Engineering Enhanced Cut and Puncture Resistance into the Thermal Micrometeoroid Garment (TMG) using Shear Thickening Fluid (STF) – Armor™ Absorber Layers

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Abstract

The low-earth orbit environment contains small micrometeoroid and orbital debris (MMOD) particles traveling at characteristic velocities of several kilometers per second. In addition to being a direct threat to astronauts and spacecraft, upon impact with the exterior surface of a space vehicle, these highly energetic MMOD particles can create cut and puncture hazards for astronauts performing extra-vehicular activities (EVA). In this work, we demonstrate that replacing the standard neoprene-coated nylon absorber layers with woven aramid textiles intercalated with colloidal shear thickening fluids, i.e., STF-Armor™, can provide a meaningful enhancement to the cut and puncture resistance of the thermal micrometeoroid garment (TMG). Quasi-static puncture testing is performed using hypodermic needles of varying gauge to simulate the cutting and puncture hazards at deformation rates characteristic of human motion. At equal areal densities, we find that a TMG lay-up containing STF-Armor™ greatly improves puncture protection with a reduction in weight and comparable flexibility.

KEYWORDS: Thermal micrometeoroid garment, extra-vehicular activity, micrometeoroids and orbital debris, shear thickening fluid, hypodermic needles
Introduction

The primary concern for spacecraft shielding engineers is mitigating the risks posed by natural micrometeoroids originating from comets and asteroids throughout the solar system [1, 2]. Over the decades, the increasing number of vehicles and satellites launched into low-earth orbit (LEO) has broadened the focus of design engineers to manmade orbital debris threats [3, 4]. These orbital debris particles, largely aluminum-based compounds broken off from LEO vehicles, typically travel at velocities of 1-15 km/s in LEO [2]. While generally on the order of a millimeter or less in size, these micrometeoroid and orbital debris particles (MMOD), are sufficiently energetic to be destructive upon impact. Of particular concern to manned missions is the threat posed by MMOD to astronauts as they perform extra-vehicular activities (EVA). To combat this threat, the current EVA suit consists of an assemblage of textile layers, known as the thermal micrometeoroid garment (TMG), which protects the exterior of the pressurized air bladder as shown in Figure 1. The design of the TMG primarily seeks to prevent MMOD particles from reaching and puncturing the air bladder upon a direct impact [5].

Figure 1. Image of the thermal micrometeoroid garment (TMG) which forms the outermost portion of the extra-vehicular activity (EVA) suit.
The probability of an MMOD impact is governed by a number of factors such as flight altitude, orientation direction, and exposure time [2]. While a direct MMOD impact into the TMG has the potential to be problematic, such events have a relatively low probability of occurring given that spacewalks generally last a few hours. An equally dangerous threat to astronauts performing an EVA results from a hypervelocity impact of an MMOD particle into the exterior of a space vehicle. MMOD impacts into metallic and ceramic surfaces have been well-studied [6] and a common feature is the formation of a raised crater lip characterized by sharp edges as shown in Figure 2. Craters on the handrails of the International Space Station (ISS) are believed to have been the cause of tears in gloves during several recent space walks [7, 8].

![Crater formation on an ISS handrail resulting from oblique (45 degree) impact of a 1.0 mm diameter Al2017-T4 sphere at 6.94 km/s from [7].](image)

While the TMG is designed to withstand direct MMOD impacts, the record of suit tears during spacewalks from sharp surfaces suggests the need to enhance the cut and puncture protection. Both cutting and puncture hazards are associated with sharp edges, but cutting threats have a continuous cutting surface that can facilitate penetration [9]. It should be recognized that these particular threats occur on energy and time scales significantly different
than those associated with the hypervelocity impact of an MMOD particle. Significant work has already been undertaken to understand the cut [9-13] and puncture [9, 14-18] resistance of fabrics and other thin materials under such quasi-static loading conditions. One approach to date to counter the threat of these sharp raised surfaces has been to increase the amount of protective material in regions of the suit that are particularly vulnerable to puncture threats [8, 19]. While this approach improves the puncture resistance, it ultimately adds mass and reduces flexibility of an already bulky TMG.

Intercalating protective textiles with colloidal shear thickening fluids (STF) has been shown to dramatically improve the penetration resistance of protective textiles to ballistic [20, 21], stab [9], shock [22], and puncture threats [23] [Cwalina et al. in prep] without compromising mass or flexibility. This technology exploits the deformation rate-dependent flow properties of concentrated colloidal dispersions and the mechanism has been extensively demonstrated [24-29]. At high shear rates, stress-bearing hydrodynamic particle clusters, or “hydroclusters”, can dramatically increase the dispersion viscosity (shear thickening) [25, 26, 30-32], and the effect can be modeled [25, 28, 32] and simulated [33-35]. For the most concentrated colloidal dispersions, this shear thickening transition can be abrupt [36, 37], and as a result, the material exhibits a rigid, solid-like response. In addition to viscous dissipation occurring within the STF, the rigid response of the STF also increases energy dissipation by restricting the motion of fibrils around an impact site and transferring stress to neighboring fibrils, thus hindering “windowing” [9]. These armor-enhancing properties of STF-treated fabrics have been replicated by a number of independent research groups [38-41]. It is important to note that the mechanism responsible for shear thickening in colloidal dispersions is governed by hydrodynamic interactions, which is fundamentally different from the frustrated dilatancy of frictional particles
in non-Brownian suspensions [42-44]. In the present work, we explore incorporating STF-Armor™ into the existing TMG with the aim of improving the resistance to cutting and puncture threats without increasing the mass or reducing the flexibility of the lay-up.

**Materials and Methods**

TMG materials were obtained from ILC Dover (Frederica, DE). A schematic of a standard TMG lay-up is shown in Figure 3 and the individual layer properties are reported in Table 1. The architecture of this standard TMG lay-up is taken from a previously published study [5] aiming to improve the hypervelocity impact resistance of the TMG. Each of the layers in the standard TMG has a design purpose in defeating a direct MMOD impact threat. The outer Orthofabric acts as a sacrificial layer to shock an incoming projectile into a high-energy state, whereupon it will fragment, melt, or in the best-case scenario, vaporize. The following seven layers of aluminized Mylar primarily serve as a radiation shield, but they also form a stand-off region over which the resulting debris cloud can expand over a larger area before reaching the absorber layers. In the standard TMG, two layers of neoprene-coated nylon are used as absorbers to “catch” the debris cloud before it reaches the urethane-coated nylon bladder cloth.

In our prototype lay-ups, a plain weave Kevlar® fabric and a commercially available STF-treated variant known as STF-Armor™ replaces the neoprene-coated nylon absorber layers. The woven Kevlar® (300 denier, 59 x 59 yarns per inch) is a correctional weave style obtained from Barrday (Cambridge, Ontario, Canada). The areal densities of the neat correctional Kevlar® and STF-Armor™ are 0.016 g/cm² and 0.018 g/cm², respectively. In comparison, the areal density of the neoprene-coated nylon is 0.028 g/cm². To match the lay-up areal densities,
three layers of neat correctional Kevlar® and STF-Armor™ were substituted for two layers of neoprene-coated nylon. Figure 3 depicts the prototype lay-ups containing neat Kevlar® and STF-Armor™ and Table 1 contains their layer properties.

![Figure 3](image.png)

Figure 3 Layer architecture of standard TMG lay-up (left), prototype TMG lay-up with neat correctional Kevlar® absorber layers (center), and prototype TMG lay-up with STF-Armor™ absorber layers (right).

Table 1. Thicknesses and areal densities of layers in standard TMG and prototype lay-ups.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Areal Density (g/cm²)</th>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Areal Density (g/cm²)</th>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Areal Density (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthofabric</td>
<td>0.56</td>
<td>0.049</td>
<td>Orthofabric</td>
<td>0.56</td>
<td>0.049</td>
<td>Orthofabric</td>
<td>0.56</td>
<td>0.049</td>
</tr>
<tr>
<td>7 layers Mylar</td>
<td>0.42</td>
<td>0.022</td>
<td>7 layers Mylar</td>
<td>0.42</td>
<td>0.022</td>
<td>7 layers Mylar</td>
<td>0.42</td>
<td>0.022</td>
</tr>
<tr>
<td>Neoprene-coated nylon</td>
<td>0.43</td>
<td>0.028</td>
<td>Neat Kevlar®</td>
<td>0.25</td>
<td>0.016</td>
<td>STF-Armor™</td>
<td>0.25</td>
<td>0.018</td>
</tr>
<tr>
<td>Neoprene-coated nylon</td>
<td>0.43</td>
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<td>0.25</td>
<td>0.016</td>
<td>STF-Armor™</td>
<td>0.25</td>
<td>0.018</td>
</tr>
<tr>
<td>Urethane-coated nylon</td>
<td>0.32</td>
<td>0.027</td>
<td>Neat Kevlar®</td>
<td>0.25</td>
<td>0.016</td>
<td>STF-Armor™</td>
<td>0.25</td>
<td>0.018</td>
</tr>
<tr>
<td>Total</td>
<td>2.16</td>
<td>0.154</td>
<td>Total</td>
<td>2.05</td>
<td>0.146</td>
<td>Total</td>
<td>2.05</td>
<td>0.152</td>
</tr>
</tbody>
</table>
Hypodermic needles were selected to simulate the cutting and puncture hazards associated with the raised crater lip surfaces found on metal surfaces after a hypervelocity impact from a MMOD particle. Hypodermic needles are complex threats because they possess both a conical puncture point combined with a continuous cutting surface that can facilitate penetration. In this study, standard 18 gauge and 21 gauge PrecisionGlide™ hypodermic needles (Becton, Dickinson, and Company; Franklin Lakes, NJ) were used. These needles have nominal outer barrel diameters of 1.270 mm and 0.820 mm, respectively. Quasi-static puncture testing was performed following the ASTM-F1342 standard with a hypodermic needle held in a chuck replacing the puncture probe as seen in Figure 4. The chuck was attached to a 500 N load cell on an Instron 5965, and the force experienced by the needle was recorded as it displaced through the target lay-ups. The point of contact is determined when the load cell registers a force exceeding 0.10 N. Twelve replicates were obtained for each type of lay-up at a loading rate of 254 mm/min. A new needle was used for each replicate to insure a consistent sharpness. A typical set of force-displacement curves is shown in Figure 5. The target in this particular case was a lay-up containing two absorber layers of neoprene-coated nylon subjected to an 18 gauge needle. The mechanism of needle puncture through fibrous materials was modelled by Termonia [18], although it should be pointed out that the needles did not possess a continuous cutting surface. For a single layer of fabric, there is an initial increase in the force-displacement curve as yarns are deflected by the needle. This is followed by an increase in the slope of the force-displacement curve as yarns are tensioned. The maximum in the force-displacement curve occurs as the needle tip slips into an inter-fiber space, at which point the fabric layer is considered to be punctured. In multi-layered fabric structures, each layer is found to be
penetrated in sequence rather than simultaneously. The force-displacement curves of the standard TMG lay-up in Figure 5 reveal that the tensioning of the yarns between replicates is fairly consistent but the point at which needle the needle tip reaches the inter-fiber space, either by slippage or yarn cutting, is statistical in nature. This behavior is typical of the puncture of fibrous structures with a heterogeneous surface topology, particularly when hypodermic needles are the penetrator [45] and [Cwalina et al. in prep].

Figure 4. (Left) Picture of the sample environment based on a modified ASTM F-132 standard used for quasi-static puncture testing. A hypodermic needle is held within a chuck which is attached to an Instron load cell that records the force on the needle as it displaces through the target. (Right) 18 gauge hypodermic needle against a correctional Kevlar® fabric backdrop.
Figure 5. Force experience by an 18 gauge hypodermic needle as a function of displacement through a TMG lay-up for 12 replicate experiments. The TMG lay-ups in these replicates contain two layers of neoprene-coated nylon as absorber layers.

Two-dimensional drape tests were performed on the standard TMG and prototype lay-ups to assess their flexibility. A schematic of the drape test is shown in Figure 6 which is based off the set-up described by Lee et al. [20]. The bending angle is a measure of the lay-up flexibility. The standard TMG lay-up and the prototype lay-ups containing neat correctional Kevlar® and STF-ArmorTM had measured bending angles of 52°, 51°, and 50°, respectively. Thus, the substitution of three layers of either neat correctional Kevlar® or STF-ArmorTM for two layers of neoprene-coated nylon does not appreciably alter the flexibility of the TMG lay-up.
Results and Discussion

The displacement-averaged loads for 18 and 21 gauge hypodermic needles are displayed in Figure 7. The peak force experienced by the needle and the displacement at which that value occurs are useful metrics for comparing the performance of TMGs containing different absorber layers. Note that prior experimental [45] and modeling [18] work has demonstrated that puncture of the needle tip through the fabric precedes the peak force; however, for the application considered here the peak force is a good metric to indicate when the material has been compromised, or “punctured”. These values are reported collectively in Table 2.
Figure 7. Displacement-averaged load as a function of displacement through target lay-ups for 18 gauge (left) and 21 gauge (right) hypodermic needles. The error bars reflect the standard error about the mean value.

Table 2. Peak needle force and displacement value for 18 and 21 gauge hypodermic needles with different absorber layers.

<table>
<thead>
<tr>
<th>Absorber Layers</th>
<th>18 Gauge</th>
<th>21 Gauge</th>
<th>21 Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Force (N)</td>
<td>Displacement (mm)</td>
<td>Peak Force (N)</td>
</tr>
<tr>
<td>2 Neoprene-coated nylon</td>
<td>12.7 ± 1.2</td>
<td>4.9</td>
<td>7.7 ± 0.2</td>
</tr>
<tr>
<td>3 Neat Correctional Kevlar®</td>
<td>26.5 ± 2.7</td>
<td>4.9</td>
<td>10.8 ± 1.0</td>
</tr>
<tr>
<td>3 STF-ArmorTM</td>
<td>35.6 ± 3.3</td>
<td>4.9</td>
<td>18.8 ± 0.5</td>
</tr>
</tbody>
</table>

For both needle gauges, replacing two layers of neoprene-coated nylon with three layers of neat correctional Kevlar® results in an increase in the peak puncture force without changing the displacement at which the peak force is recorded. The fact that the displacement does not
change suggests the overall cut resistance of TMG lay-ups containing two layers of neoprene-coated nylon as absorber layers is comparable to those containing three layers of neat correctional Kevlar®. While the TMG is an assemblage of textile layers and the bulk penetration resistance of the lay-up can depend on interactions between layers (Cwalina et al., *in prep*), the results here are not totally surprising as a recent study by Mayo and Wetzel [46] found the cut resistance of several single high-performance organic fibers was relatively similar at loading rates comparable to those performed in this study. Rather, the increase in peak force due to the substitution of neat correctional Kevlar® for the neoprene-coated nylon is most likely due to an increase in puncture resistance. As the needle moves transverse to the plane of the fabric, the dominant deformation mode experienced by the yarns will be a tensile stress. As the tensile strength of aramid fibers is roughly two orders of magnitude higher than that of nylon [47], it should follow that all else being equal, the neat correctional Kevlar® is expected to have a greater puncture resistance than comparable neoprene-coated nylon.

The efficacy of a TMG ultimately depends on its ability to absorb the kinetic energy of a penetrating threat. The energy absorbed by a TMG lay-up is calculated as the area under the force-displacement curve up until the displacement value when the peak puncture force is reached. These energy absorption measurements are presented in Figure 8. The percentage gain in the amount of energy absorbed by replacing the neoprene-coated nylon with neat correctional Kevlar® depends on the needle gauges. An 81% increase in energy absorbed is achieved by the substitution of neat correctional Kevlar® for an 18 gauge needle puncture, but only a 28% increase is obtained for a 21 gauge needle threat. This can most likely be attributed to the effect of “windowing” whereby the thinner penetrator is able to push aside yarns more easily [23, 48-50]. As a result, the thinner penetrator directly engages fewer fibers and exerts less energy to
defeat the textile layer. This behavior is quantitatively consistent with the results of Houghton et al. (2007) on assemblages of Kevlar® layers where the energy absorbed was found to be an increasing function of the needle size.

![Figure 8](image.png)

**Figure 8.** Energy absorbed up to the peak puncture force for 18 gauge (solid) and 21 gauge (striped) needles.

Intercalation of a fabric with STF is known to restrict the motion of fibers and decreases their mobility upon an impact event that exceeds the critical stress for shear thickening [9, 20, 21]. Forcing the penetrator to directly engage yarns and fibers has been shown to increase a fabric’s collective resistance to windowing against small puncture threats [9, 51]. Indeed, such
an effect manifests itself in the results of this study. When STF-Armor™ is substituted in place of the neat correctional Kevlar®, a 55% increase in the amount of energy absorbed is achieved with the thinner 21 gauge needle compared with a smaller 21% increase for the 18 gauge needle. For the thinner needle size where windowing is an important defeat mechanism, the effect of the STF in resisting the motion of fibers to windowing becomes magnified as it forces the needle to exert more energy to defeat the fabric. In addition to restricting the mobility of fibers, the STF is known to enhance the energy dissipation capability of the fabric through viscous dissipation within the STF itself and the ability of the STF to distribute stress away from the impact site to neighboring fibers [9]. These mechanisms collectively give rise to a substantial improvement in energy dissipation against hypodermic needle threats. When compared to the standard TMG lay-up, the amount of energy absorbed for lay-ups with STF-Armor™ absorber layers increased by 99% for the 21 gauge needle and 117% for the 18 gauge needle without increasing the overall areal density of the TMG lay-up. The ability of STF-Armor™ absorber layers to increase resistance to small quasi-static puncture threats makes them attractive candidates to mitigate the risks of TMG puncture caused by sharp raised crater lips on the exterior of the ISS.

Conclusions

The cut and puncture resistance of thermal micrometeoroid garment (TMG) lay-ups with correctional Kevlar® and STF-Armor™ absorber layers substituted for neoprene-coated nylon absorber layers at equal areal density was investigated using quasi-static hypodermic needle puncture testing. Hypodermic needles simulate the cutting and puncture threats associated with sharp raised crater lips characteristic of the hazards on the International Space Station created by hypervelocity MMOD impacts. Substituting neat correctional Kevlar® in place of neoprene-
coated nylon as the absorber layers significantly increases the maximum peak puncture force of the TMG. This performance enhancement is expected based on the superior tensile strength of the correctional Kevlar®. Intercalating colloidal shear thickening fluids into the correctional Kevlar® as STF-Armor™ improves the energy absorption capacity of the TMG by 117% and 99% for 18 and 21 gauge needles, respectively. The dependence of the performance enhancement on needle gauge was quantitatively consistent with prior reports of puncture failure in woven aramid textiles [23]. Thus, significant improvements in TMG puncture resistance can be achieved by substitution of STF-Armor™ for the current neoprene-coated nylon absorbers without compromising areal density or flexibility. Given that similar TMG designs containing STF-Armor™ show good efficacy in hypervelocity impact testing [52], the results provided here suggest that improving the cut and puncture resistance of particularly vulnerable regions of the TMG can be achieved without adding additional layers of protective material, and hence, more mass and a reduction in flexibility.

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References


