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TENSILE PROPERTIES OF UHMWPE SINGLE YARN AT DIFFERENT STRAIN RATES

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Summary: *In this paper, details of the experimental work to characterise the tensile properties of a UHMWPE single yarn are presented. The yarn specimens were extracted from a plain woven fabric made of Spectra® 1000 fibres, and a gripping method which could prevent yarn slippage and ensure the failure occurs in the gauge section was employed. Tensile tests were conducted at three strain rates of* 3.3×10^{-5}*,* 3.3×10^{-3}*, and* $0.33\ s^{-1}$ *with the purpose of investigating the strain-rate effect on the tensile properties. It was found that the stress-strain behaviour of a single yarn had a decrimping region, a linear elastic region, a non-linear failure region, and a post-peak region at very low strain rates. As the strain rate increased, the yarn failed in a more brittle manner by exhibiting a sharp drop in stress after the peak. The tensile strength and Young's modulus increased with strain rate while the maximum strain and toughness decreased.*

1 INTRODUCTION

Ultra high molecular weight polyethylene (UHMWPE) fibres with excellent specific tensile strength and toughness are an ideal material for use in impact resistance where large deformation and high energy absorption are required. Typically, these fibres are either twisted or only grouped together into yarn and used in the form of woven fabric such as soft body armour. A longitudinal strain wave travelling at the speed of sound in the material is generated in the fabric yarns upon impact [1]. This wave stretches the yarns and causes them to be subjected to axial tension loading. The static tensile properties for the fibre are usually available from the manufacturer, however, these characteristics cannot be extrapolated and scaled up directly for a yarn consisting of many interlocked fibres. Moreover, the strain rates during impact events are far beyond the order of magnitude of strain rates in quasi-static conditions. Therefore, there is an increasing demand for characterising the tensile properties of individual yarn in detail, in order to correlate the yarn properties with impact resistance of fabric and numerically simulate the impact response of fabric.

The tensile properties of UHMWPE single fibre have been extensively studied over the last three decades. Smith and Lemstra [2] investigated the influence of draw ratio on the tensile properties of UHMWPE fibres, and they found the modulus depended linearly on the draw ratio while the tensile strength tended to approach an upper limit at high draw ratios. Schwartz et al. [3] examined the strain rate and gauge length effects on Spectra® 900 fibres; the results showed an increase in strength of 57% as the strain rate was increased over 2.5 decades, however, no gauge length effects over the range from 10 to 200 mm was observed. Hudspeth et al. [4] twisted the Dyneema® SK76 single fibres to varying levels of shear strain and then loaded them in both quasi-static and high-rate axial tension; it was found that the single fibres retained their native axial tensile strength up to at least a torsional strain level of 14% where upon further twisting the residual strength fell off in a linear fashion. Sanborn and Weerasooriya [5] tested the Dyneema® SK76 single fibres at strain rates of 0.001, 1, and 1000 s^{-1}, and their results showed a plateau in tensile strength was reached at an intermediate strain rate of 1 s^{-1}, and the tensile strength did not depend on the gauge length of the fibre. However, experimental work on the tensile properties of UHMWPE single yarn appears to be relatively scarce in the existing literature due to the difficulties involved in yarn gripping and fibre alignment. Kromm et al. [6] studied the influence of coupling between single fibres gathered in a bundle of Dyneema® SK75 fibres, it was observed that the tensile strengths obtained on single fibre were rather close to those obtained on fibre bundle while the measured Young's moduli showed a noticeable difference between the single fibre and bundle. The experimental work by Russell et al. [7] showed a different result that the tensile strength of Dyneema® SK76 single fibre exceed that of the yarn by 20%. Furthermore, they adopted two gripping techniques and the tensile strengths of single yarn determined from these two methods showed a significant difference. It appears therefore, that more work needs to be done to examine the properties of a single yarn and to interrogate the tensile testing techniques of these types of structures.

The primary objective of this study is to investigate the effect of strain rate on the tensile properties of single yarn at a range of low strain rates, as a part of the research on the material characterisation of UHMWPE single yarn and fabric for ballistic impact resistance. The tensile properties of single yarn made of Spectra® 1000 fibres were investigated at nominal strain rates of 3.3×10^{-5}, 3.3×10^{-3}, and 0.33 s^{-1}. The tensile properties in terms of tensile strength, maximum strain, Young's modulus, and toughness were measured and compared.

2 EXPERIMENTAL METHODOLOGY

2.1 MATERIALS USED AND SPECIMEN PREPARATION

The single yarn samples were extracted from a plain woven fabric made of Spectra® 1000 fibres supplied by JPS Composite Materials. Only the weft yarns were tested in this study. Each yarn has 120 fibres and a linear density of 650 denier (the mass in grams per 9000 metres). The bulk density of the material is 0.97 g/cm^3, so the cross-sectional area of the yarn is 0.074 mm^2 calculated by dividing its linear density by the bulk density. A gripping method, which was successfully used in literature [7; 8], was employed here to clamp single yarn samples. Both ends of the yarn specimen were sandwiched by thin aluminium tabs and glued to them using an ethyl cyanoacrylate adhesive, and a gauge length of 50 mm was left in the middle. This setup would reduce stress concentration and improve load transfer so as to avoid fibre crushing and prevent any slippage in the griping region. The yarn was handled with particular care to prevent any yarn twisting when adhering it to aluminium tabs, because it has been found that the tensile strength of fibres decreases significantly with increasing torsional strain [4; 9].

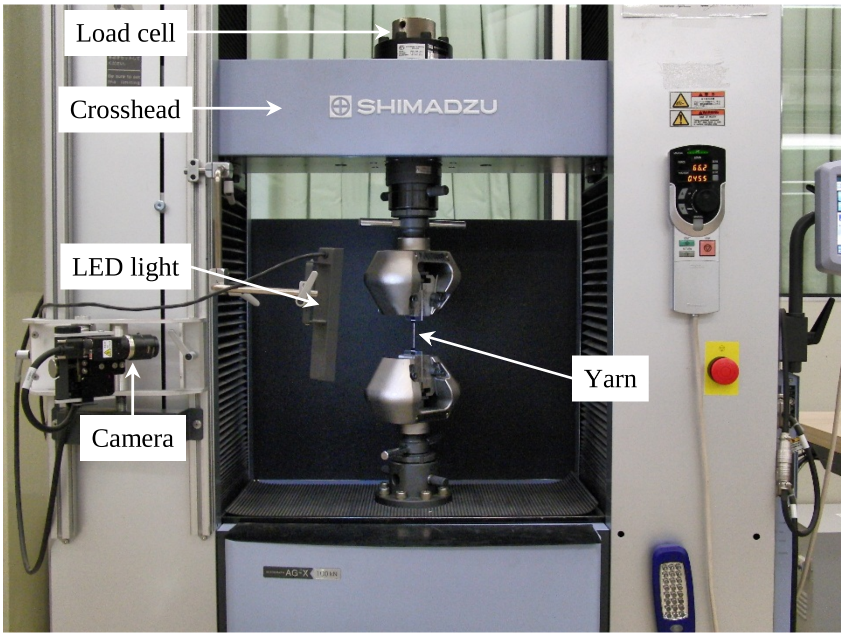

Figure 1: Setup of quasi-static tensile testing.

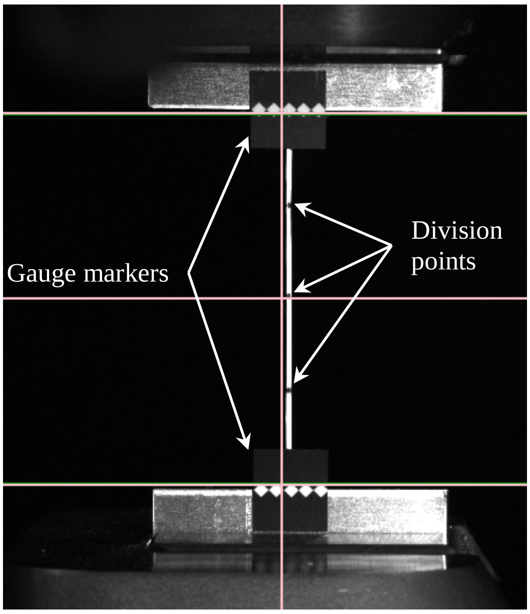

Figure 2: Alignment assistance for mounting single yarn sample.

2.2 EXPERIMENT SETUP

The tensile tests were performed using a Shimadzu AG-X universal test machine (see Figure 1), and the axial tensile force applied on the yarn sample was measured directly by the load cell of the test machine. The aluminium tabs on the yarn sample were frictionally gripped in the serrated jaws, and the tensile loading was applied through the constant movement of crosshead. The fibre fragility prevents the use of traditional strain-sensing devices, such as strain gauge and extensometer. Therefore, a non-contacting video extensometer was used to detect the elongation of single yarn specimen. Two gauge markers were stuck just on the edges of aluminium tabs (see Figure 2), and a CCD camera was employed to track the markers so as to measure the elongation of gauge length. Another advantage of using the camera is that it provides an onscreen assistance for specimen mounting to ensure the axis of yarn is aligned in-line with the axis of crosshead movement, as shown in Figure 2. The gauge length was divided into four equal divisions using a marker pen in order to examine if the gripping effect on the edge will influence the uniform stretch over the entire yarn. A high intensity LED light was used for illumination. In order to examine the strain-rate effect on the tensile properties, the specimens were subjected to the loading speeds of 0.1, 10, and 1000 mm/min corresponding to the nominal strain rates of 3.3×10^{-5}, 3.3×10^{-3}, and 0.33 s^{-1} respectively. For each strain rate, three repeated tests were carried out.

3 RESULTS AND DISCUSSION

3.1 STRESS-STRAIN BEHAVIOUR

During the tests, the fibres failed randomly within the gauge length and no yarn slippage from the grip was observed. Repeatable results were obtained for the stress-strain curves at all the tested strain rates. Figure 3 shows the stress-strain behaviour of single yarn at the strain rate of 3.3×10^{-5} s^{-1}. It can be seen that the curves have four distinct regions which are: (1) the decrimping region, (2) the linear elastic region, (3) the non-linear failure region, and (4) the post-peak region. In the beginning, the curves exhibit a relative large increase in strain for a very small increase in stress. The single yarn specimens tested in this work have an inherent residual crimp due to the weave structure of the fabric, as shown in Figure 4. Therefore during the initial stages of loading, the tensile loading essentially straightens the yarn by removing the crimp, and this initial region is defined as the decrimping region. Afterwards, the straightened yarn starts to take more stress, and the stress-strain curves show an increased linear slope. As the stress increases further, the curves exhibit some nonlinearity which is possibly due to the random failure of individual fibres within the yarn. The stress will redistribute among the undamaged fibres and the yarn is still being able to sustain more tensile loading prior to reaching the peak stress. This region is deemed as the non-linear failure region. After the peak stress has been reached, the stress starts to drop gradually and there is a very large strain increase in this post-peak region. This four-region stress-strain behaviour is similar to that observed in the dynamic tensile testing of Kevlar® single yarn [8], although a shorter post-peak region was found there.

As the strain rate increases, the single yarn fails in a more brittle manner by exhibiting a sharp drop in stress after the peak stress, as shown in Figure 5 and Figure 6 for strain rates of 3.3×10^{-3} and 0.33 s^{-1} respectively. The stress-strain curves show similar behaviour in the decrimping region, linear elastic region, and non-linear failure region. However, the stress drops suddenly from peak to zero after reaching the peak stress, and there is no post-peak region at these relative higher strain rates. This difference is likely caused by the creep of UHMWPE fibres at very low strain rates. A transition from ductile to brittle failure with increasing strain rate has previously been found to exist for UHMWPE fibres by Schwartz et al. [3], Cansfield et al. [10], van der Werff and Pennings [11], and Govaert and Peijs [12]. The results in this paper are in line with the observations of Schwartz et al. [3] where a distinct yield of fibres decreased and disappeared at strain rates greater than 1.7×10^{-3} s^{-1}, and Cansfield et al. [10] who noticed a transitional effect at approximately 3.3×10^{-3} s^{-1}.

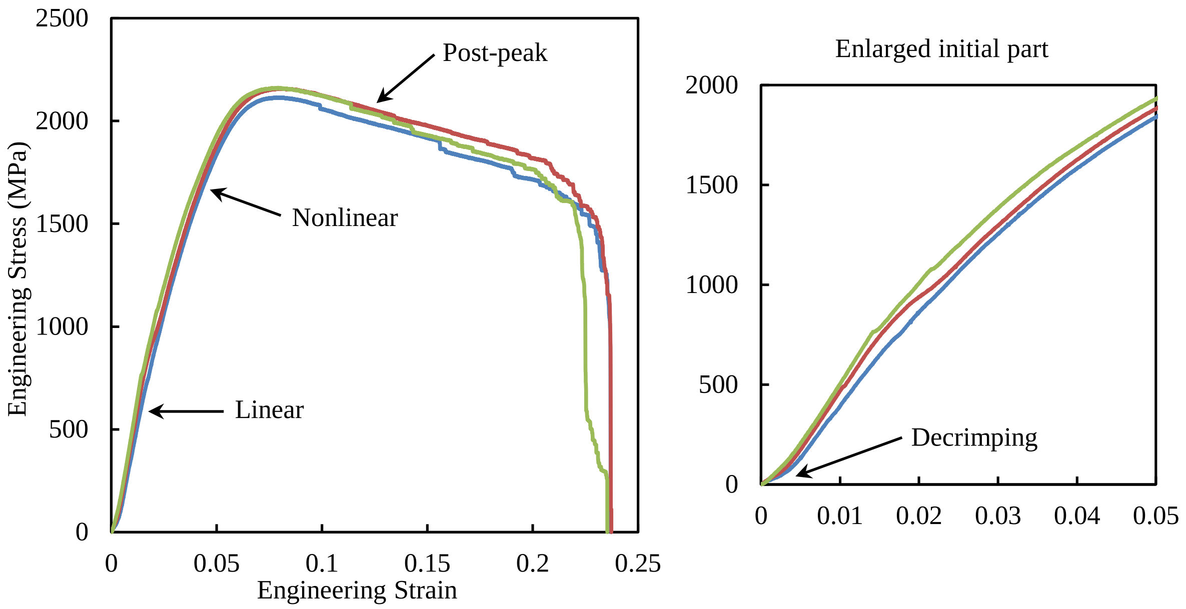

Figure 3: Stress-strain curves tested at the strain rate of 3.3×10^{-5} s^{-1}.

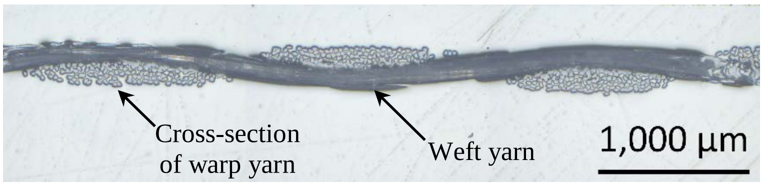

Figure 4: Optical micrograph showing the inherent waviness of yarn in the fabric.

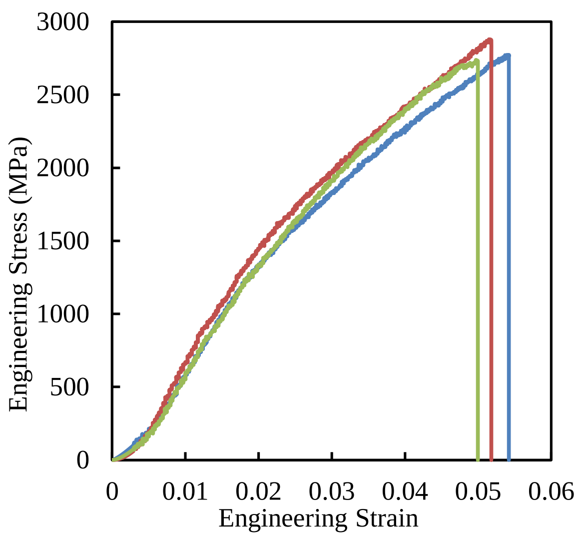

Figure 5: Stress-strain curves tested at the strain rate of 3.3×10^{-3} s^{-1}.

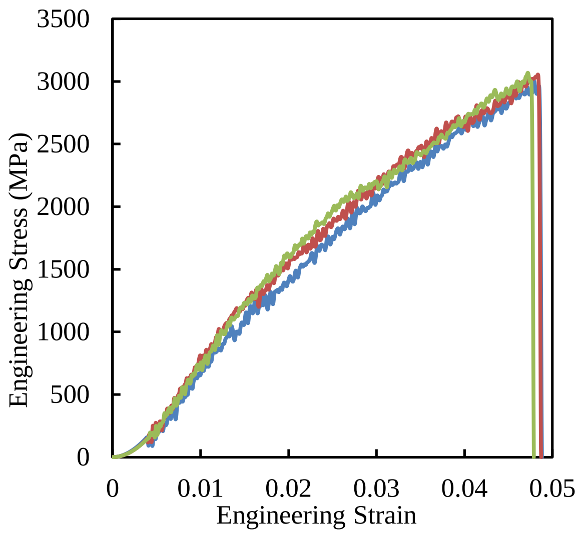

Figure 6: Stress-strain curves tested at the strain rate of 0.33 s^{-1}.

3.2 STRAIN RATE EFFECT

The strain rate effect on the tensile properties of single yarn in terms of tensile strength, maximum strain, Young's modulus, and toughness is examined. The Young's modulus is determined from the slope of the linear elastic region in the stress-strain curve, and the toughness is defined by the area under the entire stress-strain curve. The dependence of these tensile properties on the strain rate are plotted in Figures 7~10 using a logarithmic scale for the strain rate. In Figure 8, the strains corresponding to peak stress at the strain rate of 3.3×10^{-5} s^{-1} are also included for comparison. The strain energies under the stress-strain curve up to the peak stress at the strain rate of 3.3×10^{-5} s^{-1} are also plotted in Figure 10. The results indicate that the tensile properties of single UHMWPE yarn are highly sensitive to strain rate over the range tested in this study. The tensile strength and Young's modulus increases with strain rate while the maximum strain and toughness decreases.

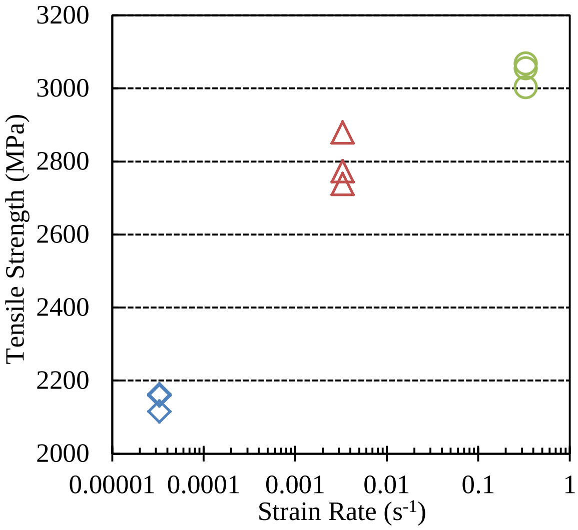

Figure 7: Tensile strength at different strain rates.

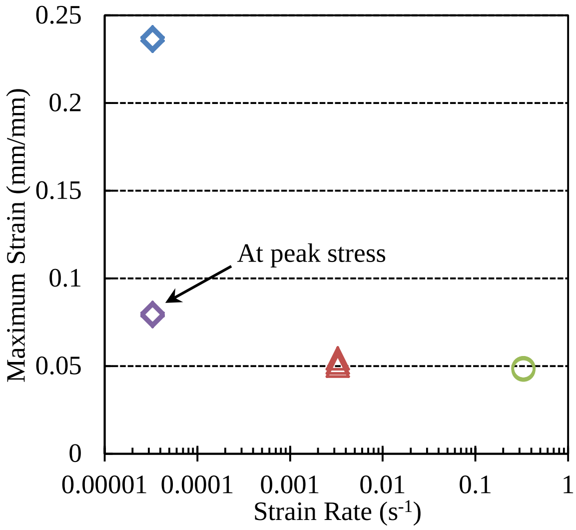

Figure 8: Maximum strain at different strain rates.

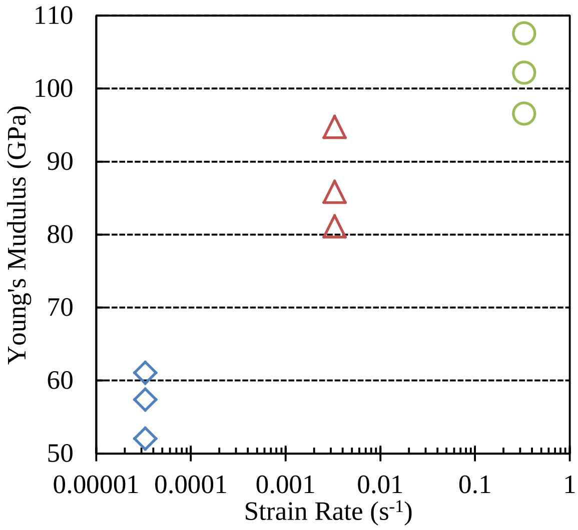

Figure 9: Young's modulus at different strain rates.

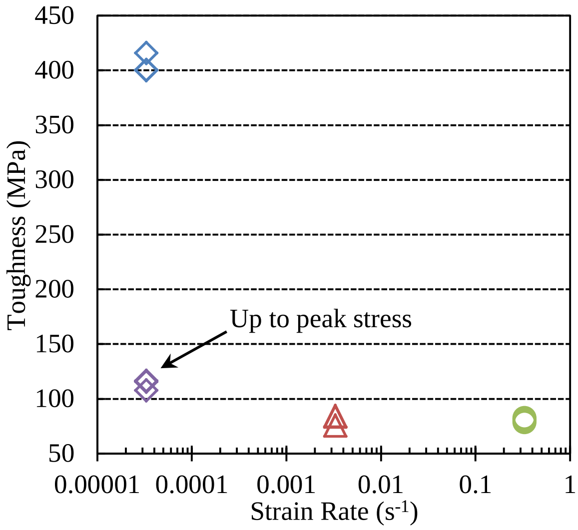

Figure 10: Toughness at different strain rates.

The average values of tensile strength, maximum strain, Young's modulus, and toughness at different strain rates are summarised in Table 1. It is instructive to compare the measured values with those provided by the manufacturer [13]. In terms of tensile strength, the measured values at strain rates of 3.3×10^{-5} and 3.3×10^{-3} s^{-1} are lower than the value range from the manufacturer. The manufacturer values are given in the form of a single fibre. The lower tensile strength values of a yarn is probably caused by the non-uniform loading among the fibres within a yarn. Besides, fibre damage during the yarn bundling and fabric weaving process will lead to the reduction in tensile strength of a yarn as well. Previous study showed the tensile strength of a single Dyneema® SK76 fibre exceeded that of a yarn by about 20%

[7]. The maximum strains measured in this study are higher than the value range from manufacturer, and this is caused by the presence of waviness in the yarn.

Strain Rate (S^{-1})	Material Form	Tensile Strength (GPa)	Maximum Strain (%)	Young's Modulus (GPa)	Toughness (MPa)
3.3×10^{-5}	Yarn	2.15	23.66 (7.92)*	56.81	405.36 (113.14)*
3.3×10^{-3}	Yarn	2.80	5.20	87.24	81.13
0.33	Yarn	3.04	4.85	102.11	80.62
Manufacturer	Fibre	2.9~3.3	2.9~3.5	97~113	-

*Values in the round brackets are corresponding to the peak stress.

Table 1: Tensile properties of single yarn at different strain rates.

4 CONCLUDING REMARKS

The tensile properties of Spectra® 1000 fibres in the yarn form were studied in detail at various low strain rates. According to the measured stress-strain behaviour, there was a transition from ductile to brittle failure mode as the strain rate increased, and this phenomenon significantly reduced the amount of energy absorbed at higher strain rates. The tensile properties of single yarn exhibited pronounced strain-rate dependence over the range of strain rates tested. More specifically, the tensile strength and Young's modulus increased with strain rate while the maximum strain and toughness decreased. This paper provides an initial insight into the strain-rate sensitivity of UHMWPE single yarn via quasi-static tensile tests.

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