CORRELATING FIBER MECHANICAL PROPERTIES AND MOLECULAR STRUCTURE WITH BALLISTIC PERFORMANCE

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1 Introduction

Laboratory studies and field return data from soft body armor (SBA) indicates that mechanical properties, of ballistic fibers [e.g., strain-to-failure (STF) and ultimate tensile strength (UTS)] can be reduced by chemical and mechanical degradation mechanisms [1,2]. For the specific case of SBA impacted by right circular cylinder (RCC) projectiles, empirical [3,4] and theoretical studies [5,6] show that ballistic performance is related to the fiber's UTS, STF, and Young's modulus. Therefore, a desirable outcome of these results is the development of an unrestricted framework that equates changes in a fiber's material properties with changes in ballistic performance. With the continued development of new fibers the ability to link ballistic performance with a fiber's molecular structure is also needed.

In this paper, a graphical approach that links the elastic energy storage capability of the fiber to its tensile wave speed is advanced as a generalized framework for interrogating the potential of high modulus fibers in SBA. Within this framework, examples are shown of how changes in a fiber's material properties or its molecular structure have the potential to influence its short and long-term performance in SBA applications.

2 Sample Preparation and Testing

Poly(paraphenylene terephthalamide) (PPTA) and poly[(benzo-[1,2-d:5,4-d']-benzoxazole-2,6-diyl)-1,4-phenylene] (PBO) single fibers were tested using a Favimat tensile fiber testing machine. The tested fibers were either extracted from a spool (virgin) or woven fabrics before and after these woven fibers were subjected to repeated folding to simulate damage caused by wear [2,7]. PBO fibers were also extracted from field returned vests and tested to assess changes in mechanical properties.

3 Discussion

3.1 Framework

The link between a fiber's elastic energy storage ($U_{storage}$) capability per unit mass and the fiber's tensile wave speed (a_{0y}) has been well established, with the explicit expressions for each factor shown below.

$$U_{storage} = \left(\frac{\sigma_y^{\max} \varepsilon_y^{\max}}{2\rho} \right) \quad (1)$$

$$a_{0y} = \sqrt{\frac{E_y}{\rho}} \quad (2)$$

where

$\sigma_y^{\max}$	is the maximum axial tensile strength
$\varepsilon_y^{\max}$	is the maximum axial tensile strain
E_y	is the longitudinal linear elastic modulus
ρ	is the density

In Figure 1, the $U_{storage}$ is plotted relative to a_{0y} for a select group of high-performance fibers that encompasses the ceramic and polymeric material classes: [(a) S-glass, (b) PPTA (Kevlar, Twaron), (c) carbon fiber, (d) polyester, (e) nylon, and (f) silk]. Although the choice of the benchmark fibers are somewhat arbitrary, these fibers have been considered for, are being used in, or are of historical

interest for ballistic applications. Excluding the nylon data points, a power function trend line has been fit through these data ($R^2 = 0.97$) to aid in interpretation.

The green curve in Figure 1 reflects a constant ballistic performance curve with respect to Kevlar 29 and Twaron type PPTA fibers using $U_{storage}$ and a_{0y} [8]. These data capture the general observation that increasing $U_{storage}$ does no good if a_{0y} is greatly reduced in the process. These data also underscore the observation that PPTA fibers, which are widely used in SBA, achieve a balance between tensile wave speed and energy absorption.

Figure 2 introduces two more types of Kevlar for comparison. Interestingly, the Kevlar KM-2 fibers, which is used in the Army's Interceptor Body Armor exhibits a slight increase in energy absorption but the same sonic velocity as Kevlar 29. According to the Dupont website, Kevlar 129 was created to achieve lightweight, high performance body armor as defined by the NIJ standard. This material exhibits slight increases in energy absorption and sonic velocity relative to Kevlar 29 (Figure 2). These differences may be related to how the fibers are processed.

3.2 Impact of Molecular Structure on Potential Ballistic Performance

Using the power law reference curve, the potential $U_{storage}$ of PBO fibers in the virgin state, from simulated folding damage and from a field return vest are shown in Figure 3. The virgin state results indicate that a change in molecular structure can increase the potential of the ballistic fibers to store energy. However, for the PBO fibers the energy absorbing potential can be greatly reduced by mechanical and chemical degradation mechanisms that lower the STF and UTS of these fibers. The degradation of these fibers with humidity has been linked to the presence of residual phosphoric acid that is chemically bound to the polymer as monoaryl phosphate ester [1], while the reduction in properties with folding has been associated with the PBO's weak compressive strength [2].

Although similar in chemical structure to PBO fibers, M-5 fibers were designed at the molecular level to overcome the low compressive strength of PBO, by increasing hydrogen bonding between molecular chains as found in PPTA fibers, while retaining a high level of specific energy absorption like PBO fibers. From Figure 4, the published M-5 properties are comparable to those of carbon fibers, with the projected enhancements bringing the specific energy absorption of the fiber in line with PBO fiber. If achieved the increased sonic velocity, would allow the fiber to dissipate the energy of the projectile away from the impact zone at a faster rate than PBO or Kevlar fibers.

Recently, Armos fibers have received attention because of their apparent enhanced ballistic performance relative to Kevlar 29 fibers. These fibers are a block copolymer composed of PPTA and 5-amino-2-(p-aminophenyl)-benzimidazole, SVM-type, units that are similar to those found in the M-5 fiber. The specific energy absorption of the SVM, 5-amino-2-(p-aminophenyl)-benzimidazole, fiber (not shown) and the Armos fiber (Figure 5) is higher than Kevlar fibers at a comparable sonic velocity, with the Armos fiber being higher than the SVM fiber. These results indicate a synergistic effect achieved by incorporating blocks of the SVM-type polymer chains with PPTA blocks that results in an enhancement of the potential ballistic performance of the resulting Armos fiber.

4 Conclusions

The construction of a ballistic property materials chart using specific strain energy and sonic velocity seems to provide a useful qualitative framework for evaluating reductions in ballistic performance arising from degradation (due to chemical or mechanical mechanisms) of a fiber's mechanical properties. Additionally, the chart seems to be a useful platform for contemplating how changes in molecular structure can potentially enhance ballistic performance. Furthermore, we observed agreement between the power law fit of the fibers that have been considered for ballistic performance and the constant ballistic performance curve generated with respect to the properties of Kevlar 29. This indicates that with respect to these first generation fibers, effective material solutions for soft body armor applications achieve a balance between specific energy absorption and the dissipation of energy away from the impact zone.

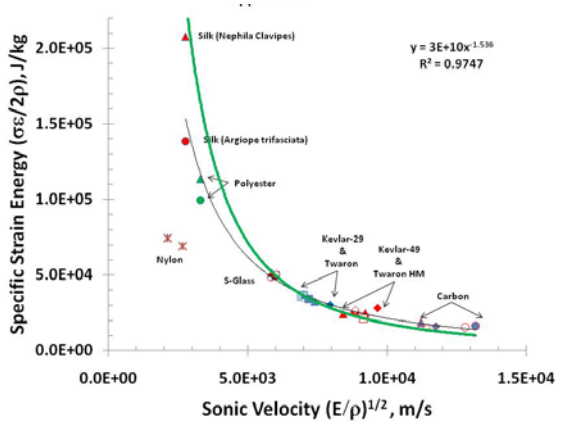

Figure 1. $U_{storage}$ versus a_{0y} for first generation high performance ballistic fibers. Black curve represent empirical power law fit. Green curve represents constant ballistic performance curve with respect to Kevlar 29 and Twaron PPTA fibers.

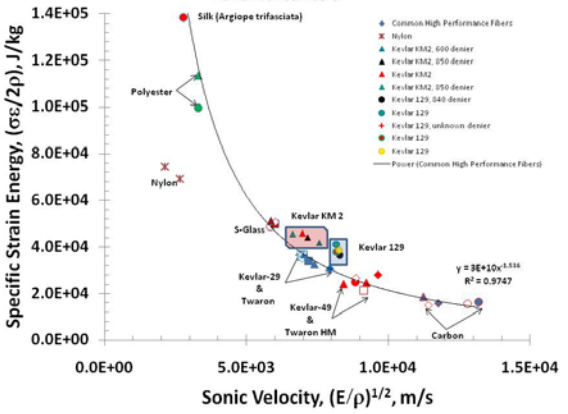

Figure 2. $U_{storage}$ versus a_{0y} for Kevlar KM 2 and Kevlar 129 high performance ballistic fibers. Black curve represent empirical power law fit.

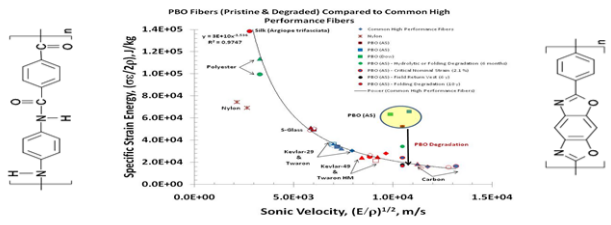

Figure 3. $U_{storage}$ versus a_{0y} for pristine and degraded PBO fibers (image on right) relative to first generation high performance ballistic fibers. Black curve represent empirical power law fit. The image on the left is the chemical structure of PPTA.

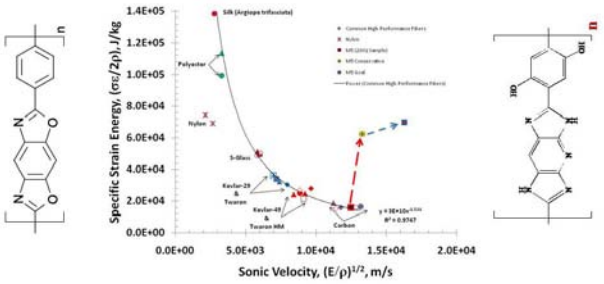

Figure 4. $U_{storage}$ versus a_{0y} for M-5 fibers (image on right) and projected enhancements through processing relative to first generation high performance ballistic fibers. Black curve represent empirical power law fit. The image on the left is the chemical structure of PBO.

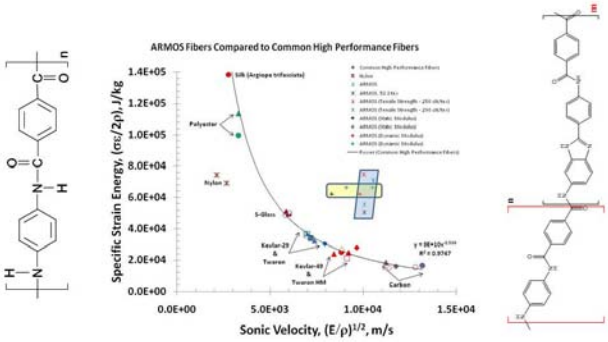

Figure 5. $U_{storage}$ versus a_{0y} for Armos fibers (image on right) relative to first generation high performance ballistic fibers. Black curve represent empirical power law fit. The image on the left is the chemical structure of PPTA.

References

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