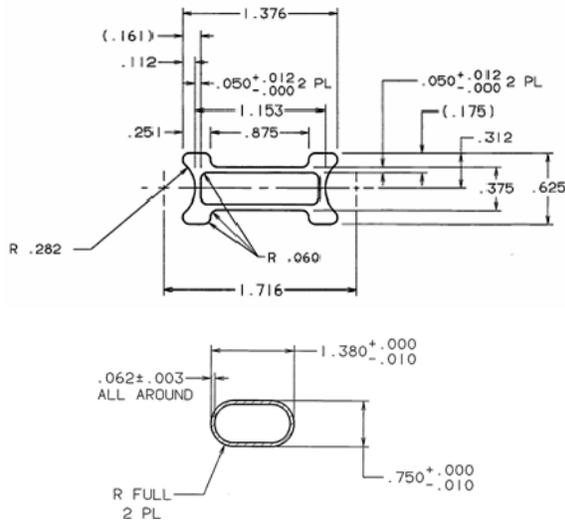


Figure 4: Cross-sectional diagram of rectangular (upper) and tubular (lower) ISS handrails subject to testing (dimensions in inches)

A total of 46 impact tests were performed on the handrail targets (all at ~7 km/s): 34 on the rectangular configuration and 12 on the tubular configuration. The impact tests considered a variety of impact locations and angles in order to provide a wide characterization base for the cut hazard assessment. Example of impact damages on the rectangular and tubular handrail targets are provided in Figure 5 and Figure 6 respectively.

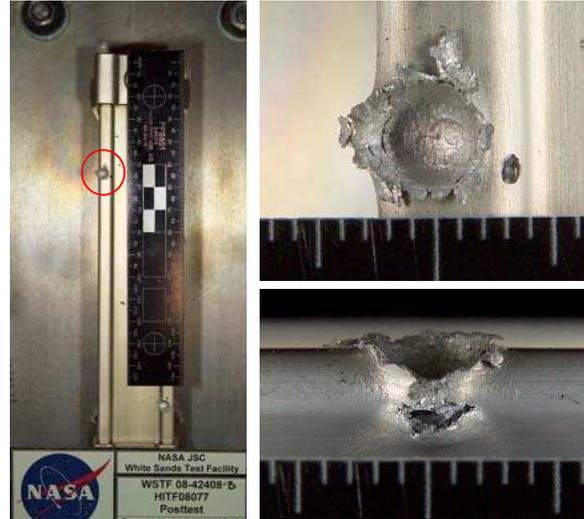


Figure 5: Impact damage on a rectangular ISS handrail induced by impact of a 0.10 cm diameter Al2017-T4 sphere at 6.94 km/s with oblique (45°) incidence

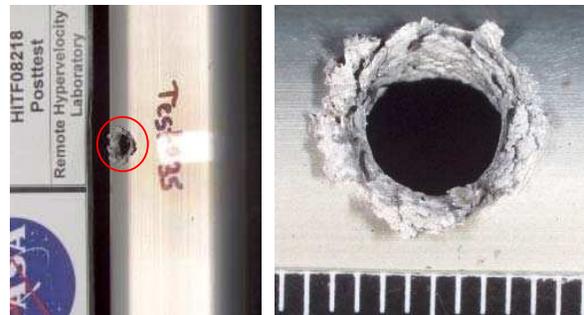


Figure 6: Impact damage on a tubular ISS handrail induced by impact of a 0.15 cm diameter Al2017-T4 sphere at 6.95 km/s with normal (0°) incidence

For the rectangular handrail configuration, typical entry hole diameters were 3-4 times that of the projectile

diameter. The damage profiles exhibited protruding crater lips in all cases, with a maximum height of 2.7 mm for impact of a 1.5 mm diameter Al2017-T4 sphere at 6.86 km/s with oblique (45°) incidence (HITF08086). For this test, the projectile impacted upon the thickened corner section of the rectangular handrail. Impacts upon thicker sections of the handrail commonly resulted in damage profiles with more hazardous (i.e. higher) crater lip formations. Generally, it was observed that an increase in projectile diameter leads to an increase in the height of the protruding crater lip. For impacts causing damage to the rear side of the impacted structure (i.e. perforation or spallation), damage features were also characterized. A maximum lip height of 4.6 mm was measured following impact of a 1.8 mm projectile at 7.06 km/s at oblique (45°) incidence on the center of the handrail upper surface.

For the tubular handrail configuration, entry hole diameters were also commonly 3-4 times the diameter of the projectile. However, impact crater lips did not protrude above the handrail surface as much as on the rectangular configuration. The more hazardous crater profiles on the rectangular handrail were found upon the thicker sections. Thus, damage profiles on the thin tubular handrails were not expected to protrude as significantly as on the reinforced sections of their rectangular counterparts. A maximum raised crater lip of 1.9 mm was measured for the tubular handrail, induced by impact of a 1.5 mm diameter Al2017-T4 sphere at 6.95 km/s with normal incidence. None of the 12 impact tests on the tubular handrail resulted in ejection of material from the rear side of the handrail target.

Preliminary evaluation of glove damage has focused on crater edge heights above 37 microns due to abrasion concerns. This value represents 1/4th the diameter of the Vectran yarn used in the Thermal Micrometeoroid Garment (TMG) of the Phase IV EMU glove. The measured crater lip heights of all 46 handrail impact tests were two orders of magnitude larger than the cutoff for abrasion concerns. Thus, it is clearly demonstrated that MMOD impact upon ISS handrails are a plausible source of cut hazard for EVA crewmember gloves.

3. MITIGATING CUT HAZARD OF MMOD IMPACT CRATERS

Two alternate means of reducing the cut hazard of MMOD impact crater sites have been evaluated:

- Flexible overwraps that can be added to existing handrails (such as ground equipment that has yet to fly) and would effectively act as padding, limiting contact between crater lips and crewmember gloves; and

- Alternative materials for ISS handrails that limit the formation of hazardous crater profiles.

3.1. Handrail Overwraps

Four overwrap configurations were considered in the test program:

- Silicon rubber coated felt-reusable surface insulation (FRSI);
- Non-reticulated open cell polyether polyurethane foam (12.54 mm thick) with aluminized beta-cloth cover (OCF+BC);
- Double layer reticulated open cell polyether polyurethane foam (6.35 mm thick) with aluminized beta-cloth cover and intermediate layer (DROCF+BC); and
- 16 layers of aluminized beta-cloth with Dacron netting spacers (Beta-cloth).

As the flexible overwrap is intended to limit contact between EMU gloves and MMOD impact sites their performance was assessed in terms of their residual thickness when compressed by a 30 kg steel block. Although this load is significantly less than handrail design requirements for crewmember induced loads (220 lbs over a 3 inch length [4]), the variance in measured residual thickness is expected to be negligible. An overview of thickness (uncompressed and compressed) and areal weight of the overwrap configurations is provided in Table 1.

Type	Uncomp. thickness (mm)	Comp. thickness (mm)	Areal weight (g/cm ²)
FRSI	3.89	2.15	0.182
OCF+BC	12.72	1.95	0.131
DROCF+BC	12.74	1.98	0.100
Beta-cloth	3.175	2.70	0.463

Table 1: Handrail overwrap configuration properties

The handrail is simulated by a 4.826 mm (0.19”) thick Al6061-T6 plate, to which the overwraps are clamped during testing. This target is representative of the reinforced corner sections of the rectangular handrail (see Figure 4), upon which the most hazardous crater profiles were generated during testing. Two impact tests were performed on the baseline target and each of the overwrap configurations. A summary of test conditions and damage measurements is provided in Table 2.

3.1.1. Test Results and Analysis

Normal impact of a 1.0 mm diameter Al2017-T4 sphere at ~6.8 km/s on the baseline Al6061-T6 target induced a 4.2 mm diameter crater with a maximum depth of 2.2 mm and a lip that protruded a maximum of 1.0 mm above the target surface. At nominally identical test conditions, all four overwrap configurations were able

Target	Projectile diameter (mm)	Impact velocity (km/s)	Impact angle (deg)	Crater dimensions (mm)	Crater depth (mm)	Lip height (mm)
Al6061-T6	1.0	6.83	0	4.2×4.2	2.2	1.0
Al6061-T6	1.5	6.87	45	6.9×6.4	2.9	0.8
FRSI	1.0	6.55	0	3.4×3.4	1.2	0.3
FRSI	1.5	6.95	45	4.7×6.5	1.2	0.7
OCF+BC	1.0	6.98	0	1.1×1.3	0.9	0.1
OCF+BC	1.5	6.85	45	3.1×3.1	1.5	0.3
DROCF+BC	1.0	6.99	0	1.0×1.0	0.1	0.1
DROCF+BC	1.5	7.03	45	2.3×2.5	1.4	0.8
Beta-cloth	1.0	6.86	0	<0.1	0.0	<0.1
Beta-cloth	1.5	6.94	45	<0.1	0.0	<0.1
MMC	1.0	6.87	0	4.3×3.0	n/a	1.0
CFRP	1.0	6.91	0	2.1×2.1	2.7	0.0
Fiberglass	1.0	6.86	0	2.6×2.6	0.6	0.8
FML	1.0	6.99	0	8.3×9.7	0.3	3.5

Table 2: ISS handrail baseline, overwrap, and alternate materials test results and damage measurements

to reduce the diameter, depth and protruding lip height of the baseline target crater. A comparison between the impact generated crater in the unshielded handrail and the handrails covered by flexible overwraps is given in Figure 7. The impact crater in the unshielded handrail target is clearly defined, with a well formed lip protruding above the plate surface. Of the overwrap configurations, only the FRSI target shows a clearly formed crater with a discernable lip. The OCF+BC target shows multiple small craters with minimally-protruding lips, while the DROCF+BC and Beta-cloth target damages are limited to discoloration and shallow denting.

For the oblique impact tests, a crater was formed in the baseline Al6061-T6 target with a diameter of 6.9 mm (maximum), a depth of 2.9 mm, and a maximum raised lip height of 0.8 mm. Similar to the normal impact tests, all four overwrap configurations were effective at reducing the height of the crater lip. In Figure 8 the FRSI target shows a cleanly formed crater with a protruding lip (smaller dimensions than the unshielded target). The OCF+BC target shows multiple overlapping craters, suggesting the projectile was fragmented upon impact with the beta-cloth cover. Although the craters are cleanly formed, there is minimal protrusion of material above the target surface. A similar damage profile is observed on the DROCF+BC target, which shows a single crater cleanly formed with reduced depth, diameter, and raised lip height than the unshielded target. The target plate shielded by the Beta-cloth overwrap shows discoloration and a minimal amount of mechanical damage.

3.2. Alternate Handrail Materials

During hypervelocity impact an evacuation flow develops behind the shock wave during projectile penetration (i.e. “splash-back”). For ductile materials,

this evacuation flow acts to form an uprange crater lip once the material is sufficiently cooled. For brittle materials, limited plastic flow is expected to minimize the formation of protruding crater lips.

Four alternate materials were selected for the test program due to their low ductility and equivalent (or superior) tensile modulus and strength properties (compared to the baseline aluminium alloy):

- Continuous Nextel 610 fiber reinforced pure aluminium (fiber content by volume, $V_f = 40\%$) metal matrix composite (MMC);
- Quasi-isotropic IM7/954-2A carbon fiber reinforced plastic (CFRP) laminate with plain weave fabric cover ($V_f = 60\%$);
- Woven glass fabric/halogen free epoxy type NP500CR fiberglass (Fiberglass); and
- Fiber metal laminate (FML) with alternating layers of Al2024-T3 and S-2/FM94 glass/epoxy composite (trade name GLARE®).

An overview of the alternate material target configurations is given in Table 3 (additional details can be found in [5]).

Material	Thickness (mm)	Density (g/cm^3)	Elastic mod (GPa)	Tensile strength (MPa)
Al6061-T6	4.826	2.70	65.9	310
MMC	3.3	3.30 ⁺	207 ⁺	1450 ⁺
CFRP	7.03	1.564 [*]	167 [*]	3105 [*]
Fiberglass	4.826	1.80	27.5	310
FML	3.74	2.17	50	300

^{*} Calculated value; ⁺ Typical property

Table 3: Alternate handrail material target configurations and key mechanical properties

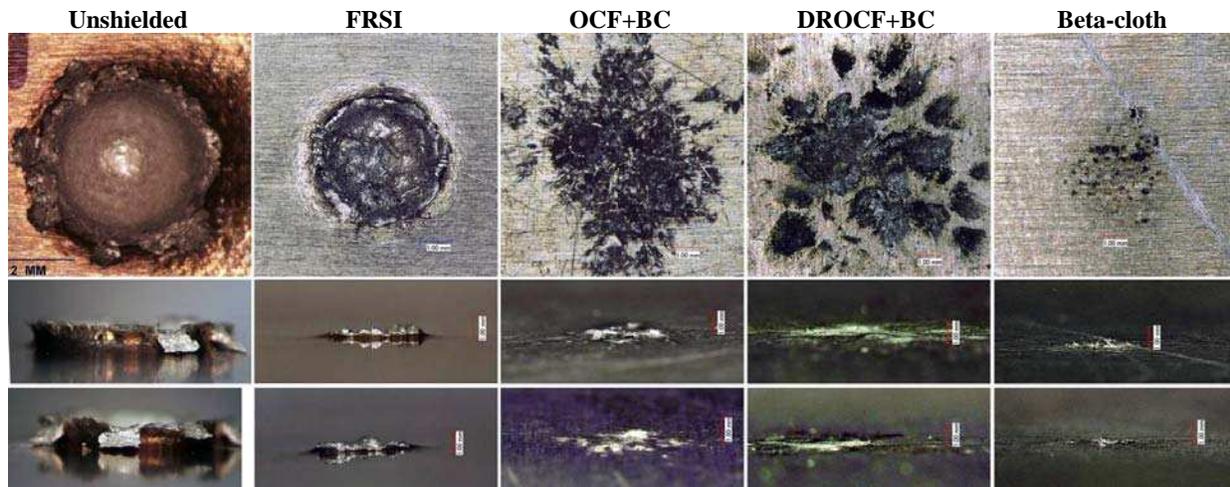


Figure 7: Comparison of impact crater profile in an unshielded ISS handrail-representative Al6061-T6 plate and overwrap-shielded plates impacted at normal incidence by a 1.0 mm diameter Al2017-T4 sphere at 6.77 ± 0.22 km/s

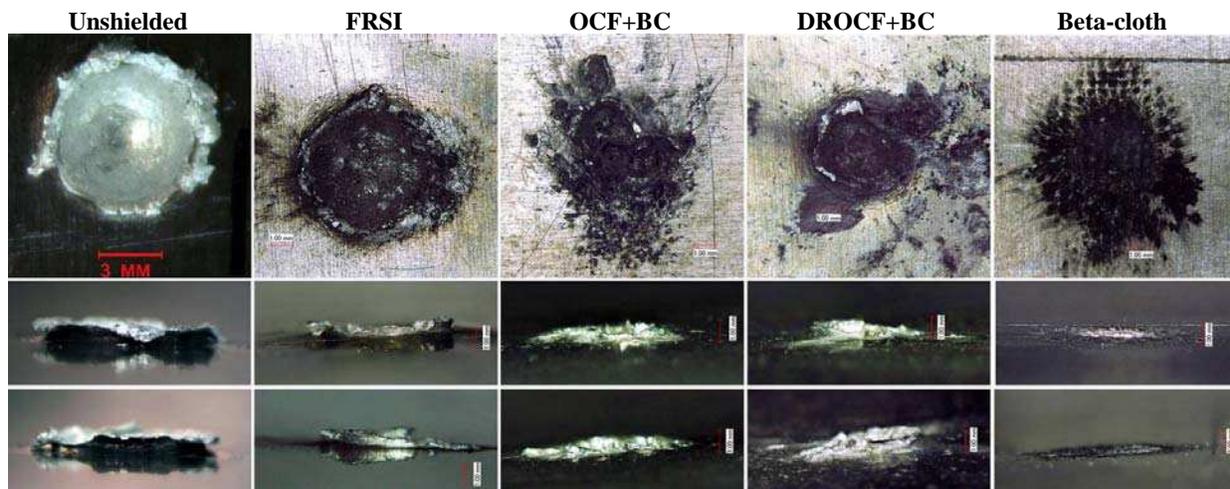


Figure 8: Comparison of impact crater profile in an unshielded ISS handrail-representative Al6061-T6 plate and overwrap-shielded plates impacted at 45° by a 1.5 mm diameter Al2017-T4 sphere at 6.94 ± 0.09 km/s

One impact tests was performed on each of the four alternate handrail material targets. A summary of test impact conditions and target damage measurements is given in Table 2. Of the four alternate materials tested, two were found to reduce the height of protruding crater lips (compared to the baseline Al6061-T6 target) for the impact conditions considered, as shown in Figure 9. There was no measurable crater lip on the CFRP target, however there was a large amount of surface spallation about the impact site, including groups of rigid unidirectional fibers that are considered to pose a puncture risk. The outer fabric layer on the CFRP laminate is used to limit the amount of surface spallation; however it is shown that multiple layers may be required to prevent spallation of puncture-hazardous material. The other material to reduce the height of the crater lip was the NP500CR fibreglass. For this

material, the area about the impact site contained fractured and delaminated glass fibers. Although protrusions extending above the target surface, these protrusions were not rigid, nor did they extend beyond the local impact site (see Figure 9). Unlike the CFRP, the epoxy has been completely removed from the protruding glass fibers and, as such, they are considered to pose minimal puncture risk. The GLARE fiber metal laminate had the highest crater lip, ~ 3.3 times that of the baseline aluminium alloy. In Figure 9 it can be observed that the outer aluminium layer of the FML peeled back from the composite layer, resulting in a large crater diameter with sharp petalled edges. Having a number of glass/epoxy composite layers on the outer surface of the laminate (instead of an aluminium alloy layer) may reduce the protrusion height of the crater lip. The Nextel 610/pure aluminium metal matrix composite provided a similar

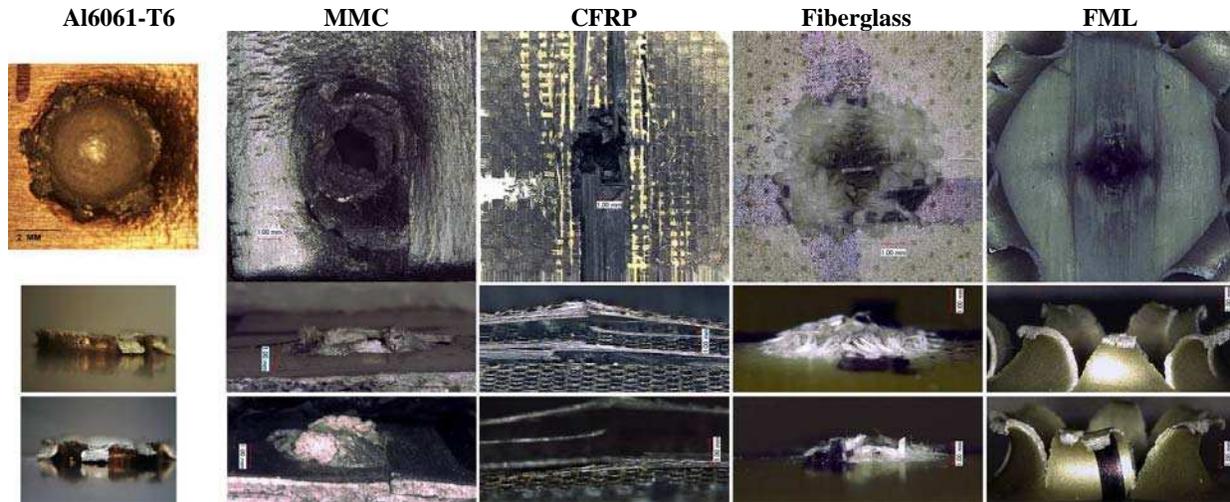


Figure 9: Comparison of impact crater profile in a simulated ISS handrail and alternate handrail materials impacted by a 1.0 mm diameter Al2017-T4 sphere at 6.91 ± 0.08 km/s with normal incidence (0°)

lip height to that of the baseline aluminium alloy. The outer layer of the MMC laminate is seen to have fractured about the impact site, resulting in minimal protrusion above the target surface. However, the second layer did not fracture in a similar manner, resulting in a 1.0 mm measured lip height. The MMC target was penetrated by the projectile, forming an exit hole that was raised 2.45 mm above the rear target rear side. Although the thickness of the MMC laminate was less than the baseline material, penetrating impacts on Al6061-T6 with larger projectiles resulted in rear side damage features less hazardous than that of the MMC. As such, the performance of the MMC is considered worse than the baseline aluminium alloy.

4. Discussion and Conclusions

During extravehicular activity (EVA) on recent ISS missions, a number of incidences of crewmember glove damage have been reported. A potential source of these damages comes from contact between EMU gloves and sharp-lipped MMOD impact craters on metallic handrails. A series of hypervelocity impact tests have been performed on ISS handrails to investigate and characterize the formation of impact craters. Raised lips generated by the impact of mm-sized particles were found to exceed minimum heights required for glove abrasion by two orders of magnitude. The most hazardous crater formations were found to occur in the thickest sections of the handrail structures. Temporary efforts to increase the cut resilience of EMU gloves are currently in place, and more thorough design modifications are being investigated. Two potential modifications to ISS handrails have been evaluated in this paper to provide a complementary means of reducing EMU cut glove occurrences.

Four flexible overwrap configurations suitable for retrofitting ground equipment were evaluated in the first phase of the study: felt-reusable surface insulation (FRSI), open cell polyether polyurethane foam with a beta cloth cover, double-layer open cell polyether polyurethane foam with beta cloth cover and intermediate layer, and a beta cloth blanket containing 16 layers of beta cloth with intermediate Dacron spacers. These materials were selected based on their pre-existing certification and use in flight (with the exception of the polyurethane foams). The purpose of the overwrap is not to protect handrails from MMOD impact, rather to limit contact between impact craters and EVA crew gloves. All overwrap configurations were found to successfully meet this requirement (under compression of a 30 kg steel block). In addition, the magnitude of damage to the underlying handrail target was found to be reduced by all four overwrap configurations.

In the second phase of the study four material alternatives to the current aluminium alloy were evaluated: Nextel 610/pure aluminium metal matrix composite (MMC), quasi-isotropic carbon fiber reinforced plastic (CFRP), woven fiberglass/epoxy composite, and a fiber metal laminate (FML) with alternating layers of Al6061-T6 and S-2/glass epoxy (trade name GLARE®). The materials were selected for their comparable (or superior) strength and stiffness properties, and for their low ductility. Of the four materials tested, only the fiberglass target was found to form a less hazardous damage profile than the baseline Al6061-T6 target. Although the CFRP laminate did not form a protruding crater lip, large surface fractures of rigid fiber groups were considered to represent a puncture risk. The fiberglass target impact crater was smaller in diameter and lip height than the baseline

material, and fragmented glass fibers about the impact site were soft and highly flexible. Although the GLARE FML performed significantly worse than the baseline aluminium alloy target, it is considered that modifications to the stacking sequence could provide improvements.

In tandem with efforts to increase the puncture and cut resilience of Phase IV EMU gloves, modification of metallic ISS handrails through the addition of flexible overwraps or the use of alternate materials provide the means to significantly reduce the cut glove hazard of MMOD impact sites.

5. REFERENCES

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