EFFECTS OF IMPACT EXPOSURE AND THERMAL ANNEALING ON MECHANICAL PROPERTIES OF AN AMERICAN FOOTBALL HELMET OUTER SHELL MATERIAL

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INTRODUCTION

Degradative effects from a multitude of impact events and environmental conditions, along with periodic reconditioning exposure over the life-span of football helmets, are poorly understood. Changes to the outer shell materials may induce a systematic reduction in protective performance, potentially leading to a higher risk for head injury in athletes. Mechanical stress placed upon rubber toughened polycarbonate (PC) or polyethylene terephthalate (PET) will generate microscopic voids via particle cavitation which will macroscopically manifest to visibly whiten the material [1]. Pilot work has elucidated whitening in collegiate helmet outer shells after a single season [2]. Further, thermal annealing just above a material’s glass transition temperature (T_g) is reported to rejuvenate its thermo-mechanical history [1].

Moreover, helmet outer shells are reused without a publicly available technical understanding between repetitive impact exposure inducing aesthetically unfavorable whitening and impact performance. The purpose of this study was to investigate the effects of impact exposure and thermal annealing on impact, bulk, and surface mechanical properties of an American football helmet outer shell material.

METHODS

Helmet-grade rubber-toughened PC/PET blend material (T_g = ~150°C) was injection molded into 4” x 6” x 1/8” plaques to match the thickness of an American football helmet outer shell. Four material conditions (non-impacted, non-impacted/annealed, impacted, and impacted/annealed) were investigated (Figure 1). Impact tests were performed upon a helmet surrogate plaque-foam system comprised of a plaque stacked atop 1” VN600 foam using an instrumented drop tower system (Dynatup 9250HV, Instron, Norwood, MA) [3]. The drop mass assembly of 5.04 kg contained a 44 kN load cell tup and a 2" diameter polyurethane dart (200H, Lixie Hammers, Central Falls, RI) with a measured Shore hardness (72 D) comparable to the helmet-grade plaque (81 D). Plaque-foam systems were impacted at 5.5 m/sec under ambient conditions against a 1” modular elastomer programmer (MEP) pad anvil [4, 5]. After an initial impact to quantify the performance of a non-impacted plaque (trial 1), an impact treatment of ten repetitive trials was performed (trials 2-11) followed by a final impact (trial 12) (Figure 1). Trials 1 and 12 were analyzed via a dependent t-test. Impact performance was measured with a 13th trial comparing impacted and impacted/annealed plaques, and results analyzed via an independent t-test. A total of 190 impacts were performed. Randomly selected plaques underwent a thermal annealing treatment at 175 °C for 5 minutes and then air cooled. Color change was quantified per CIELAB scale using a spectrophotometer (BYK Gardner, Columbia, MD) and analyzed via a one-way repeated measures ANOVA with 3 levels (pre-impact, pre-anneal, and post-anneal).

![Figure 1: Experimental design showing treatments and mechanical tests across material conditions.](image-url)
Tensile mechanical properties were measured (Insight 10, MTS, Eden Prairie, MN) at a strain rate of 25 mm/min and results analyzed via three separate one-way ANOVAs with 4 levels (material condition). Modified ASTM-D638 Type I tensile specimens (3.5" x 0.5" strips) were cut directly from plaques. Surface mechanical properties were quantified using load-controlled quasi-static nanoindentation (TI 900 Triboindenter, Hysitron, Minneapolis, MN) at pre-selected loads of 500, 1000, 1500, 2000, and 2500 μN, and analyzed with a 4 between (material condition) x 5 between (applied load) ANOVA. Post-hoc analyses were performed via Tukey HSD tests. For all statistical analyses, alpha level was set a priori at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Each impact test induced visible whitening to the plaque. Furthermore, the change in characteristic curve shape between non-impacted and impacted plaques (Figure 2) along with a significant difference in mean peak force between trials 1 and 12 ($t=7.93$, $p<0.05$, $d=1.47$) indicated the impact treatment adequately induced a change in plaque impact performance. The visible disappearance of whitening along with a significant difference in mean $L^*$ ($F_{2,8}=563.38$, $p<0.05$) indicated the thermal annealing treatment adequately erased the impact-induced whitening.

The absence of significance in mean peak force along with no qualitative change in curve shape between impacted and impacted/annealed (Figure 2) suggested that the annealing treatment did not alter the impact energy management capabilities of a plaque with an impact history of 12 repetitive trials.

For surface, a difference in mean reduced modulus was observed ($F_{3,80}=4.35$, $p<0.05$, $f=0.39$) with annealed samples lower than non-annealed ($p<0.05$) (for a given impacted condition). Therefore, only annealing altered the surface mechanical properties up to a measured depth of $\sim1 \mu m$.

Differences observed for yield stress ($F_{3,16}=6.93$, $p<0.05$, $f=1.32$) and ultimate tensile strength (UTS) ($F_{3,16}=21.21$, $p<0.05$, $f=2.30$) indicated both the impact and anneal treatments altered bulk tensile properties (Table 1). Impacted UTS was higher ($p<0.05$) than other conditions, indicating a change in strain hardening behavior during stress-strain testing. Further analysis revealed reductions in both Young’s modulus (observed trend) and reduced modulus ($p<0.05$) when comparing annealed and non-annealed conditions, thus suggesting annealing softened the material. All impacted tensile specimens preferentially yielded at the whitened area. Whereas, impacted/annealed specimens did not preferentially yield at the whitened area that existed pre-anneal. As a result, annealing just above $T_g$ aesthetically recovered the helmet-grade plaque, and potentially rejuvenated the thermo-mechanical history of the engineered material. Absence of surrogate-system differences in impact performance may be attributed to setup limitations, thus future work will employ a more accurate impact protocol. Our findings warrant exploring the effects of annealing outer shells as a potential way to mitigate the risk of head injury by providing greater helmet life-span consistency.

Table 1: Tensile properties of material conditions.

<table>
<thead>
<tr>
<th>Material Condition</th>
<th>Tensile Mechanical Properties</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Young’s Modulus (MPa)</td>
</tr>
<tr>
<td>Non-impacted</td>
<td>955.5 ± 27.1</td>
</tr>
<tr>
<td>Non-impacted/Annealed</td>
<td>920.7 ± 26.7</td>
</tr>
<tr>
<td>Impacted</td>
<td>934.6 ± 21.6</td>
</tr>
<tr>
<td>Impacted/Annealed</td>
<td>910.9 ± 32.6</td>
</tr>
</tbody>
</table>

* Matching superscript number denotes post-hoc combination significance ($p<0.05$)

REFERENCES

2. Krzeminski D. 2012 [unpublished data]
4. 001-11m11a, NOCSAE DOC (ND). 2011
5. ASTM F1446-11a. 2011. ASTM International