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Degradation of yarns recovered from soft-armor targets subjected to multiple ballistic impacts

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ABSTRACT

Post ballistic impact residual yarn mechanical properties were analyzed from two different as-received shoot packs composed solely of AuTx yarn possessing the 2/2 twill weave structure, one being impacted by 9-mm projectiles and the other by 2-grain projectiles. It was found that yarn mechanical properties from both shoot packs yielded similar results, regardless of yarn orientation, ply location, or penetrator size, which indicates that ballistic damage in the packets is very localized, producing little damage to the neighboring yarns. Mechanical properties of these woven, ballistically impacted, and then extracted yarns were compared to as-received native spooled AuTx yarn yielding a slight reduction in tensile strength, an increase in failure strain, and a reduction in elastic modulus, thereby yielding little variation in yarn toughness.

1. Introduction

Fabric panels woven from high performance fibers and yarns are increasingly employed in high strain-rate applications such as soft ballistic armor, turbine fragment containment systems, and anti-spall linings. It is well known that many parameters play a role in a soft armor system's projectile halting efficiency including but not limited to fiber–fiber friction, yarn–yarn friction, fiber–projectile friction, fabric weave structure, fiber/yarn mechanical properties, projectile impact velocity, projectile impact obliquity, projectile nose geometry, and projectile material properties [1,2]. Indeed, vest penetration is an extremely complex process, but as an initial screening procedure, yarn mechanical tensile properties can be used to indicate possible soft-armor performance with a high degree of success [3,4]. Therefore, it is of great use to analyze yarns having undergone various treatments or aging processes in order to better predict overarching fabric performance having been exposed to field-use by armed personnel.

Previous works have aimed at understanding yarn tensile behavior, both from an experimental approach and/or statistical modeling [5–15], thereby shedding much light on both yarn testing procedures and resulting deflection–load response. Although single fiber mechanical property characterization is of great importance in understanding the possible effectiveness of a given fiber type in ballistic applications, once a filament material is deemed feasible for use, yarn rupture analysis becomes of extreme interest when trying to understand energy dissipative capabilities of an armor system due to yarn seizing and scouring procedures. Furthermore, even though previous aramid single fiber testing has revealed little rate dependence and possible sample length effects on resulting mechanical properties [9,16–19], there exists a much more demonstrative variation in mechanical response on yarns via said effects due to the structural failure phenomenon of fiber breakage and load reorientation [5–8,12], thereby yielding a definite increase in stress due to an increase in testing strain rate or a decrease in the yarn gauge length [10,11,13–15]. Thus, in order to correctly uncover the key issues affecting yarn tensile behavior, it is imperative to accurately determine appropriate testing parameters which will not mask the effect of the degenerative issue being studied.

It is well known that fabric processing procedures such as yarn seizing, weaving, and scouring can alter the effectiveness of an armor system, and these effects should be fully understood before vest production [14]. Furthermore, environmental processes such as UV-degradation, humidity, temperature, or abrasion, which are all reasonably difficult to properly reproduce in lab environments, can each drastically alter the ultimate halting capabilities of an armor system [20–23]. While each of these issues has been analyzed

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in some detail, the effect of multiple loadings on a fabric system has been much less established. In many circumstances, these ballistic fabric panels may undergo several impact traumas, requiring the fabric to retain nearly all of its threat arresting capabilities during repetitive invasive strikes. Thus, while it is imperative to pursue the development of robust armor systems which are capable of withstanding long-term environmental aging, it is also of importance to ascertain an understanding of damage mechanisms of said systems due to stress wave propagations throughout the surrounding fabric structure during repeat loading activity. In light of this current lack of understanding in vest behavior, it is clearly of use to analyze single yarns removed from shoot packs having undergone repeat invasion in order to understand the degradative effects of impact on surrounding fabric zones. Therefore, two shoot packs composed of AuTx ballistic fibers, which were previously impacted by multiple projectile threats, have been investigated in order to determine residual mechanical properties of yarns being located within various proximity of impacting points. First and foremost it is the goal of this study to establish the viability of the AuTx system, but in addition it is hoped that results of this work may also shed light on the consequence of multiple impact loadings in typical soft armor from varying sized projectiles.

2. Materials and methods

Two similar AuTx shoot packs have been received for post impact analysis, each being composed of AuTx high-performance aramid fibers. Received shoot packs, SPA and SPB, were previously impacted with 2-grain flat head and 9-mm ball round projectiles, respectively. Similar shoot patterns were used on both SPA and SPB and can be found in Fig. 1. Each shoot pack consisted of 34 soft fabric plies, being woven in the 2/2 twill format depicted in Fig. 2. The warp-weft directions of the ply weave were found to randomly lie in either the 0° or 90° alignment with respect to the vertical direction of Fig. 1. The orientations of the included plies from both packs can be seen in Table 1.

Determination of the warp and weft yarn directions were decided by optical analysis of the color gradient found between adjacent yarns, as the warp yarns are typically pulled from different yarn bobbins while the weft yarns consist of a continuous strand which is oscillated back and forth perpendicular to the warp direction by an undulating trundle. Therefore, the warp direction is expected to possess a greater color variation between adjacent yarns than their weft counterparts. It is important to note that the usual method of establishing warp and weft directions by performing yarn pull-out tests [24], by measuring crimp amplitude

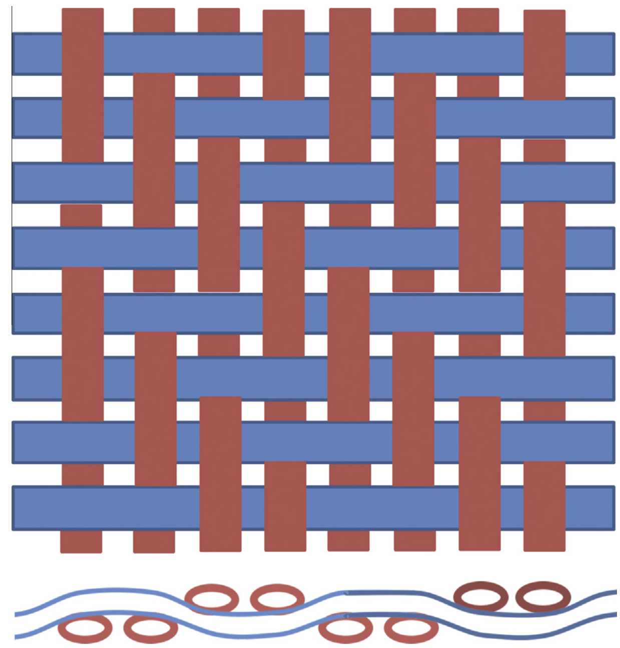

Fig. 2. 2/2 Twill weave structure found in received AuTx shoot packs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[14], or by resolving differences in yarn diameters [25] yielded inconclusive findings on this material, thus the aforementioned color gradient technique was utilized. Verification of this procedure is bolstered by the slight variation in warp-weft stress–strain history, which is described in Section 3. It is important to note that the last ply (ply 34) of SPA was initially sacrificed to create both pull-out specimens and yarn crimp samples, thus yarn tension tests from this panel could not be performed.

From each ply within the shoot packs, multiple single yarns were pulled in a strategic pattern from both the warp and weft directions, and the pull pattern can be seen in Fig. 3. Three yarns were extracted between adjacent rows and columns of impact points in an effort to determine the effect of yarn-shot proximity. Spacing between both adjacently pulled yarns and yarn-impact points was 9-mm, but it is important to note that some shot placements were not ideal, resulting in variation of the actual yarn-shot spacing. Extracted yarn specimens were then mounted onto large foam boards for storage until future testing, ensuring that minimal

(a) SPA (b) SPB

Fig. 1. Shot patterns used for both SPA and SPB. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)