Effects of Ageing on Tensile Strength of Flexible Unidirectional Composite Laminates for Body Armor

Amy Engelbrecht-Wiggans[1, 2], and Amanda Forster[1]

[1]Material Measurement Laboratory
National Institute of Standards and Technology

Gaithersburg, MD 20899

[2]Theiss Research

La Jolla, CA 92093

ABSTRACT
Many body armors are made by stacking unidirectional (UD) layers in different orientations, typically alternating 0 degree and 90 degree layers. These UD layers are constructed by laminating thin layers of high-performance fibers held in place using binder resins and thin polymer films, with the fibers in each layer oriented parallel to each other. Of interest is the long-term structural performance, and while some research has been done into the behavior of the fibers after ageing, very little has been done on the behavior of the binder resins. Thus, to accurately predict long-term performance of armors constructed from UD laminates, a better understanding of the material property changes of all its constituents with ageing is necessary. This work presents tensile data for UD laminate specimens that have been aged up to 150 days at 70 °C and 76 % relative humidity (RH). The results show evidence of degradation in strength after ageing when tested at low stress rates, indicative of binder degradation, mirroring previous observations of delamination after ageing.

Keywords: Composite laminate, strip tensile testing, body armor, aramid, ageing

INTRODUCTION

Body armor is a critical piece of life-safety equipment, and armor designers and manufacturers constantly strive to minimize weight while maximizing protection capabilities. Efforts to reduce the weight of armor systems have led to soft body armor systems made up of multiple layers of unidirectional (UD) laminates, in which thin fibers are aligned and stacked on top of similar, perpendicular fibers, using a thermoplastic resin as a binder to hold the fibers in place [1]-[3]. Of particular interest for this work is a system comprising many sheets of poly(*p*-phenylene terephthalamide) (PPTA, commonly known as aramid) where each sheet consists of two layers of perpendicular fibers [4].

Ageing and degradation of body armor are of great concern to the protection community, particularly after the well-publicized field failure of a body armor made from the material poly(*p*-phenylene-2,6-benzobisoxazole), or PBO [4] [5] [6] in 2003. Prior research has shown that aramids show very little degradation in ballistic performance when exposed to typical use environments [7]. Studies of the tensile strengths of component yarns indicate that aramids are resistant to environmental degradation [8-10].

The degradation results for aramid yarns and woven armor can be assumed to be reflective of the approximately 14 um diameter fibers used in the UD laminates. These laminates, however, contain an additional binder component so it is necessary to evaluate the effects of environmental ageing on the UD laminate system as a whole to better understand the systems' potential long-term performance. Tensile strength is a convenient metric for measuring degradation, as it requires minimal material and can be related to the ballistic performance, as described in [11-12]. This work measures the tensile strength of strips of UD laminate, before and after up to 150 days of exposure to 70 °C and 76 % RH.

BACKGROUND

The flexible UD composite laminate used in this study consisted of two layers of approximately 14-um-diameter PPTA fibers held in place with a binder resin. The laminate was aged at 70 °C and 76 % relative humidity (RH) and extracted at five different intervals. This particular ageing condition was chosen to accelerate the ageing process as much as possible without inducing new forms of degradation, such as combustion, and also because there are prior studies of PPTA fibers at this ageing condition. Specimens were prepared and tested following the procedure outlined in [13].

ANALYSIS

Figure 1 shows that the strength of the material degraded with exposure to 70 °C and 76 % RH . Before 100 days of ageing, degradation mainly occurs in the slowest loading rate. Degradation in slow loading rates but not fast ones may indicate binder degradation [14-15]. After 100 days of ageing, there is some degradation in all specimen sizes and loading rates, other than the 900 mm specimens, which have a large amount of variance within datasets and no overall trend. A similar ageing study was performed on PPTA yarns, which included the conditions of 70 °C and 76 % RH [16]. Shown in Figure 2, prior to 100 days there is no evidence for degradation of the PPTA yarns. The specimens in Figure 2 correspond most closely with the 100 mm gauge length specimens in Figure 1, and these results are consistent with each other.

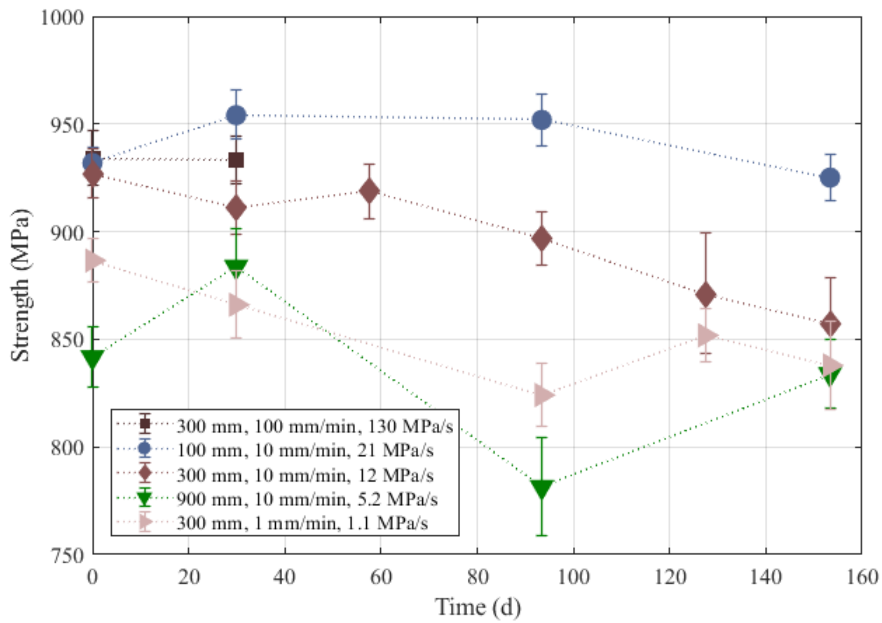


Figure 1. Weibull ultimate strength scale parameters, with the 95% maximum likelihood estimated confidence interval plotted as error bars. Specimens are all 30 mm wide, with varying gauge lengths and loading rates, as specified. Each group consists of at least 30 specimens.

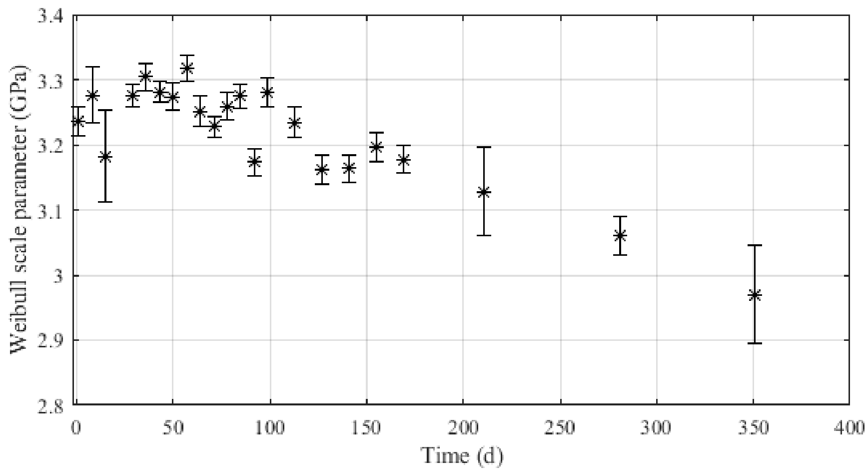
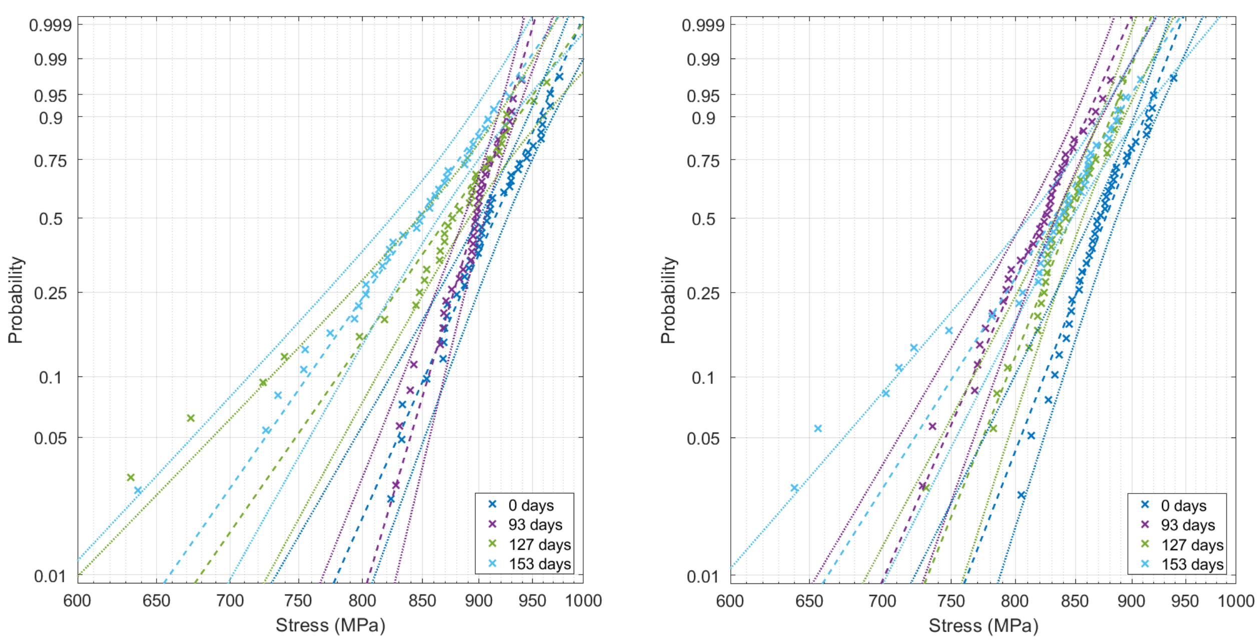


Figure 2. Weibull ultimate strength scale parameters, with the 95% confidence interval plotted as error bars, of aramid yarns after ageing at 70 °C and 76 % RH. The gauge length was 79 mm and the crosshead testing speed was 23 mm/min. Data is from [16]. Datapoints with small error bars consist of 50 specimens each, while datapoints with larger error bars consist of 15 specimens each.

Figure 1 focuses on the Weibull strength scale parameter, and for some aged data there is little separation between the aged and unaged error bars. Indeed, for the case of the 900 mm specimens the error bars overlap. To investigate potential degradation further, Figure 3 shows Weibull plots of the empirical cumulative distribution for the specimens cut with a 300 mm gauge length and a 30 mm width, and tested at a) 10 mm/min and b) 1 mm/min. From Figure 3 it can be seen that the aged distributions are distinct from the unaged distribution. In Figure 3b the distributions shift left with increased aging time, denoting a decrease in strength. Figure 3b is similar, though the shift is not as strictly dependent on time aged, as the 93 d data shows more overall degradation than the 127 d and 153 d. The disparity between this and Figure 1 is due to the large influence of the lowest strength values on the scale parameter.



a) b)

Figure 3. Weibull plots of the empirical cumulative distribution for GN2117 specimens cut with a 300 mm gauge length and 30 mm wide, tested at a) 10 mm/min and b) 1 mm/min. Maximum likelihood estimates are given as a dashed line, and 95 % confidence intervals are the dotted lines

A predicted reduction in ballistic performance can be quantified by examining the effect on V_{50}, which is the velocity at which half of the projectiles are expected to perforate the armor [17]. The reduction in V_{50} can be calculated using the relationships derived in [11-12], and the analysis of these relationships done in [16]. Across all specimens, the degradation in mean tensile strength predicts less than an 8 % reduction in V_{50}.

CONCLUSION

Degradation is observed to occur in the specimens tested herein. However, the degradation in ultimate tensile stress is less than 10 % after 150 days at 70 °C and 76 % RH. Since these samples were exposed to accelerated ageing conditions, this result is encouraging for the use of this material as a real-world body armor material, where the degradation environment would be much less harsh. This observation was underscored by only a predicted 8 % reduction in the V_{50} of armor made from this material.

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