The effectiveness of combined gripping method in tensile testing of UHMWPE single yarn

H X Wang1, P J Hazell, K Shankar, E V Morozov and J P Escobedo

School of Engineering and Information Technology, University of New South Wales
Canberra, ACT 2600, Australia

E-mail: Hongxu.Wang@student.adfa.edu.au

Abstract. This paper presents the experimental study on the effectiveness of combined gripping method employed in the tensile testing of UHMWPE (Dyneema® SK75) single yarn. Seven different solutions including epoxy, acrylic, and ethyl cyanoacrylate adhesives were tested under quasi-static loadings in order to determine the most effective adhesive for bonding UHMWPE single yarn to aluminium sheets. The ethyl cyanoacrylate adhesive combined with polyolefin surface primer was found to be the best choice which could prevent yarn slippage and ensure the failure of yarn occurs in the gauge section. The single yarns were then tested at three strain rates of 3.3×10⁻⁵, 3.3×10⁻³, and 0.33 s⁻¹. The tensile strength, maximum strain, and Young’s modulus were determined from the measured stress-strain curves and compared with the values from literature; the results showed these tensile properties of single yarn depend on strain rate over the range tested.

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) fibres are produced through gel-spinning and subsequent hot drawing. This process creates highly oriented molecular chains which exhibit outstanding specific tensile strength and stiffness [1]. In addition, their excellent chemical, fatigue, and abrasion resistance render them an attractive material for potential use in high-performance textiles and composites. Woven fabrics made of these fibres are increasingly used in impact-related applications, such as soft body armour and propulsion engine containment system, where large deformation and high energy absorption are required. These applications have stimulated a demand for numerical simulation of fabrics and in-depth study on the behaviour of yarns and their interaction, which requires experimentally verified material properties of single yarn, the basic load carrying component of a fabric. Although the quasi-static tensile properties for the single fibre form of the material are usually available from the manufacturers, these characteristics cannot be extrapolated and scaled up directly for a yarn consisting of many fibres. Previous study showed the tensile strength of a single Dyneema® SK76 fibre exceeded that of a yarn by about 20% [2]. Furthermore, the strain rates observed in impact applications are far beyond the order of magnitude of the strain rates in the quasi-static loadings [3]. Hence, the material properties of constitutive single yarn must be studied under experimental conditions similar to impact events.

1 Address for correspondence: H X Wang, School of Engineering and Information Technology, University of New South Wales Canberra, ACT 2600, Australia. E-mail: Hongxu.Wang@student.adfa.edu.au.
It is generally accepted that a longitudinal strain wave, travelling at the speed of sound in the material, is generated in fabric yarns upon impact [4]. This wave stretches the yarns and causes the material primarily subjected to axial tension loading. Although there is an increasing demand for characterising the tensile properties of high performance fibres, how to grip the fibres tightly enough without introducing excessive stress concentration is a challenging task. The principal requirements of a suitable gripping method are preventing fibre slippage while maintaining the fibre tension required to bring them to failure, and ensuring the failure occurs in the gauge section such that the failure is not initiated by the grips [3]. Several different methods for gripping fibres during tensile test were explored. The direct clamping between flat jaws is the most common method of gripping specimens in material testing. This gripping mechanism is done by either an external or a self-clamping force that is almost uniform over the entire clamped length of the specimen, with friction acting on both sides of the specimen. Shim et al. [5] tested the dynamic tensile properties of Twaron® fibres using a specially designed direct clamping device. ASTM D3379 (Standard test method for tensile strength and Young's modulus for high-modulus single-filament materials, withdrawn in 1998 with no replacement) [6] introduced an adhesive gripping method which adheres the test fibres onto a mounting tab with a centre hole or a longitudinal slot of a fixed gauge length. The mounting tab is then gripped by the test machine, and the middle part of the tab is cut or burned away, leaving the fibre specimen free to be tested. This method is also specified in the ASTM C1557 (Standard test method for tensile strength and Young's modulus of fibers, current version 2014) [7]. This adhesive gripping method has been adopted in the quasi-static tensile testing of carbon fibres and glass fibres [8, 9], and the quasi-static tensile testing of poly(p-phenylene terephthalamide) (PPTA) fibres [10, 11]. There are some other methods using different gripping mechanisms were reported in the literature. For example, PET textile cable was secured by a progressive binding on the grips in dynamic tensile tests [12]; a capstan method which grips the yarn by winding it's ends around circular pins was used in quasi-static tensile tests of Twaron® single yarn [13].

The compression strength of UHMWPE fibres is only around 1% of the tensile strength along the fibre axis [1]. So when using a direct gripping method, insufficient pressure can lead to fibre slippage, while too much pressure would easily result in fibre crush by the rigid surfaces of the clamp. Moreover, UHMWPE fibres are difficult to grip using the standard specified adhesive method due to their poor adhesion characteristic which is attributed to the non-polar nature of the (—CH2—CH2—)n backbone and the low surface energy [14]. Therefore, it is even more difficult to grip UHMWPE fibres effectively in tensile testing. Several potential methods were experimented with. Tan et al. [13] improved the direct clamping device designed by Shim et al. [5]; the Twaron® fibres were sandwiched between two layers of pliable urethane foam in order to protect the fibres from large clamping forces and increase the contact area, and then clamped by a pair of flat grips. Kim et al. [10, 15] developed a method of direct gripping on single PPTA fibre utilising two poly methyl methacrylate (PMMA) blocks, and the clamping force of the blocks was controlled by a spring. This method was also employed for tensile testing of Dyneema® SK76 single fibre at different loading rates [16]. Zhu et al. [17, 18] designed a combined gripping method to reduce stress concentration and improve load transfer in grips. Both ends of a Kevlar® single yarn were sandwiched between two aluminium sheets and glued to them using epoxy adhesive. The aluminium face-sheets were then friction gripped between steel wedges that had serrated surfaces. Russell et al. [2] also used this combined gripping method for tensile testing of Dyneema® SK76 single fibre and single yarn. The fibre and yarn samples were sandwiched between two rubber sheets and bonded to them using cyanoacrylate adhesive. Besides, Russell et al. [2] wrapped the yarn around a semicircular anvil and adhered to it by cyanoacrylate adhesive in both quasi-static and dynamic tensile tests, however, the tensile strength determined from these two gripping methods showed obvious difference.

In this paper, the effectiveness of a combined gripping method similar to that proposed by Russell et al. [2] and Zhu et al. [17, 18] has been experimentally studied for clamping Dyneema® SK75 single yarn in the tensile testing. The suitable adhesive was selected from the trial test of seven different adhesives. After the adhesive was selected, the single yarn specimens were tested at three strain rates.
of $3.3 \times 10^{-5}$, $3.3 \times 10^{-3}$, and 0.33 s$^{-1}$. The tensile strength, maximum strain, and Young’s modulus were calculated from the measured stress-strain curves and compared with the values from manufacturer and published elsewhere. Although the ultimate goal is the characterisation of yarn properties under high speed loadings mimicking the loading rates that are seen in an impact event, this initial study focuses on the assessment of the combined gripping method and the yarn properties taken under quasi-static tension loadings.

2. Experimental methodology

2.1. Specimen preparation

The as-received material was a roll of 4-harness satin weave fabric consisting of Dyneema® SK75 fibres (see figure 1). The warp yarns were randomly extracted from the fabric with care for tensile testing. The bulk density and linear density of the yarn are 0.97 g/cm$^3$ and 1500 dtex respectively. The cross-sectional area of the yarn was calculated as 0.155 mm$^2$ by dividing the linear density of the yarn by its bulk density. The yarn ends were sandwiched between cleaned aluminium plates and bonded to them using suitable adhesives, and a gauge length of 50 mm was left in the middle (see figure 2).

![Figure 1. Optical micrograph showing the 4-harness satin weave pattern of Dyneema® fabric.](image)

![Figure 2. Schematic diagram of combined gripping method for single yarn.](image)

Adhesive selection is crucial to producing a high strength bonding between the yarn specimen and aluminium sheet, because any yarn slippage will affect the force and displacement measurement.
There are many kinds of adhesives available in the market, and each one is better for use in different environments and with different material substrates. In order to find out the effective adhesive can be used in the tensile testing of UHMWPE single yarn, seven solutions were experimented with in this study. Table 1 lists the adhesive products and their chemical types which fall into three categories: epoxy, acrylic, and ethyl cyanoacrylate. Epoxy adhesive was successfully used for quasi-static and dynamic tensile testing of Kevlar® 49 single yarn [18], so two general-purpose high strength epoxy adhesives were tested in this study. Two acrylic-based adhesives, which are designed to bond low surface energy plastics including UHMWPE without special surface pre-treatment, were included in the test as well. Two ethyl cyanoacrylate adhesives were employed because this kind of adhesive was used for tensile tests of Dyneema® SK76 single fibre and yarn [2]. Except for using cyanoacrylate adhesives alone, an aliphatic amine primer was applied on the yarn ends to make the surface more suitable for bonding with corresponding cyanoacrylate adhesive. All the adhesives were used strictly according to the instruction of each product. More details of these adhesives can be found in the technical data sheet and material safety data sheet of the products.

Table 1. Adhesives tested for the combined gripping method.

| Adhesive product                          | Chemical type          |
|------------------------------------------|------------------------|
| Epirez Episet Structural Adhesive 8242   | Epoxy resin            |
| Loctite 3801 Epoxy Adhesive              | Epoxy resin            |
| Loctite 3038 Structural Adhesive         | Acrylic                |
| 3M Scotch-Weld Structural Plastic Adhesive DP-8005 | Acrylic            |
| Bostik Super Glue                        | Ethyl cyanoacrylate    |
| Loctite 401 Instant Adhesive             | Ethyl cyanoacrylate    |
| Loctite 401 Instant Adhesive & Loctite 770 Polyolefin Primer | Ethyl cyanoacrylate |

2.2. Experiment setup

The quasi-static tensile tests were conducted using a Shimadzu AG-X universal testing machine. The loading rate was controlled by the speed of the crosshead and the tensile force was measured by a load cell with a capacity of 100 kN. The loading speed was set at 0.1, 10, and 1000 mm/min for the specimen with a gauge length of 50 mm, corresponding to nominal strain rates of $3.3 \times 10^{-5}$, $3.3 \times 10^{-3}$, and $0.33 \, \text{s}^{-1}$, respectively. The traditional strain-sensing devices, such as strain gauge and extensometer, may cause damage to the delicate fibres. Therefore, a non-contacting video extensometer, Shimadzu DVE-101, was employed to perform strain measurement by using a CCD camera to capture digital images of the test specimen. The image data was then processed to calculate the elongation of the gauge length. The aluminium face-sheets were gripped by steel wedges that had serrated surfaces. As the specimen was loaded, there was a uniform stretching of the yarn until failure.

3. Results and discussion

3.1. Effectiveness of adhesives

An effective adhesive for the combined gripping method is considered to be one which could prevent yarn slippage in the gripping region and insure the fibre failure occurs in the gauge section such that there is no fibre failure initiated by the grips. Of all the adhesives tested in the experiment, the ethyl cyanoacrylate-based adhesive combined with polyolefin surface primer was found to be the best solution that meets the abovementioned requirements. Figure 3 shows the tensile process of single yarn subjected to a loading speed of 10 mm/min using Loctite 401 Instant Adhesive and Loctite 770 Polyolefin Primer. The gauge length was divided into four equal portions using a marker pen before the test. It is obvious that the four portions keep fairly equal up to the moment just before failure.
occurs (time = 16s), which means the yarn was uniformly stretched in the entire gauge length and there was negligible yarn slippage in the gripping region.

Yarn pull-out from the gripping region was observed when the acrylic-based adhesives were employed, as illustrated in figure 4. The yarn was pulled out from the upper grip because the top portion of gauge length ($L_1$) was becoming much longer than the other portions as the test progressed. Besides, there was little fibre fracture occurred during the test. The cured acrylic adhesives were semi-rigid and cannot provide enough strength to hold the yarn. When the epoxy-based adhesives were used, there was no yarn pull-out observed in the gripping region up to failure, however, some fibres fractured in the gripping region as shown in figure 5. The reason for this phenomenon may be the viscosity of the used epoxy adhesives because it was not low enough to infiltrate all the fibres within the yarn.

Figure 3. Video frames showing the uniform stretching of single yarn up to failure tested at the loading speed of 10 mm/min using Loctite 401 Instant Adhesive & Loctite 770 Polyolefin Primer.

Figure 4. Video frames showing the pull-out of yarn tested at the loading speed of 10 mm/min using Loctite 3038 Structural Adhesive.
3.2. Stress-strain curves

After the suitable adhesive was selected, the single yarn samples were tested at strain rates of $3.3 \times 10^{-5}$, $3.3 \times 10^{-3}$, and $0.33 \text{ s}^{-1}$, respectively. For each strain rate, at least three repeated tests were carried out. The tensile behaviour at the strain rate of $3.3 \times 10^{-5} \text{ s}^{-1}$ in terms of the engineering stress and engineering strain is shown in figure 6. The curves show good repeatability which means the method and adhesive used in this test can produce stable and repeatable tensile behaviour of single yarn. The quasi-static stress-strain relationships of Dyneema® SK75 single fibre and fibre bundle tested by Kromm et al. [19] are also included in figure 6 for comparison, although the strain rates for the representative curves were not indicated explicitly in their paper. It is clear that the stress-strain curves of single yarn measured here are very similar to the curve of single fibre obtained by Kromm et al. [19]. The single yarn specimens tested in this work have an inherent residual crimp due to the weave structure of the fabric (see figure 1). In the initial region, the stress-strain curves show a relative large increase in strain for a very small increase in stress, and the tensile load essentially straightens the yarn by removing the crimp at the beginning. The curve of fibre bundle tested by Kromm et al. [19] shows
a different behaviour, that is a stepped drop of stress after peak, which indicates the fibres in the
bundle failed one by one. There can be a problem of not aligning all fibres in the bundle very well
with the load applied in their work which leads to non-uniform stretching of the fibres. The method
and adhesive used here could align the fibres in the yarn properly.

### 3.3. Tensile properties at different strain rates

In order to examine the strain rate effect on the tensile properties of single yarn, the tensile strength,
maximum strain, and Young’s modulus are calculated from the measured stress-strain relationships at
different strain rates, as shown in table 2. The Young’s modulus is determined from the linear slope
after the initial decrimping region from the stress-strain curves. The results indicate the tensile
properties of Dyneema® SK75 single yarn are strain rate dependent; the tensile strength and Young’s
modulus increase with strain rate while the maximum strain decreases.

It is instructive to compare these results with the values published in the literature [19] and given
by the manufacturer [20] (see table 2). According to the results published by Kromm et al. [19], only
the maximum strain of Dyneema® SK75 single fibre exhibits some sensitivity to strain rate while the
tensile strength and Young’s modulus show no dependency on strain rate in the investigated range of
their study. When compared to the properties from the manufacturer, the measured tensile strength at
low strain rate \(3.3 \times 10^{-5} \text{ s}^{-1}\) in this study is lower. The yarn bundling and fabric weaving process will
cause damage to the fibres, which leads to the reduction in the tensile strength. It is common that the
tensile strength of a single yarn is lower than that of a single fibre [2]. The maximum strains measured
in this study are higher than the values from literature and manufacturer, and this is only because the
presence of waviness within a yarn.

| Strain Rate (s\(^{-1}\)) | Material Form | Tensile Strength (GPa) | Maximum Strain (%) | Young’s Modulus (GPa) |
|-------------------------|---------------|------------------------|--------------------|----------------------|
| \(3.3 \times 10^{-5}\)  | Yarn          | 2.63                   | 6.94               | 65.69                |
| \(3.3 \times 10^{-3}\)  | Yarn          | 3.04                   | 5.19               | 78.37                |
| 0.33                    | Yarn          | 3.33                   | 5.03               | 81.19                |
| \(1.7 \times 10^{-5}\) [19] | Fibre        | 2.4                    | 5.88               | 56                   |
| \(1.7 \times 10^{-4}\) [19] | Fibre        | 2.4                    | 3.95               | 71                   |
| \(6.7 \times 10^{-4}\) [19] | Fibre        | 2.4                    | 4                  | 71                   |
| \(1.7 \times 10^{-2}\) [19] | Fibre        | 2.4                    | 3.76               | 62                   |
| Manufacturer [20]        | Fibre         | 3.3~3.9                | 3~4                | 109~132              |

### 4. Conclusion and future work

The combined gripping method was employed to perform tensile tests of single yarn under quasi-static
loading conditions. The ethyl cyanoacrylate-based adhesive combined with polyolefin surface primer
was determined to be the ideal choice for application to UHMWPE single yarn. Image analysis
showed no yarn slippage from the aluminium sheets and the measured stress-strain curves showed
good repeatability of the results. The tensile strength and Young’s modulus of Dyneema® SK75 single
yarn was found to increase with the strain rate while the maximum strain decrease. The present work
is a step towards a complete experimental characterisation of Dyneema® SK75 single yarn, and
dynamic tensile tests using this combined gripping method will be conducted in the near future.

### Acknowledgments

The authors gratefully acknowledge Mr. D Sharp for his technical assistance during the experimental
work reported in this paper. H Wang would like to thank UNSW Canberra and the China Scholarship
Council for funding his PhD study.
References

[1] Marissen R 2011 Design with ultra strong polyethylene fibers Materials Sciences and Applications 2 319-30

[2] Russell B P, Karthikeyan K, Deshpande V S and Fleck N A 2013 The high strain rate response of Ultra High Molecular-weight Polyethylene: From fibre to laminate International Journal of Impact Engineering 60 1-9

[3] Farsi Dooraki B, Nemes J A and Bolduc M 2006 Study of parameters affecting the strength of yarns J. Phys. IV France 134 1183-8

[4] Shahkarami A, Cepus E, Vaziri R and Poursartip A 2006 Material responses to ballistic impact, Lightweight Ballistic Composites ed A Bhatnagar (England: Woodhead Publishing) pp 72-100

[5] Shim V P W, Lim C T and Foo K J 2001 Dynamic mechanical properties of fabric armour, International Journal of Impact Engineering 25 1-15

[6] ASTM International 1989 Standard test method for tensile strength and Young's Modulus for high-modulus single-filament materials (PA: West Conshohocken) ASTM D3379 (1989) e1

[7] ASTM International 2014 Standard test method for tensile strength and young's modulus of fibers (PA: West Conshohocken) ASTM C1557-14

[8] Pardini L C and Manhani L G B 2002 Influence of the testing gage length on the strength, young's modulus and Weibull modulus of carbon fibres and glass fibres Materials research 5 411-20

[9] Ilankeeran P K, Mohite P M and Kamle S 2012 Axial tensile testing of single fibres Modern Mechanical Engineering 2 151-6

[10] Kim J, Heckert N A, Leigh S, Kobayashi H, McDonough W, Rice K and Holmes G 2013 Effects of fiber gripping methods on the single fiber tensile test: I. Non-parametric statistical analysis Journal of Materials Science 48 3623-37

[11] Lim J, Zheng J Q, Masters K and Chen W W 2011 Effects of gage length, loading rates, and damage on the strength of PPTA fibers International Journal of Impact Engineering 38 219-27

[12] Güéган P, Othman R, Pasco F and Bruant R 2012 Dynamic tensile test of single PET textile cables EPJ Web of Conferences 26 01003

[13] Tan V B C, Zeng X S and Shim V P W 2008 Characterization and constitutive modeling of aramid fibers at high strain rates International Journal of Impact Engineering 35 1303-13

[14] Brennan A B, Arnold J J and Zamora M P 1995 Surface modification of ultra-high molecular weight polyethylene fibers by γ-radiation-induced grafting Journal of Adhesion Science and Technology 9 1031-48

[15] Kim J H, Alan Heckert N, Leigh S D, Rhorer R L, Kobayashi H, McDonough W G, Rice K D and Holmes G A 2014 Statistical analysis of PPTA fiber strengths measured under high strain rate condition Composites Science and Technology 98 93-9

[16] Sanborn B and Weerasooriya T 2015 Tensile properties of dyneema SK76 single fibers at multiple loading rates using a direct gripping method Dynamic Behavior of Materials vol 1 ed B Song, D Casem and J Kimberley (Berlin: Springer International Publishing) pp 1-4

[17] Zhu D, Mobasher B and Rajan S 2011 Dynamic tensile testing of Kevlar 49 Fabrics Journal of Materials in Civil Engineering 23 230-9

[18] Zhu D, Mobasher B, Erni J, Bansal S and Rajan S D 2012 Strain rate and gage length effects on tensile behavior of Kevlar 49 single yarn Composites Part A: Applied Science and Manufacturing 43 2021-9

[19] Kromm F X, Lorriot T, Coutand B, Harry R and Quenisset J M 2003 Tensile and creep properties of ultra high molecular weight PE fibres Polymer Testing 22 463-70

[20] Dyneema D S M 2008 Dyneema® high-strength, high-modulus polyethylene fiber fact sheet available at : http://www.pelicanrope.com/pdfs2010/DYNEEMA_factsheet_UHMWPE.pdf