SPECIFIC FEATURES OF THE STRENGTH DISTRIBUTION STATISTICS OF HIGH-STRENGTH POLYMERIC MATERIALS

Boiko Yu.M.[1], Marikhin V.A.[1], Myasnikova L.P.[1], Moskalyuk O.A.[2]
[1]*Ioffe Physical-Technical Institute, St. Petersburg, Russia, E-mail: yuri.boiko@mail.ioffe.ru*
[2]*St-Petersburg State University of Industrial Technologies and Design, St. Petersburg, Russia*

Commercially available and lab-scale ultra-high-molecular-weight polyethylene (UHMWPE) gel-spun oriented fibres are promising materials of various applications such as armoured protection, pull ropes, cables, nets, sport articles, etc [1,2]. This is due to their high mechanical strength σ = 2-6 GPa that is similar to that of the high-strength inorganic materials such as carbon, glass and quartz fibres (σ = 6-7 GPa) [3,4].

Traditionally, five identical samples are tested to estimate an average value of σ (σ_{av}). However, such rather small number of measurements seems not to be sufficient to reliably estimate σ_{av} for the high-strength materials. Actually, these materials are brittle or quasi-brittle. For this reason, their fracture may occur occasionally by a rapid main crack propagation from the surface defects (e.g., kink bands) across the sample bulk [1,2], thus resulting in the marked increase in the data scatter. Therefore, a proper estimation of σ_{av} of such materials requires much more (some tens) fracture tests. Besides, the fracture mechanism should be taken into consideration.

In order to overcome this problem, the Weibull model has been proposed [5] and successfully used [3,4]. In Weibull statistics, the cumulative probability function $P(\sigma)$ describing the probability of failure of identical samples at or below stress σ is given by

$$P(\sigma) = 1 - \exp\,[-(\sigma / \sigma_0)^m] \qquad (1),$$

where m is the so-called Weibull modulus which is only a measure of dispersion in the data, and σ_0 is the scale parameter (corresponds to σ_{av}). In order to carry out the Weibull analysis, a set of test results should be converted into an experimental probability distribution by ordering them from the lowest strength to highest ones. The j-th result in the set of n samples is assigned a cumulative probability of failure (P_j). To calculate these probabilities, simple relationships P_j = f (j, n), estimators, are used. One of the most correct of them is given [6] by

$$P_j = (j - 0.5) / n \qquad (2).$$

By rearranging and taking logarithm of both sides of Equation (1) twice and by replacing $P(\sigma)$ by P_j, the following Equation is obtained

$$\ln\ln[1 / (1 - P_j)] = m \cdot \ln\sigma - m \cdot \ln\sigma_0 \qquad (3).$$

Equation (3) represents a linear regression

$$y = a + bx \qquad (4),$$

where $y = \ln\ln[1 / (1 - P_j)]$, $b = m$, $x = \ln\sigma$, and $a = -m{\cdot}\ln\sigma_0$ is the intersect with the y axis (at x = 0). By estimating m as a slope of the curve $\ln\ln[1 / (1 - P_j)]$ = f ($\ln\sigma$) using a standard procedure of the linear regression analysis, one can further estimate the scale parameter σ_0 by solving Equations (5) and (6):

$$\ln\sigma_0 = -a / m \qquad (5)$$

$$\sigma_0 = \exp\,(-a / m) \qquad (6).$$

In Figure 1-a, the tensile strength shown in ascending order vs sample number for the oriented gel-spun single threads of ultra-high-molecular-weight polyethylene (UHMWPE) ultimately drawn to a very high draw ratio of 120 by using the multi-stage hot-zone drawing technique on a home-made device equipped with a pin heater [1]. Drawing was carried out in 5 stages by increasing the orienting stress and the drawing temperature in a step-wise manner. As is seen, the σ values are vary high, varying between 4 and 6 GPa. So, the scatter in the data seems to be rather broad. Therefore, the Weibull model seems to be appropriate for the analysis of the measured strength. The results of this analysis shown in Fig. 1-b reveal 2 slopes on the curve, indicating that the data scatter at low strengths (20% of the tested samples) is substantially smaller with respect to that at high strengths (80% of the tested samples). So, the Weibull analysis gives a deeper insight into the fracture mechanism showing that the low-strength samples are "equally weak". By contrast, the data description in the framework of the Gauss model seems to be unsatisfactory (see Fig 1-c).

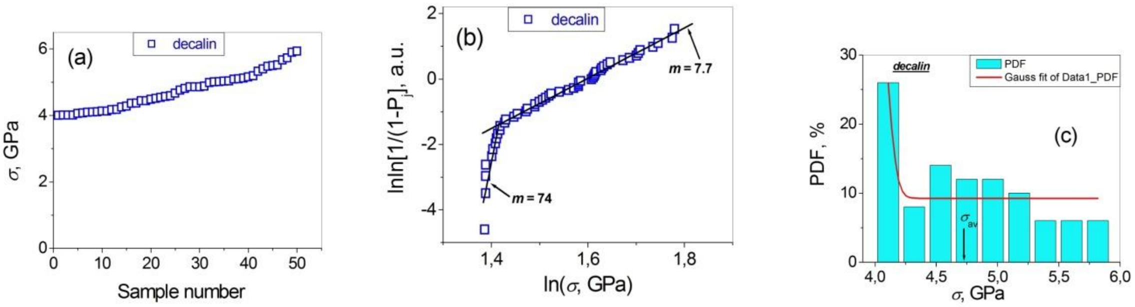

Figure 1 - (a) Tensile strength σ vs sample number shown in ascending order, (b) its Weibull plot, and (c) its Gauss plot (the probability density function, PDF, vs σ) for the oriented UHMWPE gel-spun single threads

If the above mechanism of fracture is true (the crucial role of a sudden accidental main crack propagation resulting in the premature fracture of the whole sample), the impact of this factor should be considerably reduced for the polyfilaments consisting of some tens, or even some hundreds of single fibers. In this case, a better presentation of the measured σ on a Gaussian plot is expected. Actually, the descriptions of the strength distribution for the quasi-brittle (strain at break $\varepsilon_b \approx 3\%$) oriented UHMWPE gel-spun polyfilaments consisting of 170 single fibres (see Fig. 2-a) are better both in the frameworks of the Weibull (see Fig. 2-b) and Gauss model (see Fig. 2-c) with respect to those for the single threads (see Fig. 1).

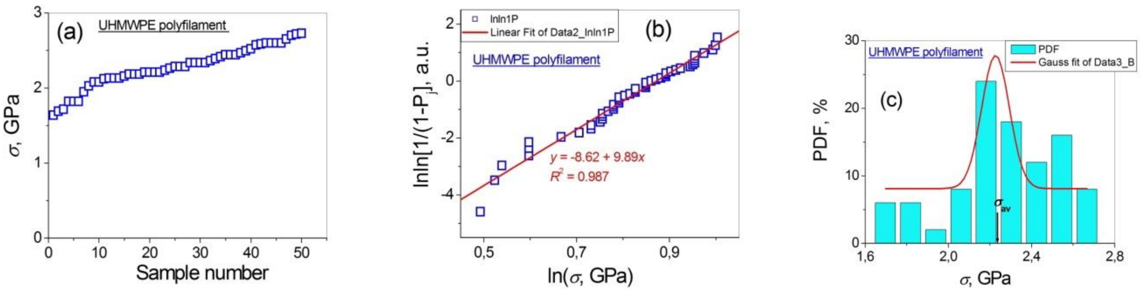

Figure 2 - (a) Tensile strength vs sample number shown in ascending order, (b) its Weibull plot, and (c) its Gauss plot for the oriented UHMWPE gel-spun polyfilaments

Basing on the above results, further improvements in the strength distribution of the high-strength polymeric materials can be received for the polyfilaments that are less brittle, i.e. by introducing a viscous deformation contribution. For this purpose, the polyfilaments of polyamide-6 (PA-6) consisting of 200 single filaments ($\varepsilon_b \approx 16\%$) has been chosen, and strength of 50 samples was measured (see Fig. 3-a). The results of the analysis have shown that, on one hand, the data can still be described within the framework of the Weibull model (see Fig. 3-b), despite this material is more ductile than the UHMWPE single threads and polyfilaments. On the other hand, as was expected, the measured strength can be described satisfactorily with a well-defined bell-shaped curve which is characteristic of the normal Gaussian distribution (see Figs. 3-c). So, to put differently, the strength distribution of the PA-6 polyfilaments demonstrate the dualism in the statistics behaviours. The latter consists in the possibility to describe the experimental results in the frameworks both of the Gaussian (by assuming that the defects are distributed uniformly among the polyfilaments of the sample) and Weibull statistics (since the material mechanical behaviour turned out to be intermediate between those of brittle and viscoelastic materials).

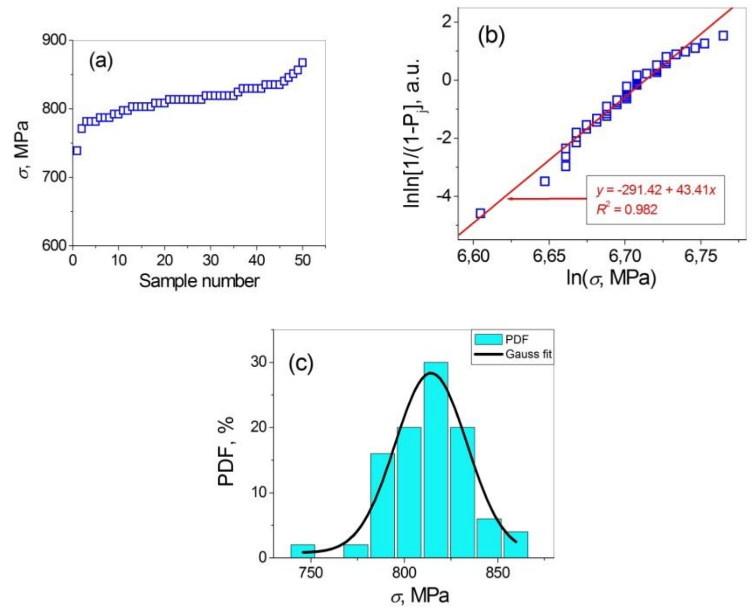

Figure 3 - (a) Tensile strength vs sample number shown in ascending order, (b) its Weibull plot, and (c) its Gauss plot for the oriented PA-6 polyfilaments

In conclusion, the distribution of the tensile strength of the high-strength UHMWPE gel-cast highly oriented single film threads and poly-filaments has been investigated by using the Weibull and Gauss statistical models on the basis of the large number of mechanical measurements (50 samples in a series). It has been shown that the tensile strength distribution of the oriented UHMWPE polyfilaments can be described both in the frameworks of the normal and of the standard Weibull distribution function while that of the ultimately drawn oriented UHMWPE single film threads cannot be described in the framework of the Gauss model. This difference in the fracture behaviours of the single threads and polyfilaments is attributed to the crucial role of a sudden accidental main crack propagation in the single thread resulting in the premature fracture of the whole sample. It has been shown that the strength distribution of the PA-6 polyfilaments demonstrate the dualism in the statistics behaviours consisting in the possibility to describe the experimental results in the frameworks both of the Gaussian and Weibull statistics. Our investigations of various high-strength polymeric materials have shown that the most proper type of distribution, Weibull's or Gaussian, is completely different, on one hand, for mono- and polyfilament samples, and, on the other hand, for quasi-brittle and viscoelastic materials. The results of this work indicate that, prior to the analysis of a data set of mechanical measurements by employing a certain statistical model, the fracture character (brittle, viscoelastic, or viscous) should be considered.

This work was supported by the Russian Foundation for Basic Research, Grant Number 18-29-17023mk.

References

[1] Marikhin VA, Myasnikova LP (1996) Structural basis of high-strength high-modulus polymers. In: Fakirov S (ed) Oriented Polymer Materials. Huthig & Wepf Verlag-Zug, Heidelberg, pp. 38-98.

[2] Boiko YuM, Marikhin VA, Myasnikova LP, Moskalyuk OA, Radovanova EI (2017) J Mater Sci 52:1727–1735. https://doi.org/10.1007/s10853-016-0464-9.

[3] Tanaka F, Okabe T, Okuda H, Kinloch IA, Young RJ (2014) Composites Part A 57:88–94. https://doi.org/10.1016/jcompositesa.2013.11.007.

[4] Baikova LG, Pesina TI, Kireenko MF, Tikhonova LV, Kurkjian CR (2015) Tech Phys 60:869–872. https://doi.org/10.1134/S1063784215060031.

[5] Weibull W (1951) J Appl Mech 18:293–297.

[6] Sullivan JD, Lauzon PH (1986) J Mater Sci Lett 5:1245–1247. https://doi.org/10.1007/BF01729379.