An Investigation of the Temperature and Strain-Rate Effects on UHMWPE Fibers

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ABSTRACT
During a ballistic impact, materials are subjected to both high strain-rates and high temperatures. Ultra High Molecular Weight Polyethylene (UHMWPE) fibers used in ballistic protection and their strength increases with increasing strain-rate and decreases with increasing temperature. To understand the impact of both factors, a single fiber heater has been fabricated to heat UHMWPE fibers up to their melting temperature (~148 °C) to measure the change in mechanical properties as a function of temperature and strain-rate. Custom grips have been fabricated for use with the single fiber heater and performed well across all strain rates and temperatures in this study. 251 tensile tests have been conducted on 10 mm gage length UHMWPE single fibers at temperature-strain-rate combinations spanning five decades of strain-rates and eleven temperatures. A non-failure boundary is found by fibers that can be strained to 25% without mechanically failing beginning at 75 °C for 10^{-3} s^{-1}, 100 °C for 10^{-2} s^{-1}, 130 °C for 10^{-3} s^{-1}, 148 °C for 10^{-0} $s^{-}1$, and fail regardless of temperature at 550 s^{-1}. It is estimated that an increase in temperature of 25 °C to 30 °C is equivalent to lowering the strain-rate by one decade. At 550 s^{s-1} strain-rate, there was little change in the strain-to-failure from 20°C to 145 °C indicating strain-rate is the dominant factor. Similar constant strains-to-failure are seen in quasi-static tests at 65 ℃ to 75 °C below the respective non-failure boundary.

Keywords: UHMWPE single fiber, strain-to-failure, Split-Hopkinson Tension Bar (SHTB), Kolsky bar, single fiber heater

BACKGROUND

Ultra-High Molecular Weight Polyethylene yarns exhibit a high strength-to-weight ratio, low density, and are commonly used in rope and body armor applications. The polymeric material is viscoelastic and the mechanical properties have a strong dependence on strain-rate and temperature. During a ballistic impact the material is subjected to high temperatures and high strain-rates. The increase in temperature decreases the strength and increases the strain-to-failure by allowing the chains a higher degree of mobility and increasing the likelihood for chain slippage. The effects from increasing the strain-rate are reversed; as the strain-rate increases, the strength increases and the strain-to-failure decreases since the chains do not have

Abu-Farha, Fadi; Mates, Steven.
"Opportunities for Inverse Analysis in Dynamic Tensile Testing."
Paper presented at Society for Experimental Mechanics 2016 Annual Meeting, Orlando, FL. June 6, 2016 - June 9, 2016.

time to move or slip on such short time scales. Understanding how these competing influences affect the overall mechanical behavior during a ballistic impact is essential for predictive modeling and advances in the design of soft body armor systems.

A single UHMWPE fiber is the smallest discernable component of the soft body armor system and is often tested to extrapolate the mechanical properties to the yarn and other higher-level constituents. Tensile tests are performed by gripping the ends of a single fiber and applying a constant strain-rate until failure. The single fibers have a low surface energy [1] making them inherently slippery and a high tensile strength, causing difficulties in proper gripping of the fibers during tensile testing [2, 3]. Capstan methods have been used to gain data about failure stresses but the failure strains from this method is often questionable due to the unknown amount of gage length within the capstan [2, 4]. Direct gluing to cardboard has shown limited success and is dependent on fiber diameter [5, 6] while a combination of glue and pressing between rubber tabs has reported success but on small numbers of tests performed [3]. Fiber-specific grips have also been developed to directly grip Kevlar fibers between two tabs of poly(methyl methacrylate) [7-9] and the same design using polycarbonate tabs has shown to be successful for UHMWPE singles fibers [10]. The gripping tabs in these designs are recessed from the grip edge making it challenging to access the length of fiber in the grip for heating experiments. To investigate the simultaneous effects of strain rate and temperature on the mechanical properties of UHMWPE single fibers, a new set of grips must be created and compliant with a single fiber heater.

SAMPLE PREPARATION

UHMWPE single fibers were teased from a spool of SK76 yarn. Samples were prepared by using cyanoacrylate to glue ends of a single fiber to a hollow rectangular mounting template cut from an acetate sheet. The hollow rectangle shape allows the 10 mm gage length and the two polycarbonate gripping tabs to fit between the glue points. He mounting template is cut away after the fiber is gripped and before tensile testing. A mounted fiber with one long side of the rectangle removed is shown in figure 1. Fiber diameters were measured using an optical microscope with 60x lens at five points along the 10 mm gage length. The average diameter of fibers used in this study was 18.63 μm with a standard deviation of 1.53 μm. The highest fiber diameter measurement was 23.11 μm and the lowest was 13.86 μm.

EXPERIMENTAL METHOD

A custom single fiber heater and a direct gripping method were used to conduct uniaxial tensile tests on UHMWPE single fibers across five decades of strain-rate and eleven temperatures from room temperature to the melting temperature.

Single Fiber Heater: There were several design requirements for a single fiber heater: the fiber be rapidly heated to minimize artificial annealing of the fibers, the heater maintain a fairly constant and uniform temperature profile along the gage length of the fiber, consistently maintain the same thermal profile between tests, provide a way to accurately measure the real-time temperature of the fiber area, and provide easy access to the fiber channel to allow loading of mounted fiber samples. A design taking into account all of these requirements is shown in Figure 2. This design is for fiber gage lengths of 10mm and the heater thickness is only 9.77 mm to allow the grips clearance from the heater. The top and bottom of the heater are made from Oxygen-free high thermal conductivity (OFHC) copper. The fiber channel is 1.016 mm (40 mil) in diameter. There are guide posts on opposite diagonals to allow the top and bottom to consistently be closed without damaging the fiber. Diagonally symmetric thermocouples are inserted close to the channel center to allow near direct measurement of the channel center. Cartridge heaters are located in the top and bottom halves of the heater. Calibration was achieved by using a butt-welded small diameter wire thermocouple placed in the fiber channel and conducting numerous heating experiments while measuring both the wire thermocouple and thermocouples inside the single fiber heater. The wire thermocouple was placed on an XYZ translation stage to allow precise movement of the thermocouple junction and to determine the thermal profile along the fiber channel. From room temperature, the center of the heater channel reaches 150 °C in 200 seconds. In the two dimensions of the diameter of the channel, the change in temperature from the center to the edge was less than 1 °C for all temperatures. Along the gage length, the change in temperature in the channel from the center to either side of the heater was less than 5 °C at the highest temperature of 150°C. For low strain-rate (10^{-3} s^{-1}) tensile tests, which last several minutes, protocols were developed using the same calibration method to rapidly heat and then hold the channel at temperature ±1 °C by varying the voltage applied to the cartridge heaters. The Heater bottom is mounted on an XYZ translation stage to allow centering of the gripped fiber in the channel, spacing adjustments between grip ends, and raising and lowering for fiber mounting. A stereo optical microscope was used to align and center the fibers in the heating channel.

Custom Grips: Grips were designed using the direct gripping method with polycarbonate tabs as the contacting material [7-10]. The grip design was modified to allow the polycarbonate tabs to extend to the edge of the grip to minimize the gage length outside the heating channel. The polycarbonate was shaped into a "T" to minimize movement of the tabs during tensile testing and the gage length can now be measured from grip-edge to grip-edge.. The grip bottoms are depicted in figure 1. The top and bottom of the heater are made from 303 stainless steel and are pressed together using two 0-80 screws with diagonally placed guide posts to allow for consistent alignment of the polycarbonate tabs and to apply uniform pressure across the gripped portion of the fiber. A precise amount of force is required to properly hold the fiber during tensile tests while being low enough to not induce failure at the fiber-grip interface at the edge of the grip. This force was determined by conducting a series of tensile experiments on single fibers and using a HIOS CL-2000 torque screwdriver to vary the torque placed on the 0-80 screws.

Quasi-Static and Intermediate Strain-rate Experiments: A Bose Electroforce 3100 was used to conduct uniaxial tensile experiments on UHMWPE single fibers at strain-rates of 10^{-3}, 10^{-2}, 10^{-1}, and 10^{0} s^{-1}. A thermal standoff was placed between the grip and the load sensor to prevent thermal effects on the force values. Fibers were heated to the desired temperature and then held within ±1 °C for the duration of the test. After the test, the heater top was removed to allow observation of fiber length protruding from each fiber-grip interface. If both grips presented fiber the event was recorded as a successful failure in the gage length. Slack was determined by comparing the start of the displacement and load curves and added to gage length for calculations.

Dynamic Strain-rate Experiments: A fiber-Split-Hopkinson Tension Bar was used to conduct uniaxial tensile experiments on UHMWPE single fibers at and average strain-rate of 550 s^{-1}. An optical setup was used to measure displacement and a dynamic load sensor was used to measure force [10]. A thermal standoff was also used to prevent thermal effects from affecting the force values. Figure 3 shows the high strain-rate setup. For stress-strain calculations at these high strain-rates, the time delay between the displacement and load curves must take into account the time required for the impact wave to travel through the thermal standoff. An impact hammer with aluminum striker was used to measure the time between impacts at the grip the load sensor. The delay was determined to be 52.3 microseconds which translated the start of the force curve to coincide with the start of displacement curve. Post-test recording was conducted consistent with the lower strain-rate experiments.

RESULTS AND DISCUSSION

Breaks in Gage Length: The custom grips performed successfully across all temperatures and strain-rates. A total of 251 tensile experiments were completed in this study spanning 55 different temperature-strain-rate combinations. Of the 251 tests, only six had failures at the fiber-grip interface. 66 fibers did not mechanically fail (non-failures) and were strained to the machine maximum (25%).The numbers of fibers pulled by strain-rate and temperature are summarized in table 1. The highlighted region indicates the temperature-strain-rate combinations where the fibers begin to have non-failures. The number of fibers pulled by strain-rate and the number of breaks at the grip interface and the comparison to Sanborn et al. are summarized in table 2. Four of the six interface failures occur at the high strain-rate and suggests that there is a strain-rate threshold where the success rate for the direct gripping method begins to decrease. Due to the high success rates seen in this study, it is difficult to draw further conclusions but this does support the findings of Sanborn et al. regarding this phenomenon. The six fibers that failed at the fiber-grip interface occurred between 20 °C and 65 °C. Five of the six interface failures have breaking strengths above the average for the samples in that temperature-strain-rate. The last one of the six was at 10^{-1} and 35 °C and was measured to have an ultimate tensile strength of 3.36 GPa while the average for that group was 3.4 ± .16 GPa. This sample is only 1.5% below the average strength while being well within the standard deviation for the rest of the group. Overall, the grips performed well and have shown a drastic improvement in rate of success over previously reported grips at high strain-rates.

The non-failures are temperature and strain-rate dependent beginning at 75 °C for 10^{-3} s^{-1}, 100 °C for 10^{-2} s^{-1}, 130 °C for 10^{-3} s^{-1}, 148 °C for 10^{-0} s-1, and are not observed for 550 s^{-1}. These regions indicate areas where the conditions exist for a near steady-state of thermally-activated chain motion (temperature) and time (strain-rate). Additionally, a qualitative estimate can be made from the step-shape of the non-failure regions in table 1that for similar mechanical response an increase in temperature of approximately 25°C to 30 °C is equivalent to raising the strain-rate by one decade.

Strain-to-Failure: Strain-to-failure is another metric for the performance of the custom grips. ASTM C1557-03 (2008) requires strains to be compliance corrected using plots of the displacement to failure, force at failure, gage length and cross sectional area of the fiber to determine the instrument compliance [11]. This method assumes a brittle fiber that has a linear-elastic stress-strain response until failure. The method is not ideal for viscoelastic materials such as UHMWPE fibers which behave non-linearly due to the presence of viscoelastic creep that increases as the fibers are heated, strained at lower strain-rates, or both. Determination of the linear portion of the stress-strain curve for Young's Modulus calculations is also challenging under these conditions [10]. Additionally, necking is observed for fibers starting at 50 °C for 10^{-3} s^{-1}, 50 °C for 10^{-2} s^{-1}, 85 °C for 10^{-3} s^{-1}, 115 °C for 10^{-0} s-1, but does not appear for 550 s^{-1}. For conditions where necking is present, the ultimate tensile strength (UTS) has a higher value than the failure stress and this is not accounted for in the standard. Considering these challenges to calculating compliance for UHMWPE single fibers, the best linear fit for compliance of the Bose Electroforce 3100 came from the 20°C 10^{-3} data where necking was absent. The compliance should not change significantly between single fiber experiments and this value of compliance was used to calculate corrected strain-to-failures for all temperatures and strain-rates using this instrument. Similarly, the best linear fit for the compliance of the fiber Split-Hopkinson Tension Bar was using the data for 50 °C and all strain-to failures were corrected with this value of compliance. Table 3 lists the average uncorrected strain-to-failure of the fibers at the temperatures and strain-rates and table 4 lists the average corrected strain-to-failure. Both the uncorrected and corrected values at 20 °C show lower strains-to-failure averages for 10 mm gage length samples at each strain-rate compared to the values of Sanborn et al. and the comparison is shown in table 5. The corrected values agree with the manufacturer's values for strain-to-failure of 3 to 4% for similar fibers [12]. These comparisons at room temperature indicate the grips are performing well and that the strain-to-failure values at higher temperatures are valid.

The data also quantitatively supports the qualitative estimate for the equivalence of approximately 25°C to 30 °C to one decade of strain-rate. The average strain-to-failure values in the quasi-static strain-rates have similar values when shifted relative to the non-failure boundary. For example, the average corrected strain-to-failures for the lowest three strain-rates are in the approximately 13% at 10 °C to 15°C below the boundary, approximately7% at 25 °C to 30°C below the boundary, and in the high 4% range at three temperature-zones below the boundary (40 °C to 45 °C).

The 550 s^{-1} corrected average strain-to-failure did not change significantly as temperature increase. At this strain-rate, the thermally-induced mobility of the chains is negligible in comparison to the time scale the strain-to failure remained around 3% for all temperatures excluding the 148 °C experiments which are just slightly lower. This behavior is observed in the quasi-static regime at 65 °C to 75 °C below the non-failure boundary. The strain-to –failure is approximately 3.15% in the temperature range between 20 °C to 75 °C at 10^{0}, 20 °C to 50 °C at 10^{-1}, and 20 °C to 30 °C at 10^{-2}. Lower experimental temperatures are needed to confirm this behavior at 10^{-3}. The data provides insight into the molecular dynamics as a function of temperature and strain-rate and supports shows promise to support time-temperature-superposition models when shifted relative to the non-failure boundary.

CONCLUSIONS

Dyneema SK76 UHMWPE single fibers with 10 mm gage lengths were successfully gripped and pulled in uniaxial tension tests over 5 decades of strain-rate and eleven temperatures from room temperature to the melting temperature using a new single fiber heater and custom grips. The new grips demonstrated a high rate of success across all strain-rates and showed lower average strain-to-failure values at room temperature compared to previous reports [3, 10]. Due to the successful performance of the grips, a high level of confidence is given to the observed changes in mechanical properties from the effects of elevated temperatures using the single fiber heater. The stress strain curves indicate a change from viscoelastic "brittle" to ductile response as temperature increases for a given strain-rate. A necking of the fibers begins at 50 °C for 10^{-3} s^{-1}, 50 °C for 10^{-2} s^{-1}, 85 °C for 10^{-3} s^{-1}, 115 °C for 10^{-0} $s^{-}1$, and is absent for 550 s^{-1}.The strain-to-failure decreases with increasing strain-rate and increases with increasing temperature. Fibers can be strained to 25% without mechanically failing beginning at 75 °C for 10^{-3} s^{-1}, 100 °C for 10^{-2} s^{-1}, 130 °C for 10^{-3} s^{-1}, 148 °C for 10^{-0} $s^{-}1$, and fail regardless of temperature at 550 s^{-1}. This non-failure boundary provides an estimate that for similar strain-to-failure values, increasing the temperature by 25 °C to 30 °C is equivalent to decreasing the strain-rate by a decade. This estimation remains valid in the quasi-static regime until the non-failure boundary reaches the melting temperature which occurs at the 10^{0} s^{-1} intermediate strain-rate. The 550 s^{-1} maintained a nearly constant strain-to-failure of 3% up until the melting temperature. This behavior was observed in the quasi-static regime at 65 °C to 75 °C below the respective non-failure boundary and suggests time-temperature superposition models can be applied when shifted relative to the non-failure boundary.

FUTURE WORK

Conducting tests at additional temperatures and using a quasi-static UTM that could strain the high temperature fibers to failure might help elucidate the non-failure boundary and allow testing of time-temperature superposition models. Additionally, investigating the strength of UHMWPE fibers as a function of temperature and strain rate will be a topic of research. The difficulty in calculating compliances according to ASTM C155-03 (2008) for instruments when using viscoelastic materials indicates a need for the development of a testing standard for polymeric single fibers. Conducting additional tensile tests would help to better fit the compliance and reduce error bars in the data. Lastly, UHMWPE has a relatively low melting temperature and scaling the single fiber heater and the grips to be able to investigate the temperature and strain-rate effects of other ballistic single fibers materials would provide a comparison between material types.

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TABLES

Table 1. Number of fiber samples tested at different temperature and strain-rate combinations, with highlighted areas indicating regions where the fibers are strained to 25% without failing

	Temperature [°C]											
Strain-rate [s^{-1}]	**20**	**35**	**50**	**65**	**75**	**85**	**100**	**115**	**130**	**145**	**148**	**Total**
10^{-3}	4 (1)	5	5	5	1/4*	5	5	5	5	5	4	**54**
10^{-2}	5	5	5	3	3	4	2/2*	4	5	5	5	**48**
10^{-1}	5	4 (1)	4	4	4	4	4	3	5	4	3	**45**
10^{0}	5	4	4	5	5	4	5	4	2	3	3/2	**46**
550	5 (1)	5	4 (1)	3 (2)	6	6	5	5	6	4	5	**58**
Total	**26**	**24**	**23**	**22**	**23**	**23**	**23**	**21**	**23**	**21**	**22**	**251**

*Number of failures in gage length (number of failures at the fiber grip interface)

**Number of failures/Number of non-failures

Table 2. Success rate of the grips at different strain-rates

Strain-rate [s^{-1}]	**Number of Fiber Samples**	**Breaks at Grip Interface**	**% Breaks in Gage Length**	**% Breaks in Gage Length by Sanborn et al.**
10^{-3}	54	1	98.15	90
10^{-2}	48	0	100.00	-
10^{-1}	45	1	97.78	-
10^{0}	46	0	100.00	91
550	66	4	93.94	-
775	**-**	**-**	**-**	**42**
Total (Excluding non-failures)	**185**	**6**	**96.76**	**-**
Total (Including non-failures)	**251**	**6**	**97.61**	**-**

Table 3. Uncorrected Strain-to-failure Averages

	Temperature [°C]										
Strain-rate [s^{-1}]	**20**	**35**	**50**	**65**	**75**	**85**	**100**	**115**	**130**	**145**	**148**
10^{-3}	4.49±.16	5.01±.56	7.20±.69	13.74±5.75	24.87±-	-	-	-	-	-	-
10^{-2}	4.15±.27	4.15±.32	4.75±.20	5.43±.51	7.84±.54	14.40±3.03	20.75±5.90	-	-	-	-
10^{-1}	4.29±.07	4.30±.15	4.02±.29	4.25±.30	4.71±.07	5.66±.43	7.92±.87	14.09±4.86	-	-	-
10^{0}	4.25±.18	4.05±.14	4.16±.15	4.27±.17	4.21±.18	4.26±.17	4.53±.15	4.77±.29	4.66±0	4.42±.86	3.99±.66
550	3.86±.79	4.30±.54	3.76±.44	3.89±.15	3.66±.46	3.74±.51	3.80±.52	3.87±.80	3.48±.46	3.64±.59	2.79±.26

Table 4. Corrected Strain-to-failure Averages

	Temperature [°C]										
Strain-rate [s^{-1}]	**20**	**35**	**50**	**65**	**75**	**85**	**100**	**115**	**130**	**145**	**148**
10^{-3}	3.52±.17	4.24±.48	6.57±.74	13.24±5.75	24.55±-	-	-	-	-	-	-
10^{-2}	3.23±.29	3.14±.39	4.00±.42	4.92±.47	7.24±.48	13.98±2.94	20.23±5.93	-	-	-	-
10^{-1}	3.20±.25	3.18±.13	3.22±.30	3.36±.23	3.84±.02	4.88±.51	7.34±.87	13.70±4.86	-	-	-
10^{0}	3.14±.25	3.11±.15	3.12±.19	3.29±.19	3.25±.12	3.41±.18	3.70±.18	4.13±.31	4.19±.88	4.13±.87	3.73±.62
550	2.97±.76	3.32±.54	2.87±.43	2.88±.12	2.80±.37	2.91±.50	3.03±.47	3.16±.76	2.85±.43	3.12±.60	2.67±.28

Table 5. Comparison of Uncorrected and Corrected Average Strain-to-failure Values for 10 mm Samples at 20 °C

Strain-rate [s^{-1}]	Uncorrected Strain-to-failure [%]	Uncorrected Strain-to-failure Sanborn et al. [%]	Corrected Strain-to-failure [%]	Corrected Strain-to-failure Sanborn et al. [%]
10^{-3}	4.49±.16	5.53±.87	3.52±.17	3.93±.96
10^{-2}	4.15±.27	-	3.23±.29	-
10^{-1}	4.29±.07	-	3.20±.25	-
10^{0}	4.25±.18	4.83±.72	3.14±.25	3.35±.25
550	3.86±.79	-	2.97±.76	-
775	-	3.71±.26	-	3.00±.24

FIGURE CAPTIONS

Fig. 1 Single fiber sample placed on the open grips for a high strain-rate tensile experiment before the grip tops are placed and the second half of the mounting template is cut away

Fig. 2 Open single fiber heater showing the location of the fiber channel, thermocouples, cartridge heaters, and guide posts

Fig. 3 Fiber-Split-Hopkinson Tension Bar setup showing a loaded fiber before the fiber mounting template is cut away and before the heater top is applied

Fig. 4 Three representative types of stress-strains curve in this study: (a) Stress vs Corrected Strain at 10^{-3} s^{-1} and 20 °C, showing a viscoelastic “brittle” failure. UTS (red) occur at the same point; (b) Stress vs Corrected Strain at 10^{-3} s^{-1} and 50 °C, showing a UTS (red), necking region, and failure; (c) Stress vs Corrected Strain at 10^{-3} s^{-1} and 65 °C, showing a UTS (red), long necking region, and viscoelastic creep after 25% strain