Proceedings of the SEM Annual Conference
June 7-10, 2010 Indianapolis, Indiana USA
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Effects of fiber gripping methods on single fiber tensile test using Kolsky bar[1]

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ABSTRACT

Preliminary data for testing fibers at high strain rates using the Kolsky bar test by Ming Cheng et al. [1] indicate minimal effect of strain rate on the tensile stress-strain behavior of poly (p-phenylene terephathalamide) fibers. However, technical issues associated with specimen preparation appear to limit the number of samples that can be tested in a reasonable time. In addition, under the Kolsky bar testing condition fiber fracture may occur at the interface between the fiber and adhesive rather than in the gage section. In this study, the authors investigate the effects of different gripping methods in order to establish a reliable, reproducible, and accurate Kolsky bar test methodology for single fiber tensile testing. As many single fiber tests have been carried out associated with ballistic research, we compare the Kolsky bar test results with the quasi-static test results to determine the tensile behavior over a wide range of strain rates.

1. INTRODUCTION

The desire for lightweight soft body armor (SBA) that enhances the survivability and comfort level of the first responder remains the development focus of new ballistic fibers or nanotechnology enhanced fiber technologies whose ballistic fiber responses and long-term durability to various environmental conditions are unknown. Furthermore, the lack of reliable deformation data at rates approximating ballistic impact speeds continues to vex

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T. Proulx (ed.), *Dynamic Behavior of Materials, Volume 1*, Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-1-4419-8228-5_19, © The Society for Experimental Mechanics, Inc. 2011

committees whose primary role is to develop certification protocols that ensure the reliability of SBAs over the projected lifespan of the product.

Within this framework, the Kolsky bar test (see Figure 1) has emerged as a promising measurement technique for providing the critical data needed to accurately assess material properties in ballistic performance that may result from different environmental exposure conditions. Compared with the conventional Kolsky bar, the setup shown in Figure 1 was designed for conducting single fiber tensile tests at high strain rates [1, 2]. The incident stress pulse generation method and the incident bar are the same as a conventional Kolsky bar, but a sensitive quartz transducer is used to detect the transmitted force signal for stress evaluation in the specimen. To carry out a successful test, the gage length of the fiber specimen is limited to a few millimeters to ensure a state of dynamic force equilibrium in the fiber specimen during an experiment.

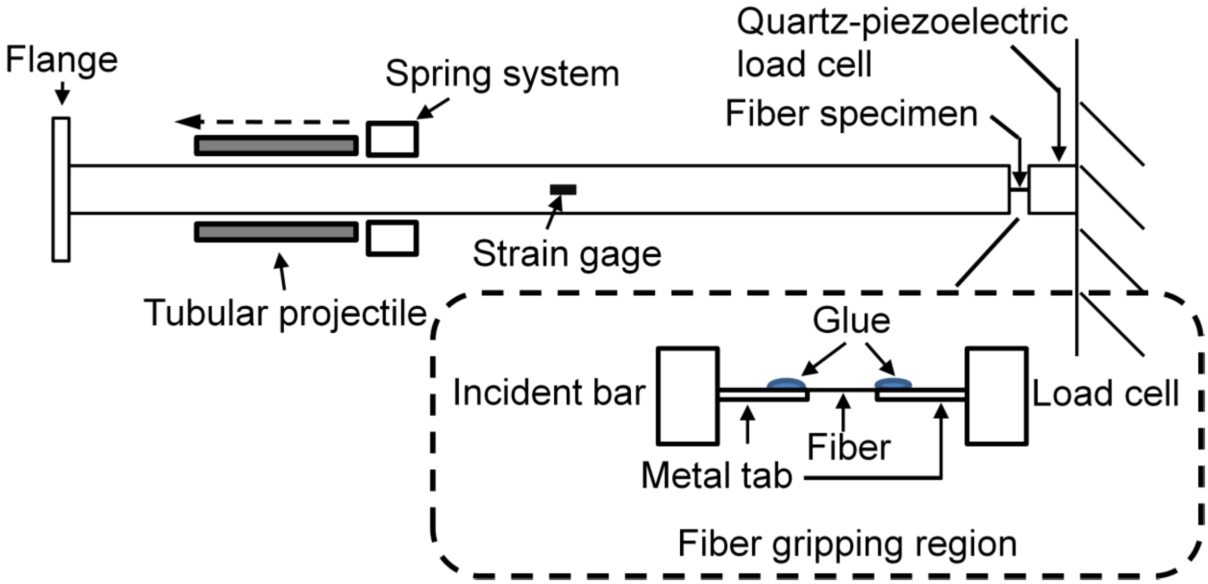


Figure 1. Schematic of the experimental setup for single fiber tensile tests using Kolsky bar.

For ballistic fibers with nominal fiber diameters of 10 µm to 15 µm, the 2 mm length used in the research has an aspect ratio of approximately 133 to 200. Until 1998, the recommended minimum recommended aspect ratio via ASTM D3379-75 [3] for static single fiber testing was 2000. This was done to minimize the amount of tested gage length perturbed by the gripping process. ASTM D3379-75 was superseded by ASTM C1557-03 in part because of the technical inaccuracies associated with the use of the average of the cross-sectional area of several fibers for the calculation of individual fiber strengths. ASTM C1557-03 allows testing of shorter lengths as long as the gage length is reported [4].

Implicit in this protocol change is the belief that the perturbed stress fields in the gripping regions are constant in the standard testing configuration. However, a problem experienced by many researchers in preparing single fiber test samples with small gage lengths is the wicking of glue that has a moderate or low viscosity along the fiber length that effectively seals flaws on the fiber surface and enhances fiber strength [5], since the effective gage length is now much shorter and essentially unknown. To avoid the influence of the glue on the test results, and to be able to conduct rapid assessment of single fiber properties such as tensile strength, modulus and ultimate strain, a direct gripping method is being evaluated for the small gage length test. In this study, single fiber tensile tests under quasi-static conditions are carried out to investigate the feasibility of the new fiber gripping device in the Kolsky bar test.

2. ISSUES ON SINGLE FIBER TEST

When measuring the fiber tensile strength in the single fiber tensile test, there is a certain probability that the fiber fails within the adhesives or tab. To address the issue of failing in the gripping area, Phoenix [6] proposed a model that depends on the fiber Weibull parameters and the fiber stress distribution within the load transfer zone. Assuming perfect alignment and the presence of a shear stress that arises between the matrix that holds the fibers in place and the fiber surface when an external force is applied, several cases are theorized to exist. In the case 1, the fiber tensile stress varies linearly within the whole clamping region. For the case 2, the stress also varies linearly but requires only a portion of the matrix to completely transfer the stress to the fiber. Therefore the difference between the case 1 and 2 is mainly the length of fiber section needed to completely transfer the stress from the matrix to the fiber embedded in the clamp matrix. The case 3 is the ideal situation which has no shear stress in the clamp area (i.e., the stress transfer is instantaneous). This last case is almost impossible to achieve with conventional test procedure. One possible approach may be to directly clamp the fiber between two metallic plates. However, this has the potential to perturb the stress in the gage length. Numerical analyses indicate that the rate of fiber failure within the clamp area (outside of gage length) increases rapidly with decreasing gage length, which may be problematic for testing in reality. [6]

On the other hand, tensile test results of fibers with high strength and modulus are often scattered due to the presence of flaws introduced during processing and handling. Assuming stress concentrations near the end of the fiber close to the grip (clamp), fibers are likely to fail due to the testing method rather than the flaw population alone. Stoner et al. [7] and Newell et al.[8] have suggested a model to account for failures caused by end effects .

In this model the survival probability of the fiber is considered to be the product of the fiber intrinsic flaws (S_f) and the end effects (S_e) (see equation 1). The probability for survival (S_t) of the fiber associated with flaws (S_f) and end effect (S_e) can be expressed in equations 2 and 3, respectively.

$$S_t = S_f \cdot S_e \qquad (1)$$

$$S_f = exp\left(-L\left(\frac{\sigma}{\gamma 1}\right)^{\beta 1}\right) \qquad (2)$$

$$S_e = exp\left(-\left(\frac{\sigma}{\gamma 2}\right)^{\beta 2}\right) \qquad (3)$$

L is the fiber length being tested, and β and γ are the Weibull parameters. Fitting the fiber strengths to the combined Weibull model in equation 1 results in an estimation of the two failure mechanisms that dominate fiber fracture during single fiber tensile test [8]. To obtain the optimized parameters for the model, statistical analyses were performed on the fiber strength distribution for several fiber lengths using the maximum likelihood estimation procedure. Using the same type of fibers, test results are shown to demonstrate the effect of fiber length and gripping method achieved from the quasi-static test (Strain rate, 0.00056 s^{-1}). These data are compared with the failure behavior predicted from the above model.

3. EXPERIMENTAL PROCEDURE

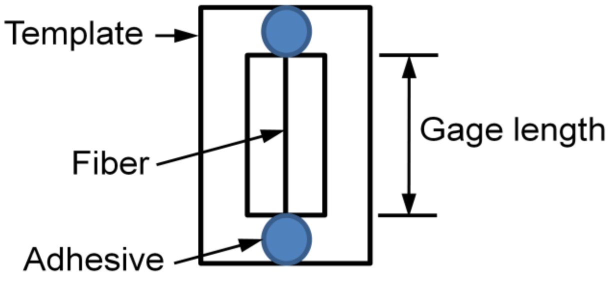
3.1 Quasi-static loading

For the tensile test under quasi-static loading, poly (p-phenylene terephthalamide) fibers (PPT) were used. Two types of fiber gripping techniques were introduced for the quasi-static tensile tests. For the test using grip 1 as shown in Figure 2 (a), the specimens and loading procedure were prepared based on ASTM C1577-03. A brief procedure for preparing single fiber tensile test specimens using grip 1 is as follows: after measuring fiber diameters on the optical microscope, individual fibers were temporarily attached to paper templates with double-sided tape. Small strips of silver reflective tape were applied to the template at the top and bottom of the section with the tabs of each fiber sample. The reflective tape allows direct elongation measurements to be made by a laser extensometer during tensile testing, so calculating the actual strain by determining the system compliance is not needed. Finally the fiber was adhered to the paper template using epoxy which was cured at room temperature for at least 48 h before the tensile test was performed. Maintaining an identical shear stress level for multiple specimens using adhesives is somewhat difficult due to various parameters such as air pockets and irregular mixing of two component adhesives, etc. For tensile testing at high strain rates, the influence from these issues may be more remarkable than for the quasi-static test due to the inconsistent internal structure of material for rapid response.

For the mechanical grip procedure (grip 2) shown in Figure 2 (b), a single PPT fiber is directly clamped between two blocks on both ends and the clamping force of the blocks is controlled by tightening a spring. A unique aspect of this test set up is measuring fiber diameter using a vibration method instead of an optical microscope.

The gage lengths of the fiber specimens on both gripping methods were 2 mm and 60 mm to investigate the effect of the fiber length on the tensile properties under the constant strain rate 0.00056 s^{-1}. Three different loading devices were used for the tensile tests due to the limitation of measurable sample size. The tensile test using grip 1 with gage length 2 mm was performed by an electro magnet driven actuator and the uncertainty of this test in load cell is 0.38 %. The tensile test using grip 1 with gage length 60 mm was performed by a screw driven machine and its uncertainty of the test in load cell is reported in elsewhere [4]. The tests using grip 2 with gage length 2 mm and 60 mm were performed by a commercial single fiber testing machine and its uncertainty in the load cell is 0.1 %.

(a) Fiber grip with adhesives (grip 1)



(b) Mechanical grip (grip 2)

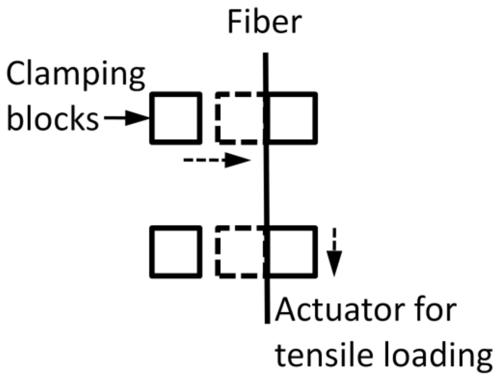


Figure 2. Schematic and closed up of the mechanical grips for quasi-static loading

3.2 High strain rate loading

In order to determine the tensile response of the PPT fiber under high strain rate, a Kolsky bar was used in this study. Owing to the small size of the specimen, the Kolsky bar as proposed by Ming Cheng et al [1]. has a load cell instead of a transmission bar to detect the failure load of a single fiber. As mentioned earlier, this study focuses on developing new fiber gripping device for the high strain rate test using the Kolsky bar. Two gripping methods tested in quasi-static test are introduced in this test. To accommodate the small bar diameter of the Kolsky bar, several modifications were performed, but the fiber gripping mechanism was the same. Detailed information of the Kolksy bar grips will be shown in the presentation.

4. RESULTS AND DISCUSSION

Figure 3 shows the survivability data for 2 mm and 60 mm gage length fibers tested by the two gripping methods. These data are further compared with the expected survivability data predicted by equation 1. The strength data were ordered from strongest to weakest based on its ranking, n, which can be expressed by (n-0.5)/total number of data points. The probability of survival of the PPT fibers was determined by plotting the fiber tensile strengths to each model. The Weibull parameters used in the model are those obtained by Newell and Sagendorf ($\beta 1=4.61$, $\gamma 1=3.44$, $\beta 2=5.23$, $\gamma 2=1.59$) [8] since the fibers used in both studies are PPT fibers and the gage lengths are comparable. For the experimental data in this report, the predicted combined probability model (equation 1, red curve) does not agree with any of the data. The reason of this discrepancy between the model and current experimental data is not known. However, differences in sample preparation and/or differences in the testing conditions and/or batch to batch differences between the PPT fibers are being investigated.

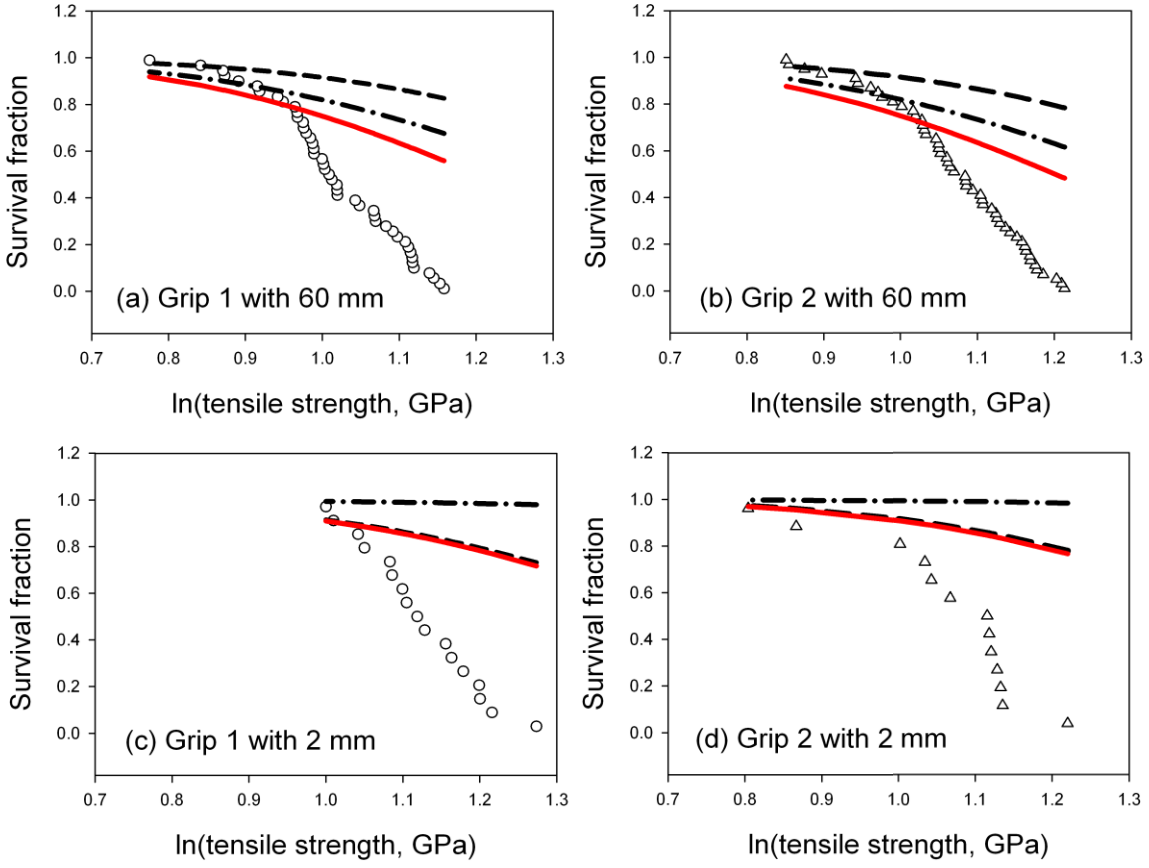


Figure 3. Survival probability plots of the fiber strengths using grip 1 and 2 with 60 mm and 2 mm gage lengths (Strain rate, 0.00056 s^{-1}). Symbols indicate the fiber strength values obtained by each test condition. Solid lines represent the survival probability of the fibers based on the total effect model, and dashed lines (– –) and dashed dot lines (–•–) represent the contribution to the survival probability based on the end effect and flaw effect, respectively.

It is worth noting that the predicted end effect and flaw effect contributions invert as the gage length changes. Although the data generated in this report do not agree, a significant change in the overall failure behavior is observed as the gage length is changed. A more detailed discussion of these results is expected with continued research.

5. CONCLUSIONS

The fiber tensile tests with multiple fiber lengths and gripping methods have been carried out under the quasi-static loading condition to assess the feasibility of gripping for high strain rate tests using the Kolsky bar. Since fiber lengths for the Kolsky bar test that have been reported are only a few millimeters, the influences of the testing conditions (especially fiber gripping) and fiber flaws on the fiber strength of samples with small gage lengths are important in determining true values under high strain loading. Preliminary results show the survival probability of the fibers with the 60 mm gage length is different from the case of fibers that had the 2 mm gage length. These differences are discussed in terms of the influence of the intrinsic fiber flaw and the impact of gripping on the fiber strength that results with changes in the fiber gage length. Additional data measured in various fiber gage lengths will clarify the effects of these two factors (i.e., intrinsic flaw and gripping method).

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